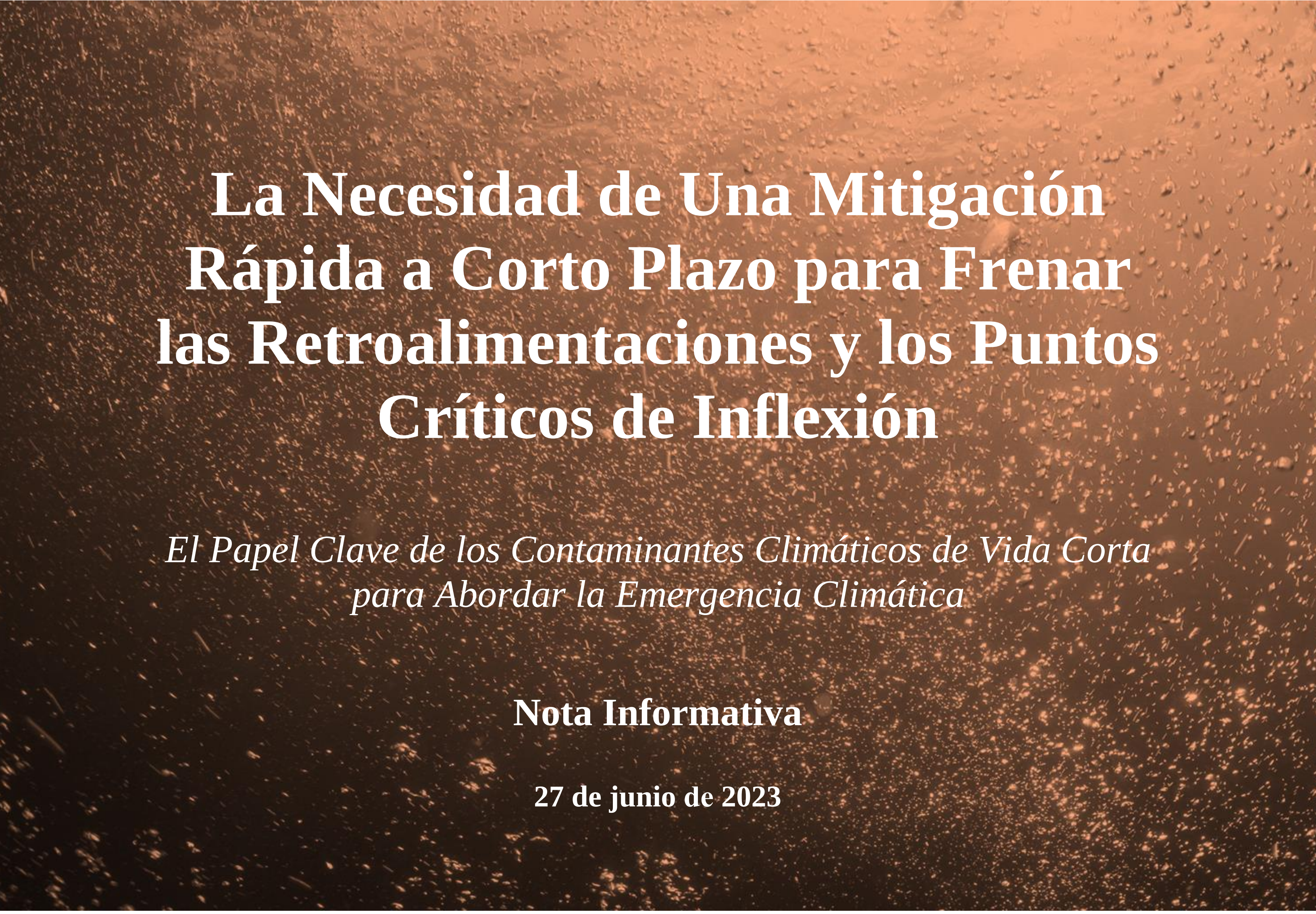

La Necesidad de Una Mitigación Rápida a Corto Plazo para Frenar las Retroalimentaciones y los Puntos Críticos de Inflexión

El Papel Clave de los Contaminantes Climáticos de Vida Corta para Abordar la Emergencia Climática

Nota Informativa

27 de junio de 2023

Institute for Governance
& Sustainable Development (IGSD)

Centro de Derechos Humanos y
Ambiente (CEDHA)

Autores Principales
Durwood Zaelke, Romina Picolotti y Gabrielle Dreyfus

Autores Colaboradores
Trina Chiemi, Kiran Ghosh, Kristin Campbell, Laura Bloomer, Blake Hite, Julie Miller y Daniel Taillant

Reconocimientos
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Institute for Governance
& Sustainable Development

Centro de Derechos Humanos y
Ambiente (CHRE/CEDHA)

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[*] La traducción al español del presente documento fue realizada por María Candela Conforti, Traductora Pública Oficial de Inglés/Español, contacto: mcctranslations@hotmail.com.

Acerca del Institute for Governance & Sustainable Development

La misión del IGSD es aumentar la resiliencia acelerando las medidas de mitigación del cambio climático para frenar el calentamiento a corto plazo y las retroalimentaciones climáticas que se refuerzan a sí mismas, evitar puntos críticos de inflexión catastróficos para el clima y la sociedad, y limitar la temperatura mundial a 1,5 °C,—o al menos mantener controlado este límite de seguridad respecto de dicha temperatura.

Las últimas investigaciones del IGSD muestran que la descarbonización por sí sola no basta para frenar el calentamiento a corto plazo y mantenernos por debajo de 1,5 ºC o incluso del límite más peligroso de 2 ºC. También concluyen que la estrategia más rápida y eficaz es combinar los esfuerzos acelerados para reducir a cero las emisiones de dióxido de carbono (CO_2) de la descarbonización del sistema energético, *con* el *sprint* para reducir rápidamente los supercontaminantes climáticos distintos del CO_2 y proteger los sumideros de carbono. Los supercontaminantes climáticos incluyen cuatro contaminantes climáticos de vida corta (CCVC)—metano (CH_4), hollín negro, ozono troposférico (O_3) e hidrofluorocarbonos (HFC)—así como el óxido nitroso (N_2O) de vida más larga.

Combinar el *sprint* de la mitigación rápida con los esfuerzos acelerados de la descarbonización ayudaría a abordar las cuestiones éticas de la equidad intra e intergeneracional, concediendo a las sociedades el tiempo que necesitan para adaptarse urgentemente a los cambios inevitables y crear resiliencia. Los últimos datos científicos sugieren que la ventana para superar el límite de seguridad de 1,5 °C podría cerrarse tan pronto como a principios de la década de 2030, por lo que esta es la década decisiva para actuar con rapidez para frenar el calentamiento. La teoría de la acción del IGSD se basa en la urgencia de responder rápida y eficazmente para evitar daños irreversibles en el sistema climático con consecuencias catastróficas para todos.

La forma más rápida de reducir el calentamiento a corto plazo en la próxima década es reducir los CCVC. Dado que sólo duran en la atmósfera por un plazo que va de días a 15 años; su reducción evitará el 90% del calentamiento previsto en una década. Las estrategias dirigidas a reducir los CCVC pueden evitar cuatro veces más calentamiento en 2050 que las dirigidas únicamente al CO_2. La reducción de los HFC puede evitar casi 0,1 °C de calentamiento para el 2050 y hasta 0,5 °C a finales de siglo. El calendario inicial de reducción progresiva de la Enmienda de Kigali al Protocolo de Montreal abarcará alrededor del 90% de este objetivo. Los esfuerzos paralelos para mejorar la eficiencia energética de los aparatos de aire acondicionado y otros aparatos de refrigeración durante la eliminación progresiva de los HFC pueden duplicar los beneficios climáticos en 2050. La reducción de las emisiones de metano puede evitar casi 0,3 °C en la década de 2040, con la posibilidad de evitar un calentamiento significativo gracias a las tecnologías emergentes para eliminar el metano atmosférico más rápidamente que su ciclo natural.

Al combinar el *sprint* de mitigación rápida con los esfuerzos acelerados para lograr la descarbonización se reduciría a la mitad la tasa de calentamiento global de 2030 a 2050, se frenaría el ritmo de calentamiento una o dos décadas antes que mediante la descarbonización por sí sola, y se haría posible que el mundo mantuviera controlado el límite de seguridad de 1,5 °C. También se reduciría en dos tercios la tasa de calentamiento del Ártico. Esto ayudaría a frenar las retroalimentaciones climáticas que se refuerzan a sí mismas en el Ártico, y así evitar, o al menos retrasar, la serie de puntos críticos de inflexión proyectados si se superasen los 1,5 °C. Reducir los riesgos climáticos y no sobrepasar los límites para lograr la adaptación es fundamental para aumentar la resiliencia.

El enfoque del IGSD para una mitigación rápida abarca los ámbitos de la ciencia, el derecho, la política y la financiación climática. El IGSD trabaja a escala mundial, regional, nacional y subnacional.

Acerca del Centro de Derechos Humanos y Ambiente (CEDHA/CHRE)

Originalmente fundado en Argentina en 1999, el Centro de Derechos Humanos y Ambiente (CEDHA) (o *Center for Human Rights and Environment*, CHRE, por sus siglas en inglés) procura construir una relación más armoniosa entre el medio ambiente y las personas. Su labor se centra en promover un mayor acceso a la justicia y garantizar el goce de los derechos humanos para las víctimas de la degradación ambiental debido al manejo no sostenible de los recursos naturales, y evitar futuras violaciones. Para ello, CEDHA promueve la formulación de políticas públicas que promuevan el desarrollo sostenible social y ambientalmente inclusivo, a través de la participación de las comunidades, el litigio en aras del interés público, el fortalecimiento de las instituciones democráticas y el desarrollo de capacidades de los principales actores.

CEDHA aborda políticas ambientales y los impactos en los derechos humanos en el contexto del cambio climático mediante numerosos programas de cabildeo que incluyen iniciativas para promover políticas de mitigación climática de acción rápida para contener y revertir el cambio climático; reducir las emisiones de los contaminantes climáticos de vida corta como el carbono negro, los HFC y el metano. Asimismo, estas iniciativas están dirigidas a proteger los glaciares y los entornos del permafrost por su gran utilidad para almacenar agua y regular las cuencas hídricas, y evitar así el impacto del deshielo sobre el nivel del mar y la consecuente influencia en las corrientes oceánicas y las corrientes de aire, considerando también su valor en el albedo global y los diferentes papeles que desempeñan los glaciares para mantener el equilibrio ecológico del Planeta. CEDHA también promueve la responsabilidad empresarial y el cumplimiento de los derechos humanos para abordar el impacto social y ambiental de las principales industrias contaminantes del clima como la producción de petróleo y gas (incluida la fracturación hidráulica), la minería, las fábricas de pasta de papel y la producción artesanal de ladrillos para la construcción.

La Necesidad de una Mitigación Rápida a Corto Plazo para Frenar las Retroalimentaciones y Evitar los Puntos Críticos de Inflexión

El Papel Clave de los Supercontaminantes de Vida Corta para Abordar la Crisis Climática

27 de junio de 2023

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1. Introducción y resumen

La presente *Nota Informativa* resume los datos científicos que respaldan la necesidad de una rápida mitigación del cambio climático para frenar el calentamiento a corto plazo (2022-2041). Se centra en la importancia de reducir los supercontaminantes climáticos y proteger los sumideros de carbono para frenar las retroalimentaciones que se refuerzan a sí mismas y evitar los puntos críticos de inflexión. También explica por qué es fundamental ganar el *sprint* de mitigación rápida de aquí a 2030 para hacer frente a la emergencia climática y cómo el mismo complementa la carrera para descarbonizar la economía y lograr emisiones netas iguales a cero para 2050 o antes.

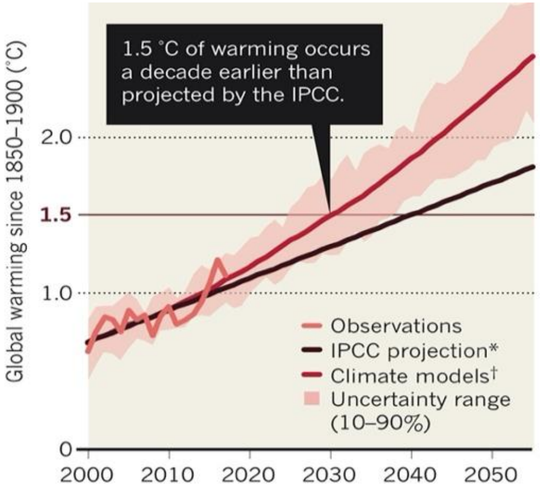
El cambio climático plantea dos retos, o carreras, que debemos afrontar simultáneamente: la carrera por estabilizar el clima a largo plazo y la carrera por desacelerar el ritmo de calentamiento a corto plazo para reducir el riesgo de fenómenos climáticos extremos que aumenta con la tasa de calentamiento y amenaza con acelerar las retroalimentaciones y desencadenar una cascada de puntos de inflexión irreversibles. La reducción de los supercontaminantes climáticos, en particular los de vida corta—carbono negro, metano (CH_4), ozono troposférico e hidrofluorocarbonos (HFC)—puede evitar un calentamiento cuatro veces mayor en 2050 que la reducción del CO_2 por sí sola[1], así como reducir el calentamiento previsto en el Ártico en dos tercios y la tasa de calentamiento global a la mitad[2]. Reducir los riesgos climáticos y no sobrepasar los límites para lograr la adaptación es fundamental para aumentar la resiliencia[3].

A. La ventana se está cerrando para mantenerse dentro de una zona climática segura

La ventana para una mitigación eficaz que permita frenar las retroalimentaciones y evitar los puntos críticos de inflexión se está reduciendo a unos 10 años o menos, incluida la ventana para evitar estrellarse contra la barrera de seguridad de 1,5 ºC.

- El mundo podría alcanzar el umbral de 1,5 °C a principios de la década de 2030 debido al aumento de las emisiones, el descenso de la contaminación atmosférica por partículas que desenmascara el calentamiento existente y la variabilidad natural del clima (**Figura 1**)[4]. La probabilidad de sobrepasar los 1,5 °C en 2026 durante al menos un año se ha duplicado desde 2020, con una probabilidad (48%) de que al menos un año sea 1,5 °C más cálido, según la Organización Meteorológica Mundial[5].
- En la actualidad, la Tierra retiene el doble de calor que en el 2005, y la pérdida de hielo marino reflectante y los cambios en las nubes contribuyen significativamente al calor adicional que retiene el planeta[6]. Los cambios en las nubes provocados por el clima actúan como una retroalimentación que se refuerza a sí misma y que conduce a un mayor calentamiento y a una mayor sensibilidad climática[7].
- Incluso con 1,2 °C de calentamiento global en 2021-2022[8], los fenómenos meteorológicos extremos son cada vez más frecuentes y graves.[9]

Figura 1. Calentamiento proyectado



Fuente: Xu Y., Ramanathan V. & Victor D. (2018) *Global warming will happen faster than we think*, Comentario, NATURE 564: 30–32.

B. Sólo un doble ataque contra el CO_2 y los supercontaminantes climáticos, en particular el metano, permitiría al mundo mantener los 1,5 °C al alcance y permanecer por debajo de los 2 °C

- Las estrategias relativas al CO_2 y los CCVC son complementarias y no intercambiables. Alcanzar el objetivo de lograr emisiones de CO_2 Netas iguales a Cero para 2050 es esencial para estabilizar el clima a finales de siglo debido a la larga vida útil del CO_2 en la atmósfera; pero no puede evitar por sí solo que las temperaturas globales superen los 1,5 °C por encima de los niveles preindustriales. Si se supera este límite de seguridad, se espera que el clima mundial pase por puntos críticos de inflexión irreversibles.
  - Los recientes informes de evaluación, IE6, confirman que la reducción de las emisiones provenientes de los combustibles fósiles—la principal fuente de CO_2—mediante la descarbonización del sistema energético y el cambio a energías limpias, *de forma aislada, en realidad empeora el calentamiento global a corto plazo*. Esto se debe a que la quema de combustibles fósiles también crea aerosoles de sulfato, que actúan enfriando el clima. Estos sulfatos refrigerantes desaparecen rápidamente de la atmósfera, mientras que el CO_2 perdura por mucho más tiempo, lo que provoca un calentamiento general durante la primera o segunda década[10].
- Además de reducir a cero las emisiones de CO_2, es esencial frenar el calentamiento a corto plazo, disminuyendo los contaminantes climáticos de vida corta (CCVC): metano (CH_4), hollín o carbono negro, ozono troposférico (O_3) e hidrofluorocarbonos (HFC). (Estos contaminantes de vida corta suelen denominarse "supercontaminantes" por su potencia y capacidad para reducir rápidamente el calentamiento. El N_2O también es un supercontaminante, pero no es de vida corta).
- Reducir los CCVC es la única forma conocida de reducir el ritmo de calentamiento a corto plazo, frenar las retroalimentaciones que se refuerzan a sí mismas y evitar puntos críticos de inflexión irreversibles.

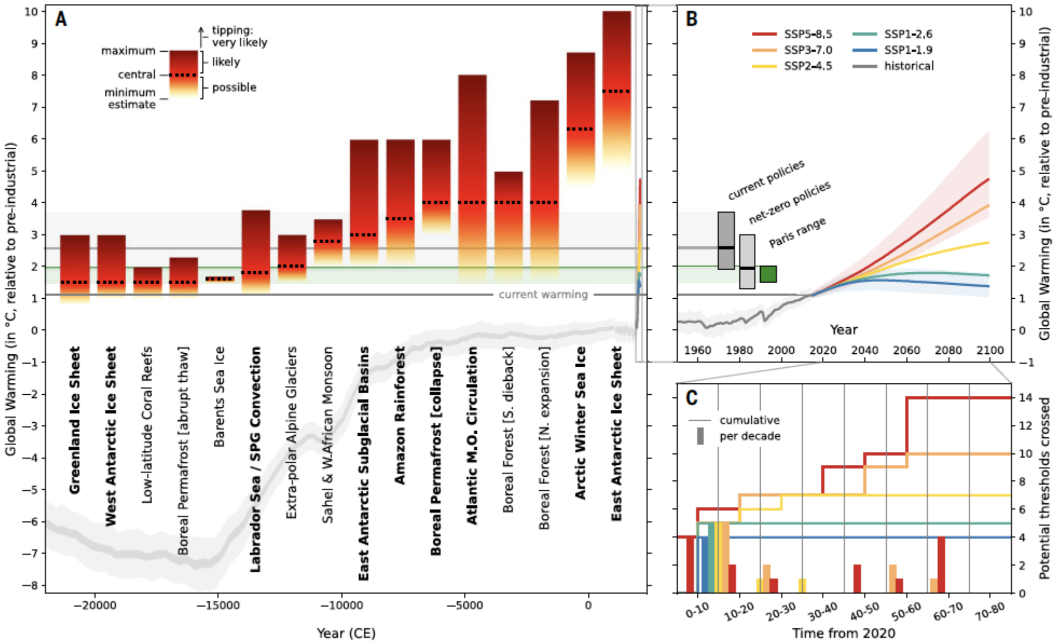
C. Es hora de ampliar la estrategia para evitar una catástrofe climática

- Para hacer frente a la emergencia climática a corto plazo es necesario seleccionar soluciones de mitigación rápidas que eviten al máximo el calentamiento en el menor tiempo posible durante la próxima década o dos[11]; frenen las retroalimentaciones que se refuerzan a sí mismas y eviten los puntos críticos de inflexión[12]; y que protejan a las personas y los ecosistemas más vulnerables[13] del calor, la sequía, las inundaciones y otros fenómenos extremos que aumentarán drásticamente en gravedad y frecuencia con cada incremento de calentamiento adicional[14].
  - Además de reducir el CO_2 y los CCVC, deben emplearse otras estrategias de mitigación rápida, incluida la protección de los sumideros[15]; este enfoque combinado es esencial para alcanzar los objetivos climáticos a corto y largo plazo.
- Según el Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC, por sus siglas en inglés), para mantener el planeta habitable limitando el calentamiento a 1,5 °C sin sobrepaso o con un sobrepaso limitado, es necesario reducir las emisiones mundiales de metano de origen humano en un 34% en 2030 y en un 44% en 2040 con respecto a los niveles modelizados para 2019, además de reducir las emisiones mundiales de CO_2 a la mitad en 2030 y en un 80% en 2040, así como reducir drásticamente otros CCVC y el óxido nitroso[16].
  - El IE6 del WGIII concluye además que "[l]a reducción drástica de las emisiones de GEI [gases de efecto invernadero] para 2030 y 2040, en particular la reducción de las emisiones de metano y un pico más bajo de calentamiento, disminuirá la probabilidad de sobrepasar los límites de calentamiento y conducirá a una menor dependencia de las emisiones netas negativas de CO_2 que invertirán el calentamiento en la segunda mitad del siglo... Debido a la corta vida del CH_4 en la atmósfera, la reducción drástica proyectada de las emisiones de CH_4 hasta que se alcancen emisiones netas de CO_2 iguales a cero en las trayectorias de mitigación modelizadas reducirá efectivamente el calentamiento global máximo (*nivel de confianza alto*)"[17]. [La traducción nos pertenece]
- Estos resultados se basan en las conclusiones del *Informe Especial del IPCC sobre el Calentamiento Global de 1,5 °C* que identificó las tres estrategias esenciales para mantener el planeta habitable:
  - i. Alcanzar emisiones de CO_2 iguales a cero a mitad de siglo;
  - ii. Realizar reducciones drásticas de supercontaminantes CCVC en las próximas décadas; y
  - iii. Eliminar hasta 1.000 billones de toneladas de CO_2 de la atmósfera para 2100[18].

2. Las retroalimentaciones y los puntos críticos de inflexión son clave para entender la emergencia planetaria

La evidencia sobre las retroalimentaciones y los puntos críticos de inflexión sugiere que ya nos encontramos en un estado de emergencia planetaria, en el que tanto el riesgo como la urgencia de la situación son agudos. El IPCC define un punto crítico como "un umbral crítico a partir del cual un sistema se reorganiza, a menudo de forma abrupta y/o irreversible"[19]. Los modelos del sistema terrestre proyectan un conjunto de seis de esos cambios repentinos entre 1 °C y 1,5 °C de calentamiento y otros once entre 1,5 °C y 2 °C[20], tal como se confirma en dos informes especiales del IPCC[21]. Según una evaluación reciente, superar los 1,5 °C aumenta la probabilidad de desencadenar o comprometer seis puntos críticos de inflexión climáticos que se propagan por sí solos (**Figura 2**)[22]. Se prevé que, las interacciones de tipo dominó entre estos sistemas reduzcan los umbrales y aumenten el riesgo de desencadenar una cascada mundial de puntos críticos de inflexión (**Figura 3**)[23]. Otros puntos críticos de inflexión que aún no se han descubierto se deben a las limitaciones de los modelos actuales y a la exclusión de procesos como los relacionados con el permafrost y otras retroalimentaciones biogeoquímicas[24]. Las retroalimentaciones que se refuerzan a sí mismas, incluida la pérdida de hielo marino en el Ártico, se encuentran entre los eslabones más vulnerables de la cadena de protección del clima[25]. Los extremos desencadenados por estas retroalimentaciones plantean otros riesgos sistémicos, como el colapso financiero y social. El mapeo del calor extremo proyectado al Índice de Estados Frágiles apunta a un gran potencial de conflicto y vulnerabilidad, que actualmente se encuentra excluido de la mayoría de los análisis económicos sobre los costos sociales de la contaminación climática[26].

Figura 2. Cambios climáticos repentinos a medida que aumenta la temperatura global



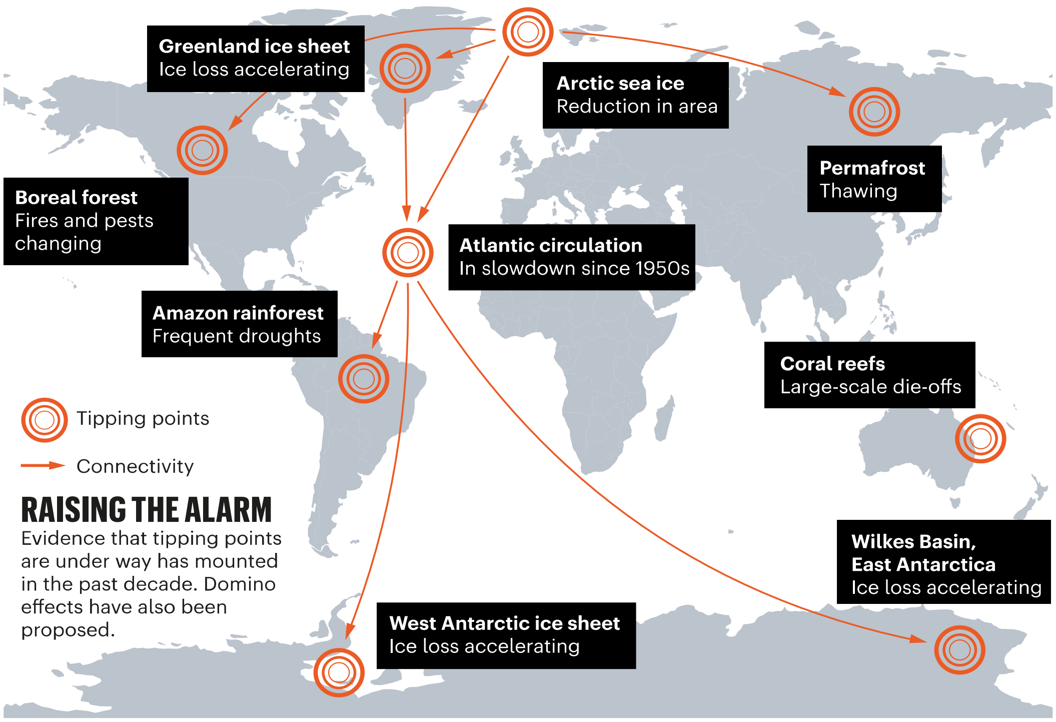
Fuente: Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J. & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): eabn7950, 1–10, Figura 2.

- La “evidencia de los puntos críticos de inflexión por sí sola sugiere que nos encontramos en un estado de emergencia planetaria: tanto el riesgo como la urgencia de la situación son agudos….”[27]
    - Incluso con un sobrepaso de 1,5 °C en el que el límite de la temperatura sólo sea superado temporalmente, algunos de los impactos serán irreversibles, aunque se reduzca el calentamiento[28].
    - Una preimpresión de abril de 2022 que analiza cuatro puntos críticos de inflexión del sistema climático que interactúan entre sí—los mantos de hielo de Groenlandia y de la Antártida occidental, la circulación meridional de retorno del Atlántico y la Selva Amazónica—concluye que incluso un sobrepaso temporal de los 2 °C puede aumentar el riesgo de cruzar estos puntos críticos de inflexión en hasta un 72%[29].

- Las concentraciones de gases de efecto invernadero en la atmósfera siguen aumentando a un ritmo sin precedentes a pesar de la pandemia y la desaceleración económica.
    - Las concentraciones atmosféricas de metano batieron récords en 2020 y 2021 con la tasa de aumento más elevada desde que comenzaron los registros en 1983, y los datos preliminares muestran que el metano superó las 1.900 partes por billón (ppb) por primera vez en septiembre de 2021[30].
    - Las concentraciones mundiales de CO_2 en la atmósfera alcanzaron un nuevo máximo de 420 partes por millón (ppm) en abril de 2022, lo que supone un aumento del 50% respecto a los niveles preindustriales y 2,5 ppm más que en 2020[31]. A modo de comparación, el aumento medio de CO_2 fue de 1,5 ppm/año en la década de 1990[32].
- Los fenómenos meteorológicos extremos son cada vez más frecuentes y graves.
    - Según el IE6 del WGI, "[e]s *prácticamente seguro* que ha aumentado la frecuencia y la intensidad de los episodios de calor extremo (incluidas las olas de calor) en la mayoría de las regiones terrestres desde la década de 1950... y hay *un nivel de confianza alto* en que el cambio climático inducido por el ser humano es la principal fuerza impulsora de estos cambios"[33].
    - La ola de calor récord de junio de 2021 en el Noroeste del Pacífico (EE.UU. y Canadá) habría sido prácticamente imposible sin el cambio climático provocado por el ser humano[34] y habría sido mucho menos grave para la salud humana[35]. La probabilidad de que se produzcan olas de calor de este tipo se multiplicará hasta por 200 en la década de 2040, con una frecuencia de entre 5 y 10 años, teniendo en cuenta nuestra trayectoria actual de emisiones[36].
    - En 2053, se prevé la formación de un "cinturón de calor extremo" que afectará a más de 100 millones de personas en el centro de EE.UU., donde las temperaturas superarán los 125 °F (~52 °C) al menos una vez al año, situándose en el "nivel de peligro extremo" según el índice de calor del Servicio Meteorológico Nacional[37].
    - El calentamiento global hizo que las olas de calor de 2019 en Europa Occidental fueran hasta 100 veces más probables[38]. En 2021, mientras Europa crepitaba bajo otra ola de calor, la región mediterránea se dirigía hacia un "punto caliente de incendios forestales" [39].
    - La frecuencia y la intensidad de las olas de calor en Europa están aumentando más rápido que en la mayor parte del planeta debido al calentamiento del sistema climático y a los cambios en la corriente en chorr[40]. El cambio climático hizo que el récord de 40 °C en el Reino Unido fuera al menos 10 veces más probable[41]. Las olas de calor récord de 2022 se considerarán como las temperaturas "promedio" del verano en Europa en 2035, incluso si se cumplen los compromisos climáticos actuales[42].
    - Con olas de calor, cuya larga duración no tiene precedentes, que afectaron a más de mil millones de personas en la India y Pakistán en 2022, los científicos señalan que "el clima actual ha cambiado de forma tan significativa que el mundo preindustrial se convierte en una base deficiente de comparación"[43].
    - La intensidad de los incendios nocturnos ha aumentado en todo el mundo un 7,2% en las dos últimas décadas debido al aumento de las temperaturas, provocando incendios más intensos, duraderos y de mayor tamaño[44].

  - Es muy probable que las inundaciones catastróficas que anegaron a un tercio de Pakistán en 2022 se agraven debido al cambio climático, que ha incrementado las precipitaciones, el deshielo de los glaciares y ha prolongado el fenómeno de La Niña en el Pacífico por tercer año consecutivo[45].
- La probabilidad de que se produzcan fenómenos climáticos extremos "que batan récords" "depende de la tasa de calentamiento, más que del nivel de calentamiento global, y por lo tanto, depende de la trayectoria"[46].
  - Según la Oficina Nacional de Administración Oceánica y Atmosférica, "[l]os siete años más cálidos desde 1880 han ocurrido desde 2014, mientras que los 10 años más cálidos han ocurrido desde 2005" [47]. Las continuas emisiones récord [de GEI] implican que la tasa de calentamiento podría aumentar de 0,2 °C por década, a 0,25-0,32 °C por década, en los próximos 25 años[48].

Figura 3. Puntos críticos de inflexión del sistema climático



Fuente: Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W. & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comentario, NATURE, 575(7784): 592–595.

A. El Ártico puede ser el eslabón más débil para salvaguardar nuestro clima

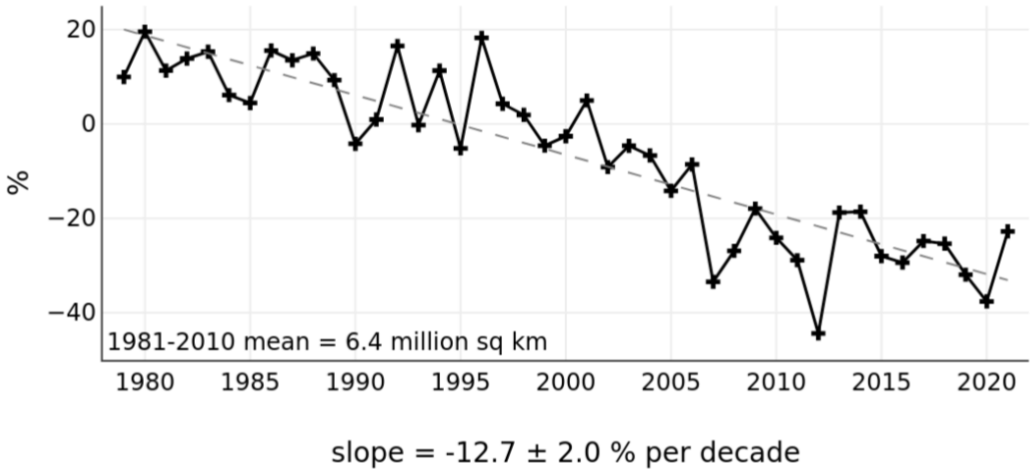
El Ártico es fundamental para la estabilización del clima, pero puede ser el eslabón más débil de la cadena de protección del sistema climático[49]. El hielo marino del Ártico constituye un "gran escudo blanco" que refleja la radiación solar entrante de forma segura hacia el espacio[50]. A medida que la extensión del hielo marino reflectante del Ártico sigue disminuyendo, aumenta la cantidad de calor que penetra en el océano más oscuro, lo que a su vez provoca que se derrita más hielo en un bucle de retroalimentación que se refuerza a sí mismo[51]. La temperatura del aire en el Ártico se está calentando a un ritmo cuatro veces superior respecto de la media mundial[52]. En septiembre sólo queda la mitad del hielo marino del Ártico durante el verano[53], con el riesgo de que, en un plazo de 10 a 15 años, no haya más hielo durante los meses de septiembre[54]. Si se perdiera todo el hielo marino del Ártico durante los meses soleados, se añadiría un calentamiento equivalente a un trillón de toneladas de dióxido de carbono, o 25 años de emisiones climáticas al ritmo actual[55]. La nieve y el hielo terrestre del Ártico también se están derritiendo y se espera que añadan una cantidad similar de calentamiento[56]. La intrusión de agua oceánica más cálida procedente tanto del Atlántico[57] como del Pacífico[58], también está contribuyendo al calentamiento del Ártico y a la fusión del hielo marino, intensificando el impacto de los ciclones de finales de verano y acelerando aún más la pérdida de hielo marino[59].

i. Un Ártico que se calienta rápidamente

- La temperatura del aire en el Ártico se está calentando a un ritmo cuatro veces superior a la media mundial[60].
    - Las temperaturas medias de la superficie del Ártico podrían aumentar hasta 10 °C a finales de siglo por encima de la media de 1985-2014[61].
    - En 2020, Siberia experimentó episodios de calor extremo que habrían sido "casi imposibles" sin el calentamiento global provocado por el ser humano, incluyendo la primera vez que se registró una temperatura de 100 °F (37,7 °C) en el norte del Círculo Polar Ártico, y una temperatura récord de 118 °F (47,7 °C) en el suelo, con extremos similares observados en la primera mitad de 2021[62].
    - La "última zona de hielo" del Ártico, el Mar de Wandel, sufrió una pérdida de hielo marino sin precedentes en agosto de 2020 debido principalmente a los patrones climáticos anormales y al calor de la superficie oceánica expuesta[63]. Se pensaba que el hielo marino estival en esta zona del norte de Groenlandia era más resistente y se esperaba que persistiera durante más décadas que en el resto del Ártico[64], proporcionando así un refugio para la flora y la fauna de la región que dependen del hielo[65].
    - Entre 1991 y 2020, la temperatura del aire en superficie en la zona del Mar de Barents experimentó un calentamiento anual récord de hasta 2,7 °C por década, y la zona septentrional del Mar de Barents se calentó a un ritmo entre 5 y 7 veces superior a las medias globales de calentamiento[66]. Durante la estación más cálida del otoño, dicha zona sufrió un calentamiento acelerado de hasta 4,0 °C por década entre 2001 y 2020[67].
- En septiembre sólo queda la mitad del hielo marino estival del Ártico[68], con el riesgo de que, en un plazo de 10 a 15 años, ya no haya más hielo durante los meses de septiembre[69]. Si se perdiera todo el hielo marino del Ártico durante los meses soleados, se añadiría un calentamiento equivalente a un trillón de toneladas de dióxido de carbono[70].
    - El hielo marino del Ártico alcanza su extensión mínima, o cobertura, cada mes de septiembre. Entre 1982 y 2020, la extensión mínima de septiembre ha disminuido significativamente, reduciéndose a un ritmo del 13% por década[71]. Además de su extensión, el espesor y el volumen del hielo marino del Ártico también se han reducido. Durante las mínimas de septiembre de 1982-2020:
        - La *extensión* del hielo marino del Ártico disminuyó un 44% (de 7,6 millones de km^2 en 1982 a 4,3 millones de km^2 en 2020)[72]. Esto equivale a un tercio de todo EE.UU., incluidos los estados y territorios no contiguos[73].
        - El *espesor* del hielo marino del Ártico disminuyó un 48%[74].

        - El *volumen* del hielo marino del Árctico decreció un 72%[75].
        - Los 16 meses de septiembre con menor extensión de hielo marino han ocurrido en los últimos 16 años; el 15 de septiembre de 2020, alcanzó la segunda mayor reducción de su extensión registrada por satélite[76]. El 18 de septiembre de 2022 está empatado con el décimo mínimo de hielo más bajo registrado, mientras que el 16 de septiembre de 2021 fue el duodécimo más bajo en ese entonces, con uno de los niveles de hielo plurianual más bajo registrado[77].
    - La viabilidad del hielo marino estival se ve aún más comprometida por la pérdida del hielo marino del Ártico más fuerte y antiguo (>4 años), que abarcaba solo el 4,4% del océano Ártico en marzo de 2020; el hielo joven de primer año—que es más delgado, más frágil y más susceptible a disminuir—comprende ahora alrededor del 70% de la capa de hielo[78]. Entre 1985 y 2018, el hielo marino multianual del Ártico se ha reducido en un 95%[79].
- La nieve y el hielo terrestre del Ártico también se están fundiendo y se espera que añadan una cantidad similar de calentamiento. Según el Dr. Peter Wadhams[80]:
    - La pérdida de nieve y hielo terrestre reflectante es “de la misma magnitud que la anomalía negativa del hielo marino durante el mismo periodo, y el cambio en el albedo es aproximadamente el mismo entre la tierra cubierta de nieve y la tundra sin nieve que entre el hielo marino y las aguas abiertas”.
    - “[L]a similitud de las magnitudes significa que el retroceso de la línea de nieve y el retroceso del hielo marino añaden cada uno aproximadamente la misma cantidad al calentamiento global”.
- Los glaciares y los mantos de hielo de todo el mundo están desapareciendo, con graves consecuencias para el clima, el aumento del nivel del mar y la seguridad hídrica.
    - Entre los periodos 1992-1999 y 2010-2019, la tasa de pérdida de glaciares y mantos de hielo se multiplicó por cuatro y, junto con la pérdida de masa glaciar, fue el factor que más contribuyó al aumento del nivel del mar entre 2006-2018[81].
    - En un estudio que combina las observaciones por satélite con modelos numéricos se concluyó que, entre 1994 y 2017, los glaciares y los mantos de hielo han perdido 28 trillones de toneladas de hielo[82] (un trillón de toneladas de hielo equivale a un cubo de hielo más alto que el monte Everest[83]). Según los autores del estudio, “no cabe duda de que la mayor parte de la pérdida de hielo de la Tierra es consecuencia directa del calentamiento climático”[84].

Figura 4. Anomalías mensuales de la extensión del hielo marino



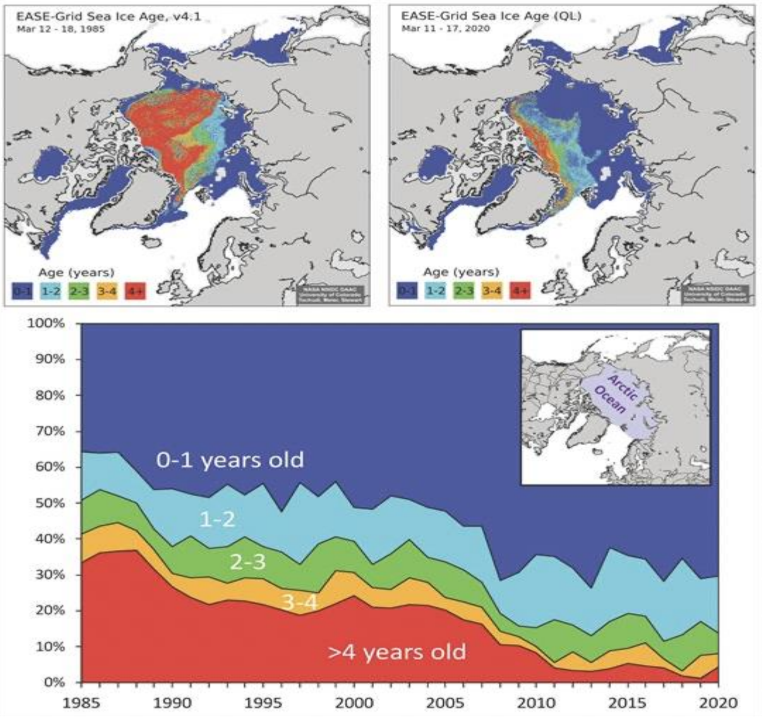
Fuente: National Snow and Ice Data Center, *Sea Ice Index*, “Monthly Sea Ice Extent Anomaly Graph” (*última visita* el 10 de mayo de 2022) (“Este gráfico muestra las anomalías mensuales de la extensión de hielo representadas como una serie temporal de la diferencia porcentual entre la extensión del mes en cuestión y la media de ese mes basada en los datos de enero de 1981 a diciembre de 2021. Los puntos de datos anómalos se representan con el signo más y la línea de tendencia con una línea discontinua gris”.).

ii. Amplificación del calentamiento del Ártico y pérdida de hielo marino — retroalimentaciones e impactos

- El hielo marino del Ártico está disminuyendo a un ritmo acelerado.
    - La tasa de disminución del espesor del hielo marino del Ártico entre 2002 y 2018 puede estar subestimada entre un 60 y un 100% en cuatro de los siete mares marginales, según un estudio reciente que utiliza “datos de nieve con una variabilidad y tendencias más realistas” [85].
    - El aumento de la temperatura de los océanos también está acelerando la pérdida de hielo marino, ya que las aguas más cálidas del Atlántico[86] y del Pacífico[87] transportan “cantidades de calor sin precedentes” al Océano Ártico, reduciendo aún más el espesor del hielo marino. Las aguas más cálidas y saladas del océano Atlántico penetran cada vez más en el Ártico en un proceso denominado “atlantificación del océano Ártico”[88] que se propaga hacia el norte. Es probable que la intensidad de este calentamiento esté subestimada en los modelos CMIP6[89].
    - En la zona septentrional del Mar de Barents, la pérdida de hielo marino invernal debido a las aguas más cálidas que transportan calor desde el océano Atlántico es más pronunciada, y a medida que las aguas se calientan y se vuelven más saladas, la estratificación oceánica se debilita, impidiendo aún más la formación de hielo marino[90].
    - Menos hielo marino en el Océano Ártico permite que crezcan más las olas del océano, lo que genera una aceleración de la ruptura y el retroceso del hielo[91], que se ve agravada por los ciclones de finales de verano que continúan rompiendo el hielo[92].

  - El invierno de 2020/21 se caracterizó por un forzamiento del viento excepcionalmente alto que provocó una pérdida récord del hielo multianual del Ártico impulsado hacia el mar de Beaufort[93], “donde el hielo, cada vez más, no puede sobrevivir al verano” [94].
  - El calentamiento del Ártico también conduce a un mayor número de ciclones cada vez más intensos[95], lo que agrava aún más la disminución del hielo marino del Ártico y viceversa[96].

Figura 5. Hielo marino en el Ártico al final del invierno



Fuente: Perovich D., Meier W., Tschudi M., Hendricks S., Petty A. A., Divine D., Farrell S., Gerlan S., Haas C., Kaleschke L., Pavlova O., Ricker R., Tian-Kunze X., Webster M. & Wood K. (2020) *Sea Ice*, *en* ARCTIC REPORT CARD 2020, Thoman R. L., Richter-Menge J. & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 49 (“Fig. 3. Mapa de cobertura de la edad del hielo marino de finales de invierno para la semana del 12 al 18 de marzo de 1985 (arriba a la izquierda) y del 11 al 17 de marzo de 2020 (arriba a la derecha). Abajo: Porcentaje de edad del hielo marino dentro del Océano Ártico para la semana del 11-18 de marzo de 1985-2020. Datos del NSIDC (Tschudi et al. 2019, 2020).”).

iii. Estamos peligrosamente cerca de perder el control climático del Ártico

- El Ártico podría quedar casi sin hielo marino durante los meses de septiembre en un plazo de 10 a 15 años, lo que reduciría aún más su capacidad para reflejar el calor[97].
  - La ausencia de hielo durante varios meses de verano se produjo probablemente durante el último período interglaciar, lo que refuerza las predicciones de una ausencia de hielo para finales de verano en 2035[98].

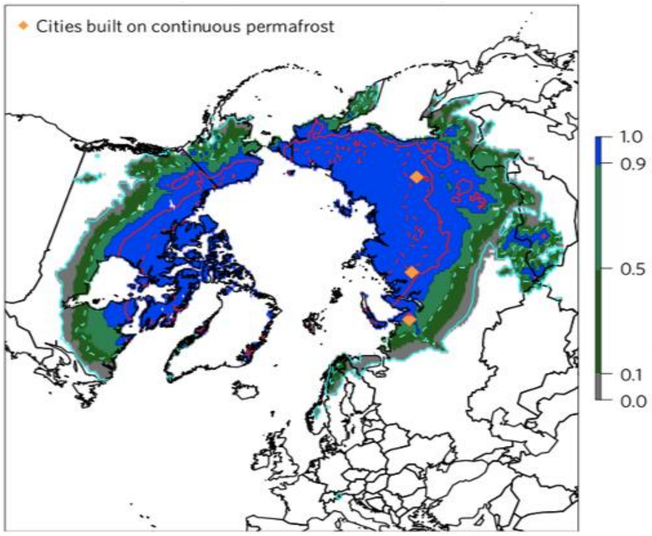
  - El Mar de Barents y el Mar de Groenlandia podrían quedar sin hielo durante todo el año a finales de siglo en escenarios de emisiones elevadas[99].
- En el caso extremo de que se perdiera todo el hielo marino del Ártico durante los meses soleados, como podría ocurrir a mediados de siglo[100], se produciría un calentamiento equivalente a un trillón de toneladas de CO_2—además del forzamiento de los 2,4 trillones de toneladas de CO_2 añadidas durante los 270 años transcurridos desde la Revolución Industrial—, precipitando el calentamiento unos 25 años antes de lo previsto[101].
  - Este calentamiento adicional equivaldría a añadir 56 ppm de CO_2 a la concentración actual de CO_2[102].
  - El forzamiento añadido en el Ártico sería de 21 W/m^2; un promedio global equivaldría a 0,71 W/m^2 de forzamiento global[103], comparado con los 2,16 W/m^2 añadidos por las emisiones antropogénicas de CO_2 desde la Revolución Industrial[104].
  - Si toda la cobertura de nubes sobre el Ártico se disipara junto con la pérdida de todo el hielo marino, el calentamiento añadido del Ártico podría ser tres veces mayor, el equivalente a tres trillones de toneladas de CO_2; por el contrario, incluso si las nubes aumentaran hasta crear cielos completamente cubiertos sobre el Ártico, el calentamiento seguiría añadiendo a la atmósfera el equivalente a 500 billones de toneladas de CO_2[105].
- Otros factores que contribuyen a una mayor pérdida de nieve y hielo en el Ártico.
  - La reducción del manto de nieve en el Ártico está aumentando el riesgo de incendios forestales, que emiten carbono negro, otro supercontaminante climático, mientras que también se destruyen sumideros y se emite CO_2[106]; los incendios forestales y el deshielo del permafrost pueden "actuar conjuntamente para exponer y transferir el carbono del derretimiento del permafrost a la atmósfera con gran rapidez" [107].
  - El calentamiento del Ártico también ha experimentado tres veces más rayos en la última década[108], provocando más incendios y amenazando con acelerar el deshielo del permafrost[109]. Los incendios boreales que arden en suelos orgánicos y resurgen al cabo de meses, denominados "incendios zombis" o "incendios invernales", emitieron unos 3,5 millones de toneladas métricas de carbono entre 2002 y 2018[110].
  - El rápido derretimiento en el Ártico abre nuevas rutas marítimas, lo que desencadena una mayor contaminación y calentamiento, ya que el aumento del transporte marítimo, la prospección de petróleo y gas y el turismo queman combustóleo (fueloil) pesado y emiten carbono negro[111]. El aumento de las rutas marítimas del Ártico también acarrea problemas geopolíticos y otros riesgos de seguridad en evolución[112].

B. La retroalimentación del deshielo del permafrost podría rivalizar con los principales emisores de CO_2, CH_4 y N_2O

El calentamiento acelerado del Ártico y la pérdida de hielo marino corren el riesgo de desencadenar otra retroalimentación que se refuerce a sí misma—el deshielo del permafrost[113]—que amplificaría aún más el calentamiento al liberar CO_2 y metano (CH_4)[114], así como también óxido nitroso (N_2O), que también destruye el ozono estratosférico[115].

- Entre 2007 y 2016, la temperatura media mundial del suelo del permafrost aumentó 0,29 °C; en ese periodo, el permafrost de las montañas se calentó 0,19 °C y el de la Antártida, 0,37 °C[116].
- La cantidad de carbono almacenada en el permafrost es casi el doble de la que ya hay en la atmósfera—1.700 Gt (gigatoneladas) de carbono en el permafrost contra 850 Gt de carbono en la atmósfera[117].
    - Se han observado temperaturas récord en la capa superior del permafrost, con lugares que registran un aumento de más de 1 °C con respecto a los niveles de 1978[118].
    - El IE6 del WGI evalúa que la retroalimentación de CO_2 del permafrost por grado de calentamiento global podría alcanzar 41 PgC $°C^{-1}$ de aquí a 2100. Además, se prevé que las emisiones de metano procedentes del deshielo del permafrost alcancen hasta 19 $GtCO_2e$ $°C^{-1}$ [5,3 PgC_{eq} $°C^{-1}$] para 2100; y más allá de 2100, la magnitud de la retroalimentación de carbono del permafrost se refuerza en un escenario de altas emisiones[119].
    - De los aproximadamente 15 millones de kilómetros cuadrados de permafrost en tierra[120], 3,4 millones de kilómetros cuadrados ya se han descongelado; y con el calentamiento de 1,5 °C que se avecina, otros 4,8 millones de kilómetros cuadrados podrían descongelarse gradualmente[121].
    - En el escenario RCP8.5 sin mitigación, el deshielo gradual del permafrost por sí solo podría liberar tanto CO_2 como el presupuesto de carbono restante para que haya una chance probable de permanecer por debajo de 1,5 °C a finales de siglo[122].
    - Sin embargo, el deshielo abrupto "se producirá probablemente en <20% de la zona de permafrost, pero podría afectar a la mitad del carbono del permafrost", y "los modelos que sólo consideran el deshielo gradual del permafrost están subestimando sustancialmente las emisiones de carbono" en un 40%[123].
    - Además, el deshielo del permafrost submarino bajo el Océano Ártico podría añadir un 20% más de emisiones de aquí a 2100 en un escenario RCP8.5, según la opinión de los expertos[124].
    - Los presupuestos de carbono para las trayectorias que apuntan a 1,5 o 2 °C en este siglo, subestiman las posibles retroalimentaciones del permafrost, donde un sobrepaso de 0,5 °C podría dar lugar a un aumento del doble de emisiones derivadas del deshielo del permafrost[125].
    - Además de acelerar el deshielo del permafrost, las olas de calor en el Ártico Siberiano en 2020, que alcanzaron un máximo de 6 °C por encima de las temperaturas normales, también pueden estar provocando fugas de gas metano fósil de las formaciones rocosas[126].
- Si el permafrost fuera un país: para 2100, sus emisiones podrían equivaler a las emisiones acumuladas de Estados Unidos, pero el 82% de los modelos del IPCC no incluyen las emisiones de carbono procedentes del deshielo del permafrost[127].

Figura 6. Cambios en el permafrost



Fuente: Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G. & Westermann S. (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NAT. CLIM. CHANGE 7(5): 340–344 ("Figura 4 | Cambios en los patrones espaciales del permafrost bajo futuros escenarios de estabilización. a,b, Las áreas sombreadas muestran la distribución histórica estimada del permafrost (1960-1990), y los contornos muestran el rango plausible de los límites zonales bajo estabilización de 1,5 C (a) y bajo estabilización de 2 C (b).").

- Además de la retroalimentación del permafrost que acelera el calentamiento, su pérdida repercute en los asentamientos humanos y en la salud:
  - 3,3 millones de personas, el 42% de los asentamientos y el 70% de la infraestructura actual en el área del permafrost corren el riesgo de sufrir graves daños debido al deshielo del mismo de aquí a 2050, incluido el 45% de los yacimientos de producción de petróleo y gas del Ártico ruso[128].
  - Sólo los daños causados a la infraestructura rusa por el deshielo del permafrost podrían costar 69.000 millones de dólares de aquí a 2050[129].

C. Otra amenaza relacionada con el metano acecha a la Plataforma Ártica de Siberia Oriental

También existe el riesgo de que se emita metano desde el lecho marino poco profundo de la Plataforma Ártica de Siberia Oriental a medida que se caliente el Océano Ártico, lo que aceleraría otros efectos del calentamiento global[130].

- Las mediciones realizadas en octubre de 2020 por una expedición internacional a bordo de un buque de investigación ruso muestran una elevada liberación de metano de la plataforma ártica, según un artículo de Jonathan Watts en *The Guardian*[131]. El artículo cita al científico sueco Örjan Gustafsson, de la Universidad de Estocolmo, quien afirma que "el sistema de hidrato de metano de la vertiente siberiana oriental ha sido perturbado y el proceso seguirá en curso". El análisis del elevado nivel de metano medido en dicha zona en 2014 sugiere una fuente de metano fósil bajo el lecho marino que "puede ser de naturaleza más eruptiva"[132].

- Según un análisis isotópico anterior del metano procedente de un registro de un núcleo de hielo antártico, hasta el 27% de las emisiones de metano durante la última deglaciación pueden haber provenido de antiguos depósitos de carbono del permafrost y los hidratos; aunque esto “sólo sirve como análogo parcial al calentamiento antropogénico actual”, los autores afirmaron que es “poco probable” que el calentamiento antropogénico actual libere el carbono de estos antiguos depósitos[133].

D. La proximidad de los puntos críticos de inflexión en el manto de hielo

Si el calentamiento supera los 1,5 °C durante más de varias décadas, numerosos puntos de inflexión climáticos corren peligro de activarse. El manto de hielo de Groenlandia y el manto de hielo de la Antártida Occidental ya muestran signos de aproximación a umbrales de inflexión estimados en torno a 1,5 o 2 °C[134]. Una vez desencadenada, la pérdida significativa de hielo es irreversible, incluso con la implementación de estrategias de eliminación de dióxido de carbono[135]. En 2021, Groenlandia y la Antártida alcanzaron los niveles de masa de hielo más bajos registrados, y los glaciares perdieron un 31% más de nieve y hielo al año que hace tan sólo 15 años[136]. El deshielo del manto de hielo de Groenlandia ya es el principal contribuyente a la tasa de aumento de la media global del nivel del mar[137], y se espera que pierda 110 trillones de toneladas de hielo para finales de siglo, lo que elevaría el nivel del mar en casi un pie (27 cm)[138]. El IE6 del WGI excluye la posibilidad de un aumento del nivel del mar de hasta 7,5 pies (2,3 metros) para 2100 debido a la falta de certeza sobre los procesos del manto de hielo[139].

i. El Manto de Hielo de Groenlandia se está derritiendo a un ritmo acelerado

- Las primeras señales de alerta sugieren que el manto de hielo de Groenlandia está cerca de un punto crítico de inflexión[140]. Actualmente, la mejor estimación del umbral para el deshielo irreversible de dicho manto de hielo se sitúa en torno a 1,6 °C (0,8-3,2 °C)[141].
    - En las últimas dos décadas, la tasa de deshielo en Groenlandia aumentó entre un 250 y un 575%[142], y la descarga de hielo de dicho manto aumentó sustancialmente; es probable que esto persista en los próximos años[143]. El 28 de julio de 2021, Groenlandia experimentó un deshielo masivo que por sí solo bastaría para cubrir el estado de Florida con cinco centímetros (2 pulgadas) de agua[144].
    - Si toda Groenlandia se derritiera, contribuiría a elevar el nivel del mar entre 5 y 7 metros; y aunque pueden pasar miles de años hasta que se observe el alcance total del aumento del nivel del mar, la “escala temporal del deshielo depende en gran medida de la magnitud y la duración del sobrepaso de la temperatura”[145].
    - El 14 de agosto de 2021, se produjeron precipitaciones en el punto más alto del manto de hielo de Groenlandia, nunca antes registradas en ese lugar (72,58°N 38,46°O)[146].
- Un nuevo análisis ha calculado que el 3,3% del manto de hielo de Groenlandia (que equivale a 110 trillones de toneladas de hielo) se derretirá inevitablemente a finales de siglo, independientemente de cualquier escenario de emisiones climáticas, lo que provocará un aumento del nivel del mar de al menos 27,4 cm (10,8 pulgadas) a escala mundial y que podría llegar hasta 78,2 cm (30,8 pulgadas)[147].
- El deshielo de Groenlandia también contribuye al debilitamiento de la Circulación Meridional de Retorno del Atlántico (AMOC, por sus siglas en inglés), que ha alcanzado una fase crítica de “retorno”; los datos de observación sugieren que “este declive puede

estar asociado a una pérdida casi total de estabilidad de la AMOC en el transcurso del último siglo,[148] y que la AMOC podría estar próxima a una transición crítica hacia su modo de circulación débil" [149]

  - Según el IE6 del WGI, es "muy probable" que la AMOC se debilite durante el siglo XXI, con un "nivel de confianza medio" en que no habrá un colapso antes de 2100[150].
  - El colapso de la AMOC puede provocar un aumento más rápido del nivel del mar a lo largo de algunas partes de la zona este de Estados Unidos y Europa, huracanes más fuertes en el sudeste de Estados Unidos y una disminución de las precipitaciones en todo el Sahel[151]. Si el nivel del mar a lo largo de las costas de Estados Unidos aumentara de 25 a 30 cm (10 a 12 pulgadas) para 2050, la ocurrencia de inundaciones destructivas se quintuplicaría[152]. Este colapso modificaría los patrones meteorológicos en todo el mundo, con consecuencias potencialmente devastadoras[153].

ii. El Manto de Hielo de la Antártida Occidental se está desestabilizando

- En la Antártida Occidental, la pérdida del glaciar Thwaites, que actualmente tiene el tamaño de Florida o Gran Bretaña, podría elevar el nivel del mar en más de 65 cm[154]. Una vez que el glaciar Thwaites retroceda más allá de una cresta 50 km río arriba, el retroceso del mismo "sería imparable"[155].
  - Un nuevo estudio advierte que el glaciar Thwaites se ha derretido más rápido de lo observado anteriormente y que en el futuro podría producirse un ritmo similar de deshielo acelerado[156].
  - El glaciar Thwaites ya contribuye en un 4% al aumento del nivel del mar[157]. En los últimos 20 años, este glaciar ha perdido más de 1.000 billones de toneladas de hielo y lo sigue perdiendo a un ritmo que crece rápidamente[158].
  - Un glaciólogo descubrió que la plataforma de hielo que sostiene al glaciar Thwaites podría derrumbarse en tan sólo cinco años debido a fracturas masivas causadas por el agua más cálida del océano que debilita la plataforma de hielo, desencadenando una "reacción en cadena" que podría eventualmente añadir de 60 cm a 3mts (2 a 10 pies) de aumento del nivel del mar durante siglos[159].

E. El océano es una batería de calor

Agravando el riesgo de retroalimentaciones que se refuerzan a sí mismas y puntos críticos de inflexión, el calentamiento continuará mucho después de que cesen las emisiones; alrededor del 93% del desequilibrio energético se acumula en los océanos en forma de aumento de calor[160], y este volverá a la atmósfera en una escala temporal de décadas a siglos después de que cesen las emisiones[161]. Entre 2003 y 2018, la tasa de calentamiento de los océanos se multiplicó por diez con respecto a los niveles de 1958-1973[162]. Como se señala en el IE6 del WGI:

> "Es *prácticamente seguro* que el océano a escala mundial se ha calentado desde al menos 1971, representando cerca del 90% del aumento del inventario mundial de la energía... y actualmente se está calentando más rápido que en cualquier otro momento desde al menos la última transición de desglaciación (*nivel de confianza medio*).... Es *sumamente probable*

que la influencia humana haya sido el principal motor del calentamiento de los océanos. El calentamiento de los océanos continuará durante el siglo XXI (*prácticamente seguro*)... [y] será irreversible a lo largo de siglos a milenios (*nivel de confianza medio*)"[163]. [La traducción nos pertenece]

3. Reducir el CO_2 por sí solo no frenará el calentamiento a corto plazo

Descarbonizar el sistema energético y alcanzar emisiones netas iguales a cero es fundamental para estabilizar el clima y mantener las temperaturas por debajo de 1,5 °C a finales de este siglo. Sin embargo, dejar de quemar combustibles fósiles, como el carbón y el gasóleo, también implica reducir los aerosoles refrigerantes co-emitidos. Estos aerosoles se desprenden de la atmósfera en cuestión de días o meses, lo que contrarrestará las reducciones del calentamiento derivadas de la descarbonización hasta aproximadamente 2050, y probablemente, incluso acelerará el calentamiento durante la primera década o más[164]. Tal como afirma el científico del clima y autor del IPCC, Joeri Rogelj: "La eliminación de la contaminación atmosférica, ya sea a través de medidas destinadas a mejorar la calidad del aire o porque se eliminen progresivamente los procesos de combustión para deshacerse del CO_2, provocará un aumento de la tasa de calentamiento resultante... Las únicas medidas que pueden contrarrestar este aumento de la tasa de calentamiento en las próximas décadas son las reducciones de metano"[165].

- La contaminación atmosférica que se emite junto con el CO_2 al quemar carbón y petróleo que contienen azufre da lugar a partículas que reflejan la luz solar. Estos "aerosoles refrigerantes" actualmente "enmascaran" un calentamiento de unos 0,51 °C; y mientras que el CO_2 acumulado en la atmósfera seguirá provocando calentamiento durante décadas o siglos, los aerosoles refrigerantes desaparecerán de la atmósfera en cuestión de días o meses, desenmascarando más del calentamiento existente[166].
  - Los efectos de enfriamiento temporal de los aerosoles han quedado demostrados en el pasado. La erupción del Monte Pinatubo en 1991 inyectó 15 millones de toneladas de dióxido de azufre en la atmósfera, enfriando temporalmente el planeta 0,5 °C durante casi dos años[167].
  - Un estudio reciente de datos satelitales y otras pruebas concluye que el efecto neto del forzamiento antropogénico por aerosoles ha cambiado de signo, pasando de negativo (enfriamiento) a positivo (calentamiento) en las últimas dos décadas, contribuyendo al equivalente del 15-50% de aumento del forzamiento debido al CO_2 en el mismo periodo de tiempo, y concluyendo que "[e]s muy probable que esta señal continúe en el futuro, lo que aumenta la urgencia de adoptar medidas enérgicas para reducir las emisiones de gases de efecto invernadero..."[168].
- Un estudio anterior calculó que una reducción rápida del CO_2 podría evitar 0,1 °C de calentamiento de aquí a 2050 y hasta 1,6 °C para 2100[169], sin tener en cuenta el calentamiento debido al desenmascaramiento[170].
  - Esto requeriría que las emisiones de CO_2 alcanzaran su punto máximo en 2030 y disminuyeran un 5,5% anual hasta lograr la neutralidad de carbono en torno a 2060–2070, tras lo cual las emisiones se estabilizarían[171].
  - Si las emisiones de CO_2 alcanzaran su punto máximo en 2030 y disminuyeran a un ritmo del 5,5% anual hasta lograr la neutralidad de carbono (hacia mediados de siglo) y luego se estabilizasen, este escenario extremo podría evitar un

calentamiento de 0,3 °C para 2050 y de hasta 1,9 °C para 2100, aunque el desenmascaramiento de los aerosoles refrigerantes seguiría provocando un calentamiento neto a corto plazo[172].

- En otro estudio se calculó un calentamiento a corto plazo de 0,02-0,10 °C en las próximas dos décadas, debido a la reducción de las emisiones de CO_2 de los combustibles fósiles y a las reducciones asociadas de los aerosoles refrigerantes[173].

Figura 7. Respuesta de la temperatura a raíz de las estrategias de mitigación centradas únicamente en el CO_2 (descarbonización por sí sola) en comparación con la descarbonización más medidas dirigidas a los CCVC.

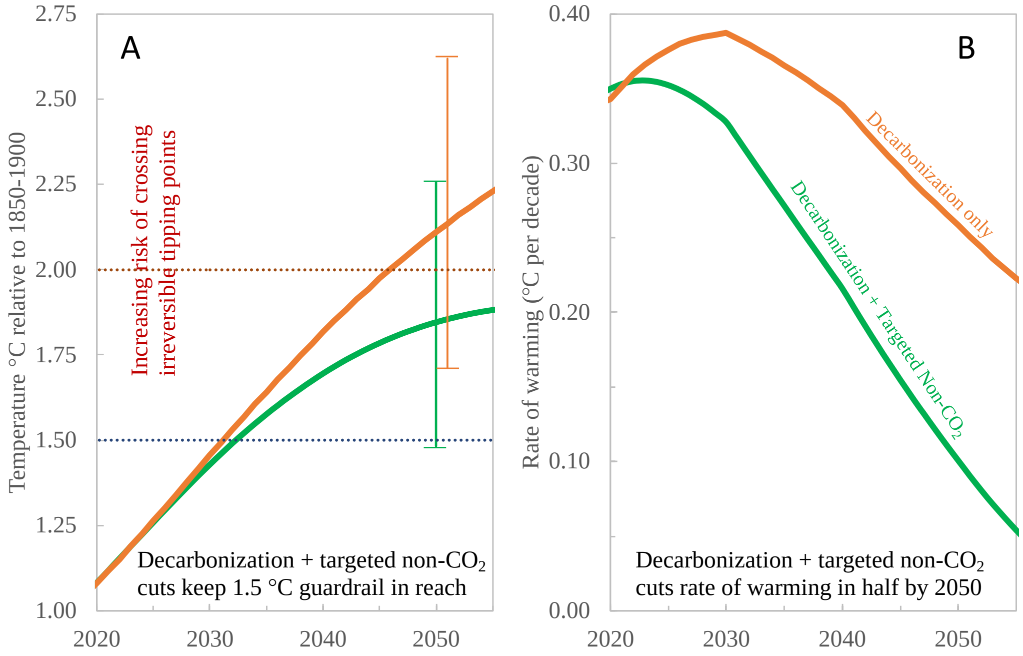


Gráfico A: Temperatura global del aire en superficie respecto a la era preindustrial para dos escenarios: descarbonización por sí sola (naranja) y descarbonización más medidas dirigidas a los contaminantes distintos del CO_2, incluidos el metano, los refrigerantes de hidrofluorocarbono, el hollín de carbono negro, el smog de ozono a nivel del suelo y el óxido nitroso (verde). Las líneas verticales ilustran el rango adaptado a partir de la dispersión entre modelos (5% a 95%) para el escenario SSP1-1.9 de la Figura SPM.8a del IE6 WGI del IPCC. *Véase* Grupo Intergubernamental de Expertos sobre el Cambio Climático (2021) *Resumen para Responsables de Políticas* en Cambio Climático 2021: Bases Físicas, *Contribución del Grupo de Trabajo I al Sexto Informe de Evaluación del Informe del Grupo Intergubernamental de Expertos sobre el Cambio Climático*, Masson-Delmotte V. y Otros (eds.) (Figura SPM.8a).
Gráfico B: Tasa de calentamiento por década para cada escenario. *Adaptado de* Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D. & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): e2123536119.

4. La única manera de frenar el calentamiento a corto plazo es centrarse en los supercontaminantes climáticos de vida corta

La mitigación enérgica de los contaminantes climáticos de vida corta (CCVC)—metano, ozono troposférico, carbono negro e hidrofluorocarbonos (HFC)—es fundamental para la protección del sistema climático a corto y largo plazo. Estos CCVC también son conocidos como "supercontaminantes climáticos". El IE6 del WGI incluye por primera vez un capítulo sobre contaminantes climáticos de vida corta, que concluye que "[l]a mitigación sostenida del metano, dondequiera que se produzca, se destaca como una opción que combina ganancias a corto y largo plazo en la temperatura de la superficie (*nivel de confianza alto*) y conduce a beneficios en la calidad del aire mediante la reducción de los niveles de ozono en superficie a nivel mundial (*nivel de confianza alto*).... La mitigación adicional de CH_4 y BC contribuiría a compensar el calentamiento adicional asociado con las reducciones de SO_2 que acompañarían a la descarbonización (*nivel de confianza alto*)"[174].

- Reducir los CCVC es la única forma plausible de limitar el calentamiento debido al desenmascaramiento de los aerosoles refrigerantes en los próximos 20 años[175].
- Teniendo en cuenta la co-emisión de aerosoles refrigerantes procedentes de la quema de combustibles fósiles, un nuevo estudio concluyó que las estrategias centradas exclusivamente en la reducción de las emisiones de combustibles fósiles podrían dar lugar a un "calentamiento débil a corto plazo" que podría hacer que las temperaturas superaran el nivel de 1,5 °C para 2035 y el de 2 °C para 2050. Por el contrario, la estrategia dual por medio de la cual se reducen simultáneamente los contaminantes distintos del dióxido de carbono, especialmente los de vida corta, daría lugar a un calentamiento neto evitado para 2050 cuatro veces mayor que el efecto neto de la descarbonización por sí sola, permitiría al mundo mantenerse muy por debajo del límite de 2 °C y mejoraría significativamente las posibilidades de permanecer por debajo de la barrera de 1,5 °C[176].
- A diferencia de la reducción limitada de calentamiento que se produciría en 2050 al reducir las emisiones de CO_2 procedente de los combustibles fósiles, una reducción rápida de los CCVC podría evitar hasta 0,6 °C de calentamiento para 2050, y hasta 1,2 °C para 2100[177], lo que disminuiría el calentamiento previsto en el Ártico en dos tercios y la tasa de calentamiento global a la mitad[178].
    - El IE6 del WGIII concluye que para limitar el calentamiento a 1,5 °C sin sobrepaso o con un sobrepaso limitado es necesario reducir drásticamente las emisiones de CCVC, en particular reduciendo las emisiones de metano en un 34 % en 2030 y en un 44 % en 2040 con respecto al modelo de 2019 y reduciendo las emisiones de HFC en un 85 % en 2050 con respecto a 2019[179]. Esto reafirma la conclusión del Informe Especial del IPCC sobre el Calentamiento Global de 1,5 °C de que reducir los CCVC es esencial para mantenerse por debajo de 1,5 °C[180].
    - Del mismo modo, la alerta de la emergencia climática emitida en noviembre de 2019 por parte de 11.000 científicos también hace hincapié en la importancia de reducir los CCVC:

        > "Debemos reducir rápidamente las emisiones de contaminantes climáticos de vida corta, como el metano (figura 2b), el carbono negro (hollín) y los hidrofluorocarbonos (HFC). Hacer esto podría frenar los bucles de retroalimentación climática y reducir potencialmente la tendencia de

calentamiento a corto plazo en más de un 50% en las próximas décadas, al tiempo que se salvan millones de vidas y se aumenta el rendimiento de los cultivos debido a la reducción de la contaminación atmosférica (Shindell et al. 2017[181]). Se acoge con satisfacción la enmienda de Kigali de 2016 para reducir gradualmente los HFC"[182].

- En su actualización de 2021, los científicos subrayaron la urgencia de una "acción climática a gran escala" debido a la creciente gravedad del impacto y los riesgos derivados de "los numerosos bucles de retroalimentación que se refuerzan y los posibles puntos críticos de inflexión" y apelan a "reducciones inmediatas y drásticas de los peligrosos gases de efecto invernadero de vida corta, especialmente el metano"[183].

Recuadro. Métricas de tiempo y temperatura del metano: utilizar el PCG$_{20}$ es bueno, ¡medir la temperatura es aún mejor!

Reducir los riesgos asociados con la aceleración del calentamiento exige estrategias de mitigación, como la reducción de las emisiones de metano, que pueden frenar el calentamiento a corto plazo. Evaluar cómo afectan las estrategias al calentamiento a corto plazo requiere considerar las emisiones individuales por contaminante en unidades de masa, tal como exigen las directrices de información de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC) y recomiendan los científicos en materia climática[184]. También es necesario tener en cuenta las co-emisiones por fuente, ya que las políticas actúan sobre las fuentes y no sobre los contaminantes individuales.

Una opción ideal para evaluar el impacto sobre la temperatura es convertir las emisiones por fuente, en términos de contaminante y co-emisiones en impactos sobre la temperatura, utilizando herramientas como la Herramienta de Evaluación de los Beneficios Ambientales y Sociales de la Reducción del Metano o la Herramienta para Medir la Trayectoria de la Temperatura de la CCAC. Alternativamente, cuando se comparan los impactos climáticos de los contaminantes climáticos de vida corta como el metano, utilizar el potencial de calentamiento global a 20 años (PCG$_{20}$) capta mejor el impacto del calentamiento a corto plazo que el PCG a 100 años (PCG$_{100}$), además de estar más alineado con el alcance del objetivo de 1,5 °C[185]. Aunque la CMNUCC exige actualmente el uso de la métrica PCG$_{100}$ al notificar emisiones o absorciones agregadas, que infravalora sistemáticamente el impacto climático del metano, las Partes notificantes pueden utilizar además otras métricas, como el PCG$_{20}$ o los potenciales absolutos de temperatura[186]. El IE6 ha actualizado las métricas para el metano de la siguiente manera: PCG$_{20}$ es 81,2 y PCG$_{100}$ es 27,9[187].

Cuadro 1. Valores de PCG para el metano de los informes del IPCC

		IE6	**IE5**		**IE4**	**TIE**	**SIE**
Metano (CH_4)	**PCG$_{20}$**	81,2	84	86*	72	62	56
	PCG$_{100}$	27,9	28	34*	25	23	21
Fósil CH_4	**PCG$_{20}$**	82,5 ± 25,8	85		--	--	--
	PCG$_{100}$	29,8 ± 11	30		--	--	--
No-fósil CH_4	**PCG$_{20}$**	80,8 ± 25,8	--		--	--	--
	PCG$_{100}$	27,2 ± 11	--		--	--	--

*con retroalimentación del ciclo de carbono. Todo el metano evaluado por el IE6 incluye la retroalimentación del ciclo de carbono.

IE6 = 2021 Sexto Informe de Evaluación WGI (Cuadro 7.SM.7; Cuadro 7.15); **IE5** = 2013 Quinto Informe de Evaluación WGI (Cuadro 8.A.1; Tablea 8.7); **IE4** = 2007 Cuarto Informe de Evaluación (Cuadro 2.14); **TIE** = 2001 Tercer Informe de Evaluación (Cuadro 6.7); **SIE** = 1995 Segundo Informe de Evaluación (Cuadro 2.9).

La mayoría de las métricas agregadas están diseñadas para compararse con el CO_2 de larga vida. Las métricas como la equivalencia de CO_2 en términos de PCG y PCG* se basan en relaciones matemáticas que pretenden hacer que CCVC como el metano sean comparables al impacto de calentamiento a largo plazo de las emisiones de CO_2[188]. Estas métricas agregadas suelen ignorar los contaminantes co-emitidos con importantes impactos climáticos a corto plazo, como los aerosoles refrigerantes. La métrica PCG* intenta tomar en cuenta la vida más corta del metano diferenciando las emisiones históricas de los cambios en la tasa de emisiones[189]. Una de las críticas a este enfoque es que básicamente "excluye" las emisiones históricas, de modo que cuando es aplicada a la escala de emisores de metano regionales o individuales, las fuentes con emisiones históricas elevadas pueden acusar un PCG* negativo reduciendo su tasa de emisiones. Este ocurre incluso si sus emisiones en un año determinado son equivalentes a las de una nueva fuente sin emisiones históricas. Esto ha llevado a un uso incorrecto de estas métricas para afirmar que algunos sectores con grandes emisiones históricas y tasas de emisiones actuales estables o decrecientes han contribuido en menor medida al calentamiento global[190].

Por estas razones, el presente *Manual sobre el Metano* se basa en la convención de la *Evaluación Global del Metano* del PNUMA/CCAC al utilizar las métricas basadas en la masa, tales como el millón de toneladas métricas del metano ($MtCH_4$), y el impacto en la temperatura en lugar de las métricas de PCG.

A. Metano (CH_4)

La contaminación por metano ya ha provocado un calentamiento de 0,51 °C—el cual aumentará si las emisiones siguen creciendo—del calentamiento total observado para 2019 de 1,06 °C (0,88-1,21 °C)[191]. El metano también es un forzador indirecto del clima como precursor de otros GEI, especialmente del ozono troposférico[192]. Tal como señaló la Casa Blanca, "el metano es un potente gas de efecto invernadero y, según el último informe del Grupo Intergubernamental de Expertos sobre el Cambio Climático, es responsable de aproximadamente la mitad del aumento neto de 1,0 grados centígrados de la temperatura media mundial desde la era preindustrial"[193]. Cada vez son más los dirigentes que empiezan a reconocer la importancia del metano, entre ellos el ex presidente de EE.UU. Barack Obama, que declaró en la 26ª Conferencia de las Partes (COP26) que "frenar las emisiones de metano es actualmente la forma más rápida y eficaz de limitar el calentamiento"[194].

Evaluación Global del Metano

- Reducir las emisiones de metano es la mejor y más rápida estrategia para frenar el calentamiento y mantener 1,5 °C a nuestro alcance[195]. La *Evaluación Global del Metano* (GMA, por sus siglas en inglés) de la CCAC y el PNUMA, dirigida por el Dr. Drew Shindell, concluye que las medidas de mitigación actualmente disponibles podrían reducir las emisiones de metano causadas por el ser humano en un 45% para 2030, en comparación con los niveles previstos para 2030, y evitar un calentamiento de casi 0,3 °C para la década de 2040[196].
    - Esto evitaría 255.000 muertes prematuras, 775.000 visitas hospitalarias relacionadas con el asma, 73.000 millones de horas de trabajo perdidas por el calor extremo y 26 millones de toneladas de pérdidas de cultivos en todo el mundo (valor anual comenzando en el 2030)[197]. Cada tonelada de metano reducida genera 4.300 dólares en beneficios para la salud, la productividad y otros[198]. Además, las estrategias de mitigación del metano proporcionan mayores reducciones de costos y ganancias derivadas de la eficiencia en el sector privado, crean empleo, estimulan la innovación tecnológica.
    - Aproximadamente el 60% de las medidas específicas disponibles tienen costos de mitigación bajos (definidos como inferiores a 21 dólares por tonelada de CO_2e para un PCG_{100} y a 7 dólares por tonelada de CO_2e para un PCG_{20}), y algo más del 50% de ellas tienen costos negativos.

Cuadro 2. Potencial de mitigación del metano en 2030 por sector en MtCH$_4$/año y Mt/año de CO$_2$e

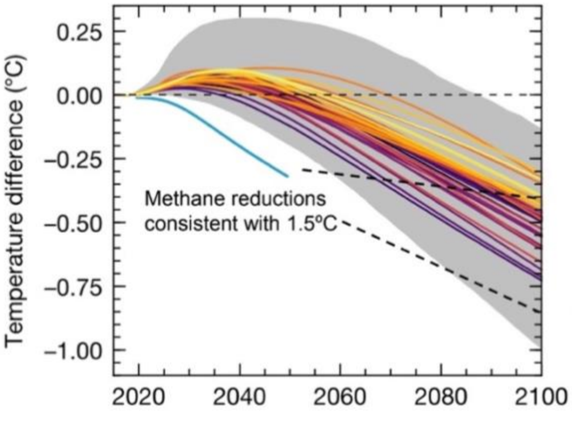
	Mt CH_4/año	**Mt CO_2e/año PCG_{100}**	**Mt CO_2e/año PCG_{20}**
Petróleo y gas	29–57	812–1.596	2.436–4.788
Residuos	29–36	812–1.008	2.436–3.024
Agricultura	10–51	280–1.428	2.840–4.284
Carbón	12–25	336–700	1.008–2.100

Fuente: Programa de las Naciones Unidas para el Medio Ambiente y Coalición Clima y Aire Limpio (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*.

- Como señala la GMA, "cualquier medida que se tome para reducir las emisiones tendrá una recompensa inmediata para el clima, además de para la salud humana y la producción agrícola en el presente y en un futuro próximo..... De hecho, la expectativa de que una reducción de las emisiones arroje resultados rápidos, en el orden de una década, está confirmada y subraya la importancia del metano”[199].

- La implementación de todas las medidas de mitigación del metano disponibles reduciría la tasa de calentamiento global en un 30% a mediados de siglo[200]. Esto es coherente con la Evaluación del PNUMA y la OMM de 2011, que mostró que la plena aplicación de medidas dirigidas al metano y al carbono negro podría reducir la tasa de calentamiento global a la mitad y reducir el calentamiento del Ártico en dos tercios[201].
    - Las estrategias para reducir las emisiones de metano evitan el calentamiento del Ártico en un 60% más que la media mundial, con un potencial para evitar 0,5 °C de aquí a 2050[202].
    - Una reducción rápida de las emisiones de metano también podría disminuir el riesgo de la pérdida del hielo marino reflectante del Ártico en verano[203].
- Los IE6 del WGII y del WGIII confirman las conclusiones de la GMA de que “[l]a mitigación sostenida del metano, dondequiera que se produzca, se destaca como una opción que combina ganancias a corto y largo plazo respecto de la temperatura en superficie (*nivel de confianza alto*) y conduce a beneficios en la calidad del aire mediante la reducción de los niveles de ozono en superficie a nivel mundial (*nivel de confianza alto*)”. Las medidas dirigidas específicamente al metano son esenciales, ya que las acciones más amplias de descarbonización sólo pueden lograr el 30% de las reducciones necesarias[204].
    - El informe más reciente sobre soluciones climáticas, el IE6 del WGIII, refuerza la conclusión de que una reducción profunda y rápida de las emisiones de metano es esencial para limitar el calentamiento a corto plazo y evitar que el pico de calentamiento supere los 1,5 ºC[205]. Para limitar el calentamiento a 1,5 °C sin sobrepaso o con un sobrepaso limitado, es necesario reducir las emisiones mundiales de metano de origen humano en un 34% en 2030 y en un 44% en 2040 con respecto a los niveles previstos para 2019[206].

Figura 8. Reducciones del Metano comparadas con las respuestas de la temperatura media global en superficie a los cambios en las emisiones relacionadas con los combustibles fósiles ($CO_2 + SO_2$)



Fuente: Shindell D. (25 de mayo de 2021) *Benefits and Costs of Methane Mitigatio*n, Presentación en la Reunión del Grupo de Trabajo de la CCAC. *Actualización* de la Figura 3d de Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411. *Véase también* Programa de las Naciones Unidas para el Medio Ambiente y

Coalición Clima y Aire Limpio (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*.

Mitigación y Eliminación

- Las emisiones antropogénicas, que representan aproximadamente el 60%[207] del total de las emisiones globales de metano, provienen principalmente de tres sectores: la producción de energía (~35%), la agricultura (~40%) y los residuos (~20%)[208]. Las medidas de mitigación actualmente disponibles podrían reducir las emisiones de estos sectores en unos 180 millones de toneladas métricas de metano al año (MtCH$_4$/año), aproximadamente un 45%, para 2030[209].
- Las medidas específicas para reducir las emisiones de metano incluyen:
  - Fortalecer las políticas de mitigación del metano aplicando al máximo las tecnologías, leyes y estructuras de gobernanza ya disponibles y estudiando formas de ampliar la mitigación del metano a través de otras vías disponibles[210];
  - Reducir las fugas[211] y el venteo[212] en el sector del petróleo y el gas. *Clean Air Task Force* afirma que prohibir el venteo de gas natural puede reducir las emisiones en un 95%[213];
  - Eliminar la quema en antorcha de las operaciones de petróleo y gas, al tiempo que se pasa a las energías limpias[214];
  - Mejorar la alimentación y la gestión del estiércol en las granjas. En Estados Unidos, esto podría reducir las emisiones procedentes del estiércol hasta un 70% y las de la fermentación entérica un 30%[215];
  - Mejorar el tratamiento de residuos sólidos y de aguas residuales[216]; y
  - Reducir el desperdicio de alimentos, desviar los residuos orgánicos de los vertederos y mejorar la gestión de los mismos, lo que podría reducir las emisiones de los vertederos en Estados Unidos en un 50% para 2030[217].
- También se está investigando cuál es el mejor método para eliminar el metano atmosférico[218]. Esto es especialmente importante, ya que el 35-50% de las emisiones de metano procede de fuentes naturales[219]. La eliminación del metano se trata con más detalle en la **Sección 5C**.
  - Un estudio de modelización elaborado por un equipo dirigido por la Universidad de Stanford calcula que la eliminación de las emisiones de metano causadas por el ser humano en unos tres años reduciría el calentamiento en 0,21°C[220]. La organización sin fines de lucro *Methane Action* ha declarado que la eliminación de metano junto con la reducción de las emisiones de metano puede bajar un calentamiento estimado de 0,4-0,6 °C[221].

Compromiso Mundial sobre el Metano

- El *Compromiso Mundial sobre el Metano* se lanzó formalmente en el segmento de alto nivel de la COP26 el 2 de noviembre de 2021[222]. Anunciado inicialmente por Estados Unidos y la Unión Europea en el Foro de las Principales Economías organizado el 17 de septiembre de 2021 por el Presidente Biden[223], este acuerdo compromete a los gobiernos a un objetivo colectivo mundial de reducción de las emisiones mundiales de metano en *al menos* un 30% con respecto a los niveles de 2020 para 2030 y a avanzar hacia el uso de las metodologías de inventario de buenas prácticas de nivel superior del IPCC para cuantificar las emisiones de metano, con especial atención a las fuentes de altas emisiones. Además de Estados Unidos y la Unión Europea, más de 100 países firmaron el compromiso,[224] lo que representa el 70% de la economía mundial y casi la mitad de las emisiones antropogénicas de metano[225]. Al menos 20 organizaciones filantrópicas de todo el mundo prometieron destinar 328 millones de dólares para apoyar los esfuerzos de reducción del metano[226].

  - La aplicación exitosa del *Compromiso Mundial sobre el Metano* reduciría el calentamiento en al menos 0,2 °C para 2050[227], y mantendría al planeta en una trayectoria coherente con el objetivo de no superar los 1,5 °C[228]. Esto equivale aproximadamente a una reducción del 35% por debajo de los niveles proyectados para 2030. El despliegue de todas las medidas disponibles y adicionales, tal como se describe en la GMA, podría conducir a una reducción del 45% por debajo de los niveles de 2030 para alcanzar casi 0,3 °C de calentamiento evitado en la década de 2040[229].

- En junio de 2022, Estados Unidos, la Unión Europea y otros 11 países pusieron en marcha la Vía de Energía del Compromiso Mundial sobre el Metano, que incluye 59 millones de dólares en financiación para apoyar la reducción de metano en el sector del petróleo y el gas[230]. La financiación contempla 4 millones de dólares para apoyar la Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial, 5,5 millones de dólares para apoyar la Iniciativa Global del Metano, hasta 9,5 millones de dólares del Observatorio Internacional de Emisiones de Metano del PNUMA para apoyar las evaluaciones científicas de las emisiones de metano y el potencial de mitigación, y hasta 40 millones de dólares anuales del *Global Methane Hub* filantrópico para apoyar la mitigación del metano en el sector de la energía fósil.
- En agosto de 2022 se promulgó la Ley de Reducción de la Inflación, que destina 369.000 millones de dólares a políticas climáticas y de energía limpia, incluidos unos 20.000 millones de dólares en incentivos para reducir las emisiones de gases de efecto invernadero, incluido el metano del sector agrícola, y 1.500 millones de dólares en ayudas para reducir las emisiones de metano del sector del petróleo y el gas a través del Programa de Reducción de Emisiones de Metano y el pago de una tasa sobre las fugas de metano[231]. Se calcula que esta ley reducirá para 2030 las emisiones de gases de efecto invernadero de Estados Unidos un 40% por debajo de los niveles de 2005[232].

El *Manual sobre la Reducción del Metano: la Mejor Estrategia para Frenar el Calentamiento en la Década de 2030* (2022) elaborado por el IGSD y CEDHA brinda más información sobre las bases científicas de la mitigación del metano y explica las razones por las que es necesario emprender acciones urgentes; describe las oportunidades de mitigación actuales y emergentes para cada sector; los esfuerzos nacionales, regionales e internacionales que pueden servir de base para la acción mundial de emergencia sobre el metano y enumera las iniciativas de financiación para garantizar el apoyo destinado a su rápida reducción.

B. Ozono troposférico (O_3)

El ozono troposférico es un contaminante atmosférico local y un importante GEI. El ozono no se emite directamente, sino que es producto de reacciones atmosféricas con contaminantes precursores, sobre todo metano y otros compuestos orgánicos volátiles y óxidos de nitrógeno (NOx). Además de contribuir al calentamiento, es responsable de millones de muertes prematuras[233], de la pérdida de cosechas por un valor de miles de millones de dólares al año[234] y del debilitamiento de los sumideros de carbono[235].

Mitigación

- Reducir el metano tiene el efecto añadido de reducir los niveles de ozono troposférico. Un estudio reciente estimó en un 35% la contribución del metano a la carga actual de ozono troposférico[236]. Es probable que el metano desempeñe un papel más importante en la formación de ozono troposférico a medida que disminuyan las emisiones de otros precursores debido a los controles de la contaminación atmosférica[237].
    - A través del ozono troposférico, el metano podría añadirse al Protocolo de 1999 para reducir la acidificación, la eutrofización y el ozono troposférico (Protocolo de Gotemburgo) al Convenio de la CEPE sobre la contaminación atmosférica transfronteriza a gran distancia (LRTAP, por sus siglas en inglés)[238]. El LRTAP es un tratado regional entre Europa, América del Norte, Rusia y los países del antiguo bloque del Este para reducir la contaminación atmosférica transfronteriza y comprender la ciencia relacionada[239]. El metano es el último de los principales precursores del ozono que no está explícitamente controlado por el Protocolo de Gotemburgo, en su versión actual[240].
    - Detener las fugas de metano del petróleo y el gas también reduce los precursores del ozono distintos del metano y contribuye a mejorar la calidad del aire local[241].
- Como contaminante atmosférico local, el ozono troposférico (y el carbono negro, del que se habla en la sección siguiente) puede abordarse en el marco de la legislación nacional o regional sobre contaminación atmosférica.

C. Carbono negro

El carbono negro y el ozono troposférico son contaminantes atmosféricos locales y suelen abordarse en el marco de la legislación nacional o regional sobre contaminación atmosférica, así como a través de los programas voluntarios de la CCAC[242]. El carbono negro no es un gas de efecto invernadero, sino un potente aerosol que calienta el clima y es un componente de las partículas finas (concretamente, $PM_{2,5}$) que entran en la atmósfera a través de la combustión incompleta de combustibles fósiles, así como de biocombustibles y biomasa[243]. La combustión de combustibles fósiles es la mayor fuente de partículas contaminantes del aire y de ozono troposférico, que mata a entre 8 y 10 millones[244] de personas al año. Reducir el carbono negro y el ozono troposférico puede salvar hasta 2,4 millones de vidas al año y aumentar la producción anual de cultivos en más de 50 millones de toneladas, por un valor de entre 4.000 y 33.000 millones de dólares al año, según cálculos de 2011[245].

Mitigación

- Es posible reducir el 70% de las emisiones mundiales de carbono negro de aquí a 2030[246], entre otras cosas, aplicando las siguientes medidas:
    - Garantizar la rápida ratificación del Protocolo de Gotemburgo y la enmienda de 2012 que incluye controles sobre el carbono negro[247];
    - Reducir las emisiones de diésel en carretera y fuera de ella mediante la imposición de filtros de partículas diésel, mientras se exige la eliminación de los vehículos

    - diésel y de otros vehículos que generan altas emisiones y se hace un cambio a formas limpias de transporte[248];
    - Eliminar la quema en antorcha y pasar a energías limpias[249];
    - Cambiar a métodos limpios de cocina y calefacción[250]; y
    - Prohibir el combustóleo pesado en el Ártico y establecer normas sobre emisiones de carbono negro para los buques mediante la modificación del Anexo VI del Convenio Internacional para Prevenir la Contaminación por los Buques (MARPOL, por sus siglas en inglés)[251].

D. Hidrofluorocarbonos (HFC)

Los hidrofluorocarbonos (HFC) son sustancias químicas de fabricación industrial que se utilizan principalmente en refrigeración, aparatos de aire acondicionado, espumas aislantes y propulsores de aerosoles, con usos menores como solventes y la protección contra incendios.

Mitigación

- El Protocolo de Montreal relativo a las sustancias que agotan la capa de ozono (Protocolo de Montreal) ha conseguido eliminar progresivamente la producción y el uso de los clorofluorocarbonos (CFC) y los hidroclorofluorocarbonos (HCFC)—potentes contaminantes climáticos que agotan la capa de ozono—evitando así las emisiones de GEI que, de otro modo, podrían haber igualado o superado las emisiones de CO_2 en 2010[252].
    - Para finales de siglo, el progreso constante del Protocolo de Montreal en sus 33 años de aplicación evitará hasta 2,5 °C de calentamiento que, de otro modo, ya habría conducido al planeta más allá de puntos críticos de inflexión irreversibles; además de alcanzar su objetivo original de poner la capa de ozono estratosférico en vías de recuperación[253].
    - Alrededor de 1,7 °C de este calentamiento evitado proviene de la reducción obligatoria, en el marco del Protocolo, de los productos químicos supercontaminantes—CFC, HCFC y ahora HFC—utilizados principalmente como refrigerantes en los equipos de refrigeración.
    - Se evitará un calentamiento adicional de 0,85 °C mediante la protección de los bosques de nuestro planeta, y de otros "sumideros" de carbono, frente a la dañina radiación ultravioleta que reduce su capacidad para extraer CO_2 de la atmósfera y almacenarlo de forma segura en sumideros terrestres.
- Los HFC se están reduciendo gradualmente en virtud de la Enmienda de Kigali del Protocolo de Montreal, con el potencial de evitar hasta 0,5 °C de calentamiento para 2100[254].
    - El calendario inicial de reducción progresiva de la Enmienda de Kigali fijaría las reducciones que limitarían el calentamiento de los HFC en 2100 a unos 0,04 °C, evitando aproximadamente el 90% del potencial, o hasta 0,44 °C[255].
    - Acelerar la eliminación progresiva podría reducir las emisiones de HFC en un 72% adicional en 2050, lo que aumentaría las posibilidades de mantenerse por debajo de 1,5 °C este siglo[256].
    - Un calendario de reducción progresiva más rápido; la recogida y destrucción de los HFC al final de la vida útil de los productos, el reciclado y la destrucción de los "bancos" de HFC integrados en los productos y equipos, la sustitución temprana de

  los equipos de refrigeración más antiguos e ineficientes que utilizan refrigerantes HFC y la reducción de las fugas de refrigerantes mediante un mejor diseño, fabricación y mantenimiento; todas estas acciones ofrecen mayores posibilidades de mitigación[257].
  - La Enmienda de Kigali también exige a las Partes que destruyan el HFC-23, un subproducto de la producción de HCFC-22, en la medida de lo posible, y esto proporcionará una mitigación adicional no incluida en el cálculo de 0,5 °C[258].
  - La mejora de la eficiencia energética de los equipos de refrigeración durante la eliminación gradual de los HFC puede más que duplicar los beneficios climáticos en términos de CO_{2e} al reducir las emisiones de las centrales eléctricas que suministran electricidad para hacer funcionar estos equipos[259].
  - En junio de 2023, 150 países habían aceptado, ratificado o aprobado la Enmienda de Kigali, entre ellos China y la India[260].
  - Estados Unidos está aplicando el calendario de reducción progresiva de Kigali a través de la Ley de Innovación y Fabricación Estadounidense (*American Innovation and Manufacturing Act*, AIM, por sus siglas en inglés) promulgada en diciembre de 2020. La Ley AIM y la implementación de regulaciones relacionadas reducirán la producción y el consumo de HFC en un 85% para 2036[261]. Doce estados han instituido prohibiciones de HFC para productos y equipos para los que existan alternativas disponibles con bajo PCG, y otros seis han propuesto prohibiciones al uso de HFC[262]. El 21 de septiembre de 2022, el Senado de Estados Unidos aprobó la ratificación de la Enmienda de Kigali[263].

E. Óxido Nitroso (N_2O)

Aunque no es un CCVC, el óxido nitroso (N_2O) de larga vida es el gas antropogénico de efecto invernadero más importante que agota la capa de ozono y que todavía no está controlado por el Protocolo de Montreal[264]. Mediante medidas de control obligatorias, el Protocolo de Montreal podría promover la adopción de tecnologías para reducir las emisiones de N_2O, que contribuyen a un calentamiento equivalente al 10% del CO_2 actual[265].

Mitigación

- El control de las emisiones de N_2O podría proporcionar una mitigación climática de alrededor de 1,67 $GtCO_{2e}$ PCG_{100} en 2050, con 0,94 $GtCO_{2e}$ procedente de la agricultura y alrededor de 0,6 $GtCO_{2e}$ procedente de la industria en 2050[266]. En el sector industrial, la tecnología de reducción ya está disponible y ha sido utilizada por los fabricantes de los países desarrollados desde la década de 1990[267]. Además, sólo cinco países producen el 86% del N_2O industrial: China, Estados Unidos, Singapur, Egipto y Rusia[268].
- En el sector agrícola, se han encontrado varias soluciones rentables para reducir las emisiones de N_2O procedentes de los procesos agrícolas: la agricultura de precisión con tecnología de tasa variable y los inhibidores de nitrógeno que suprimen la actividad microbiana que produce N_2O. Los estudios han concluido que la tecnología de tasa variable puede aumentar el rendimiento entre un 1% y un 10%, reduciendo al mismo tiempo entre un 4% y un 37% la fertilización nitrogenada[269]. Además, permitir un aumento continuo de las emisiones de N_2O mientras se reducen las de CO_2 y CH_4 podría socavar los avances en la recuperación de la capa de ozono estratosférico[270].

    - Otra solución es la línea de productos SOP[271] que estimula la absorción de nitrógeno en los cultivos e inhibe las emisiones de GEI procedentes del estiércol[272].

5. Otras estrategias de mitigación rápida pueden complementar los esfuerzos para frenar el calentamiento a corto plazo

A. Proteger el albedo y el permafrost del Ártico

La reducción rápida de los CCVC es clave para proteger el Ártico. La *Evaluación Global del Metano* calculó que las estrategias para reducir las emisiones de metano en un 40–45% para 2030 podrían evitar casi 0,3 °C para la década de 2040, y 0,5 °C en el Ártico para 2050, un 60% más que la media mundial[273]. La Evaluación Integrada del Carbono Negro y el Ozono Troposférico del PNUMA y la OMM de 2011 calculó que la plena aplicación de medidas dirigidas al metano y al carbono negro podría reducir a la mitad la tasa de calentamiento global y a dos tercios el calentamiento del Ártico[274].

- El Ártico es casi cinco veces más sensible al carbono negro emitido en la región Ártica que a emisiones similares en las latitudes medias[275]. En el Ártico, el carbono negro no sólo calienta la atmósfera, sino que facilita un calentamiento adicional al oscurecer la nieve y el hielo y reducir el albedo, o reflectividad, lo que permite que la superficie más oscura absorba más radiación solar y provoque un mayor deshielo[276].
    - El combustóleo (gasoil) pesado (HFO) utilizado en el transporte marítimo es una fuente importante de carbono negro, y la Organización Marítima Internacional (OMI) prohibirá el uso de HFO en el Ártico a partir de julio de 2024 para algunos buques, con excepciones y exenciones para otros hasta julio de 2029[277]. (El HFO está prohibido en la Antártida desde 2011[278].)
    - Debido a las exenciones, la prohibición del HFO no tendrá un gran impacto esta década. Si las medidas que entrarán en vigor en julio de 2024 hubieran estado en vigor en 2019, habrían prohibido sólo el 16% del HFO utilizado en el Ártico y reducido sólo el 5% del carbono negro[279]. Sin embargo, si la prohibición del HFO en el Ártico se hubieran impuesto sin las excepciones o exenciones, las emisiones de carbono negro podrían haberse reducido en un 30%[280].
    - En 2019, los países del Consejo Ártico establecieron el objetivo colectivo de reducir las emisiones de carbono negro en un 25–33% para 2025 en comparación con los niveles de 2013[281]. La adopción de las mejores técnicas disponibles podría reducir a la mitad las emisiones de carbono negro para 2025 y superar el objetivo actual[282]. Estas reducciones mejorarían la calidad del aire al reducir la exposición a las concentraciones de partículas finas de 18 millones a 1 millón de personas para 2050 y evitarían el 40% de las muertes relacionadas con la contaminación atmosférica en los países del Consejo Ártico para mediados de siglo[283].
    - En 2021, la OMI adoptó una resolución voluntaria para reducir las emisiones de carbono negro en el Ártico tras la reunión anual del Comité de Protección del Medio Marino de la OMI. Además de esta resolución, el Comité también acordó revisar su Estrategia de GEI, adoptar una resolución voluntaria sobre el uso de combustible más limpio en el Ártico y abordar los desechos plásticos marinos procedentes de los buques[284].

    - Prohibir las inversiones en la explotación de petróleo y gas en el Ártico puede contribuir a proteger aún más la región. Todos los grandes bancos estadounidenses —Bank of America, Goldman Sachs, JP Morgan Chase, Wells Fargo, Citi y Morgan Stanley—se han comprometido a no financiar prospecciones de petróleo y gas en el Ártico[285]. Las compañías de seguros también están empezando a comprometerse a prohibir la cobertura de proyectos petrolíferos en el Ártico, entre ellas AXA, Swiss RE y Zurich Insurance[286].
- En cuanto a la gestión del hielo del Ártico, entre las estrategias adicionales que se están investigando para protegerlo y restaurarlo, figuran el aumento y el engrosamiento del albedo del hielo marino del Ártico[287].

B. Proteger los bosques y otros sumideros

La deforestación combinada con el calentamiento global corre el riesgo de potenciar las retroalimentaciones del calentamiento y traspasar los puntos críticos de inflexión de los ecosistemas[288]. Detener la destrucción de nuestros bosques y otros sumideros de carbono[289] para que sigan almacenando carbono y no se conviertan en fuentes de CO_2 puede proporcionar una rápida mitigación, al tiempo que se protege la biodiversidad[290].

- Ya se ha destruido entre el 17% y el 20% de la selva amazónica[291], y se prevé un punto crítico de inflexión cuando se pierda entre el 20% y el 40%[292]. La continua deforestación y desecación del Amazonas en escenarios de altas emisiones podría provocar una pérdida de hasta el 50% de la cubierta forestal para 2050[293].
    - Los cambios en el ciclo hidrológico global pueden estar llevando al Amazonas a un punto crítico de inflexión[294]. La combinación de condiciones más secas, deforestación y calentamiento ha ido reduciendo la resistencia de los bosques amazónicos desde el año 2000, aumentando el riesgo de muerte[295].
    - Con el aumento de la deforestación, incluso a causa de incendios, mayores perturbaciones y temperaturas más altas, se sobrepasaría un punto más allá del cual la selva amazónica sería difícil de restablecer[296]; mediciones recientes sugieren que la zona sureste del Amazonas ya ha pasado a ser una fuente neta de carbono a medida que aumenta la mortalidad de los árboles y disminuye la fotosíntesis[297].
    - El deterioro de la salud de los bosques tropicales y boreales podría contribuir hasta 200 PgC [733 $GtCO_2$] para 2100[298].
- *Conservation International* calcula que los ecosistemas de la Tierra contienen 139 billones de toneladas métricas (Gt C) [510 $GtCO_2$] de "carbono irrecuperable", definido como el carbono almacenado en sistemas naturales que "son vulnerables a la liberación por la actividad humana y, si se pierden, no podrían recuperarse para 2050". Las mayores concentraciones de carbono irrecuperable se encuentran en el Amazonas (31,5 Gt C) [115,5 $GtCO_2$], la cuenca del Congo (8,1 Gt C) [29,7 $GtCO_2$] y Nueva Guinea (7,3 Gt C) [26,8 $GtCO_2$], con reservas adicionales en bosques boreales, manglares y turberas[299].
- Con las tendencias actuales de calentamiento, el sumidero terrestre mundial, que ahora mitiga aproximadamente ~30% de las emisiones de carbono[300], podría reducirse a la mitad ya en 2040, dado que el aumento de las temperaturas reduce la fotosíntesis y acelera la respiración[301], lo que afecta los compromisos nacionales en virtud del Acuerdo de París, que dependen en gran medida de la absorción de carbono por la tierra para cumplir los objetivos de mitigación[302].

Las soluciones basadas en la naturaleza ayudan a limitar el calentamiento de tres maneras: en primer lugar, la protección de bosques y sumideros evita la liberación de carbono; en segundo lugar, la restauración de bosques y sumideros críticos secuestra carbono; y en tercer lugar, la mejora de la gestión de la tierra puede tanto reducir las emisiones de carbono, metano y óxido nitroso como secuestrar carbono[303].

- Entre las formas eficaces de proteger los bosques, las turberas y otros sumideros se incluyen:
    - Promover la protección de los bosques y la forestación para que los bosques existentes alcancen todo su potencial ecológico[304];
    - Preservar las turberas existentes y restaurar las turberas degradadas[305];
    - Restaurar los ecosistemas costeros de “carbono azul” [306]; y
    - Prohibir la bioenergía[307].
- Los esfuerzos mundiales dirigidos por los gobiernos para proteger los bosques están aumentando.
    - En la COP26, los líderes mundiales acordaron detener la deforestación para 2030 en la Declaración de los Líderes de Glasgow sobre los Bosques y el Uso de la Tierra. Para junio de 2023, 145 países se habían comprometido con este acuerdo, entre ellos Brasil, China, Estados Unidos y Rusia, que representan alrededor del 91% de los bosques del mundo[308]. La declaración incluye 12.000 millones de dólares en fondos para la financiación climática relacionada con los bosques entre 2021–2025, 7.000 millones de dólares adicionales en financiación de empresas privadas y una hoja de ruta global para hacer que el 75% de las cadenas de suministro de productos forestales sean sostenibles[309].
    - Estados Unidos puso en marcha un Plan nacional paralelo para Conservar los Bosques Mundiales: Sumideros Críticos de Carbono; se trata de un “esfuerzo de todo el gobierno” para poner fin a la pérdida de bosques naturales, preservar los ecosistemas mundiales, incluidos los sumideros de carbono, y restaurar al menos 200 millones de hectáreas adicionales de bosques y otros ecosistemas para 2030, con un fondo específico de 9.000 millones de dólares para apoyar este esfuerzo[310].

C. Eliminar los supercontaminantes de la atmósfera

Científicos y financiadores están elaborando un programa de investigación para eliminar de la atmósfera el metano y otros gases de efecto invernadero distintos del CO_2[311]. Entre las vías que se están estudiando para la eliminación del metano se encuentra la oxidación catalítica, los filtros microbianos y el aumento de los sumideros naturales[312]. Es probable que los sistemas catalíticos utilicen tecnología ya desarrollada para su aplicación en entornos con elevadas concentraciones de metano, como las minas de carbón y los establos lecheros.

- El Gobierno de Estados Unidos ha comenzado a explorar opciones para eliminar el metano de la atmósfera.
    - En abril de 2021, la Agencia de Proyectos de Investigación Avanzada-Energía (ARPA-E, por sus siglas en inglés) del Departamento de Energía anunció un programa de 35 millones de dólares para reducir las emisiones de metano, denominado REMEDY (*Reducing Emissions of Methane Every Day of the Year*). Este programa de investigación de tres años pretende reducir las emisiones de

  metano procedentes de los sectores del petróleo, el gas y el carbón. Según ARPA-E, estas tres fuentes contribuyen al menos al 10% de las emisiones antropogénicas de metano de Estados Unidos[313]. Al desarrollar el programa REMEDY, ARPA-E reconoció la necesidad de seguir investigando sobre la captura de metano del aire en paralelo a los esfuerzos para capturar CO_2[314].
  - En diciembre de 2021, ARPA-E concedió subvenciones para un sistema de oxidación catalítica destinado a los gases de escape de motores de gas natural de combustión pobre, múltiples sistemas basados en la catálisis para la ventilación de minas de carbón y el desarrollo de un catalizador de bajo costo basado en el cobre[315].
  - En julio de 2022, el presupuesto de ARPA-E se duplicó gracias a la Ley de Creación de Incentivos Útiles para la Producción de Semiconductores y Ciencia (CHIPS, por sus siglas en inglés) [316].
- Otras intervenciones para la eliminación de metano podrían dirigirse a fuentes naturales de metano.
  - Una empresa está probando instalar sistemas pasivos para capturar y quemar el metano burbujeante de los lagos del Ártico[317].
- Estos esfuerzos de eliminación de metano y otros gases distintos del CO_2 podrían complementar los proyectos de eliminación de carbono en Estados Unidos[318], Europa[319] y otros países[320].

La publicación *Background Note on Methane Removal* (2022) del IGSD brinda mayor información sobre los esfuerzos de investigación propuestos y en marcha.

6. Conclusión

Se prevé que el calentamiento global cruce el umbral de 1,5 °C ya a principios de la década de 2030. Las políticas que se basan únicamente en la descarbonización son insuficientes para frenar el calentamiento a corto plazo y mantener el planeta incluso por debajo del umbral más peligroso de 2,0 °C.

Tenemos que ampliar urgentemente nuestro enfoque a la mitigación del cambio climático para centrarnos tanto en el dióxido de carbono (CO_2) como en otros contaminantes en gran medida desatendidos para abordar los impactos a corto y largo plazo de la perturbación del sistema climático, reducir el riesgo de cruzar puntos críticos de inflexión irreversibles y mantener un planeta habitable[321].

Al combinar los esfuerzos para reducir las emisiones de CO_2 mediante la descarbonización del sistema energético *con* medidas de mitigación dirigidas al metano, los CCVC distintos del CO_2, los refrigerantes HFC, el hollín de carbono negro y el smog de ozono a nivel del suelo, así como el óxido nitroso, se reduciría la tasa de calentamiento a la mitad entre 2030 y 2050, lo que frenaría la tasa de calentamiento una o dos décadas antes que la descarbonización por sí sola y *haría posible que el mundo se mantuviera por debajo del límite de seguridad de 1,5 °C*[322]. Esta estrategia, que incluye un *sprint* en esta década para frenar el calentamiento a corto plazo reduciendo los CCVC y protegiendo los sumideros de carbono mediante soluciones basadas en la naturaleza, complementa la maratón para lograr emisiones netas iguales a cero de aquí a 2050 con el fin de estabilizar las temperaturas más a largo plazo[323].

El IE6 es un "código rojo" para la emergencia climática[324]. El *Informe Especial del IPCC sobre 1,5 °C* de 2018 presentó las tres estrategias esenciales para mantener el planeta relativamente seguro: reducir el CO_2, disminuir los CCVC y eliminar hasta 1 trillón de toneladas de CO_2 de la atmósfera para 2100[325]. Reducir los CCVC es la única estrategia conocida que puede frenar el calentamiento y las retroalimentaciones a tiempo para evitar impactos catastróficos y quizás existenciales[326] de la *Hothouse Earth* (Tierra Invernadero)[327], aparte de la gestión de la radiación solar, que conlleva sus propios riesgos[328].

En 2021, más líderes y responsables de políticas reconocieron más que nunca la importancia y el potencial de centrarse en los supercontaminantes climáticos. Está empezando a surgir una nueva arquitectura climática, tal como demuestra el reajuste de los objetivos de la retrasada COP26 de 2021, en comparación con los objetivos anunciados en 2020:

> "Cuatro cambios de enfoque reflejan esta nueva arquitectura: en primer lugar, el reconocimiento casi unánime de la inminente emergencia climática y de la necesidad de limitar el calentamiento a 1,5 grados centígrados; en segundo lugar, el reconocimiento de que "2030 es el nuevo 2050", como dijo el presidente francés Emmanuel Macron, y de que en esta década es necesario lograr grandes reducciones de las emisiones (nótese también que la Declaración Conjunta de Glasgow de EE.UU.-China fue la primera vez que Estados Unidos y China reconocieron la urgencia de la acción climática en esta "década crítica" de 2020); en tercer lugar, el reconocimiento de que la reducción de las emisiones más allá del CO_2 (en particular del metano) es esencial para frenar el calentamiento en las próximas dos décadas, y de que las reducciones de CO_2 por sí solas no pueden hacer frente a la emergencia a corto plazo; y en cuarto lugar, la incorporación de enfoques sectoriales específicos donde se reconozca que a menudo es más eficiente y eficaz abordar sectores individuales de la economía para alcanzar soluciones climáticas" [329].

Referencias

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[1] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): 1–8, 1, 5 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."; "Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5)."). *See also* Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10321 ("Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050… The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).").

[2] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."; "Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change."). *See also* Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, Science 335(6065): 183–189, 184–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. …Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to

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albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic)."); *and* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally *(high confidence*).").

[3] von Braun J., Ramanathan V., & Turkson P. K. A. (2022) *Resilience of people and ecosystems under climate stress*, Pontifical Academy of Sciences, 6 ("Recommendations: *Resilience building must rest on three pillars*: Mitigation, Adaptation & Transformation. Mitigation: *Reduce climate risks*…. Adaptation: *Reduce exposure and vulnerability to unavoidable climate risks*. Exposure & vulnerability reduction has three faces: Reductions in sensitivity to climate change; Reductions in risk exposure; & enhancement of adaptative capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits."); where the definition of resilience is taken from Möller V., van Diemen R., Matthews J. B. R., Méndez C., Semenov S., Fuglestvedt J. S., & Resinger A. (2022) *Annex II: Glossary*, *in* Climate Change 2022: Impacts, Adaptation, and Vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), 2920–2921 ("The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016).").

[4] Diffenbaugh N. S. & Barnes E. A. (2023) *Data-driven predictions of the time remaining until critical global warming thresholds are reached*, Proc. Nat'l. Acad. Sci. 120(6): 1–9, 2 ("For 1.5 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2035 (2030 to 2040) in the High scenario, 2033 (2028 to 2039) in the Intermediate scenario, and 2033 (2026 to 2041) in the Low scenario (Fig. 3). For 2 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2050 (2043 to 2058) in the High scenario, 2049 (2043 to 2055) in the Intermediate scenario, and 2054 (2044 to 2065) in the Low scenario."); *discussed in* Harvey C. (31 January 2023) *AI Predicts Warming Will Surpass 1.5 C in a Decade*, Scientific American. *See also* Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Comment, Nature 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: *see* Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"). *See also* Dvorak M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022) *Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming*, Nat. Clim. Change 12: 547–552, 547 ("Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming peak within a decade, followed by slow cooling as GHG concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels before reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter

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until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2–4.5), we find that we are already committed to peak warming greater than 1.5 °C with 42% probability, increasing to 66% by 2029 (340 $GtCO_2$ relative to 2021). Probability of peak warming greater than 2.0 °C is currently 2%, increasing to 66% by 2057 (1,550 $GtCO_2$ relative to 2021). Because climate will cool from peak warming as GHG concentrations decline, committed warming of 1.5 °C in 2100 will not occur with at least 66% probability until 2055."); *and* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IZV. Atmos. Ocean. Phys. (*preprint*): 1–62, 39 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate of at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 25).").

[5] Madge G. (8 May 2022) *Temporary breaching of 1.5C in next five years?*, UK Met Office ("The chance of at least one year exceeding 1.5°C above pre-industrial levels between 2022-2026 is about as likely as not (48%). However, there is only a very small chance (10%) of the five-year mean exceeding this threshold."); *discussing* World Meteorological Organization (2022) Global Annual to Decadal Climate Update. *See also* Hook L. (9 May 2022) *World on course to breach global 1.5C warming threshold within five years*, Financial Times. For previous years, *see* World Meteorological Organization (2021) WMO Global Annual to Decadal Climate Update, 5 ("Relative to pre-industrial conditions, the annual mean global near surface temperature is predicted to be between 0.9°C and 1.8°C higher (90% confidence interval). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 44% and is increasing with time. There is a very small chance (10%) of the five-year mean exceeding this threshold. The Paris Agreement refers to a global temperature increase of 1.5°C, which is normally interpreted as the long-term warming, but temporary exceedances would be expected as global temperatures approach the threshold."); *discussed in* Hodgson C. (26 May 2021) *Chance of temporarily reaching 1.5C in warming is rising, WMO says*, Financial Times. *Compare with* World Meteorological Organization (2020) United in Science 2020, 16 ("Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5 °C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré et al. 2020 and Carbonbrief.org).").

[6] Loeb N. G., Johnson G. C., Thorsen T. J., Lyman J. M., Rose F. G., & Kato S. (2021) *Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate*, Geophys. Res. Lett. 48(13): 1–8, 1 ("Marked decreases in clouds and sea-ice and increases in trace gases and water vapor combine to increase the rate of planetary heat uptake."); *discussed in* Bekiempis V. (17 June 2021) *Earth is trapping 'unprecedented' amount of heat, Nasa says*, The Guardian. *See also* von Schuckmann K., *et al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?*, Earth Syst. Sci. Data 15(4): 1675–1709, 1694 ("In IPCC AR6, the total heat rate has been assessed by 0.57 (0.43 to 0.72) $W\ m^{-2}$ for the period 1971–2018 and 0.79 (0.52 to 1.06) $W\ m^{-2}$ for the period 2006–2018 (Forster et al., 2021). Consistently, we further infer a total heating rate of $0.76 \pm 0.2\ W\ m^{-2}$ for the most recent era (2006–2020). Thus, the rate of heat accumulation across the Earth system has increased during the most recent era as compared to the long-term estimate – an outcome which reconfirms the earlier finding in von Schuckmann et al. (2020) and which had then been concurrently and independently confirmed in Foster et al. (2021), Hakuba et al. (2021), Loeb et al. (2021), Liu et al. (2020), Raghuraman et al. (2021), and Kramer et al. (2021). The drivers of a larger EEI in the 2000s than in the long-term period since 1971 are still unclear, and several mechanisms are discussed in literature. For example, Loeb et al. (2021) argue for a decreased reflection of energy back into space by clouds (including aerosol cloud interactions) and sea ice and increases in well-mixed greenhouse gases (GHG) and water vapor to account for this increase in EEI. Kramer et al. (2021) refer to a combination of rising concentrations of well-mixed GHG and recent reductions in aerosol emissions to be accounting for the increase, and Liu et al. (2020) address changes in surface heat flux together with planetary heat redistribution and changes in ocean heat storage.").

[7] Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-59 ("The net effect of changes in clouds in response to global warming is to amplify human-induced warming, that is, the net cloud feedback is positive (*high confidence*).") *See also* Ceppi P. &

Nowack P. (2021) *Observational evidence that cloud feedback amplifies global warming*, Proc. Nat'l. Acad. Sci. 118(30): 1–7, 1, 4 ("Global warming drives changes in Earth's cloud cover, which, in turn, may amplify or dampen climate change. This "cloud feedback" is the single most important cause of uncertainty in Equilibrium Climate Sensitivity (ECS)—the equilibrium global warming following a doubling of atmospheric carbon dioxide. Using data from Earth observations and climate model simulations, we here develop a statistical learning analysis of how clouds respond to changes in the environment. We show that global cloud feedback is dominated by the sensitivity of clouds to surface temperature and tropospheric stability. Considering changes in just these two factors, we are able to constrain global cloud feedback to 0.43 ± 0.35 $W \cdot m^{-2} \cdot K^{-1}$ (90% confidence), implying a robustly amplifying effect of clouds on global warming and only a 0.5% chance of ECS below 2 K. … Our global constraint implies that a globally positive cloud feedback is virtually certain, thus strengthening prior theoretical and modeling evidence that clouds will provide a moderate amplifying feedback on global warming through a combination of [terrestrial] LW [longwave] and [solar] SW [shortwave] changes. This positive cloud feedback renders ECS lower than 2 K extremely unlikely, confirming scientific understanding that sustained greenhouse gas emissions will cause substantial future warming and potentially dangerous climate change."); *discussed in* Berwyn B. (19 July 2021) *Climate-Driven Changes in Clouds are Likely to Amplify Global Warming*, Inside Climate News ("New research, using machine learning, helps project how the buildup of greenhouse gases will change clouds in ways that further heat the planet.").

[8] *See* Copernicus Climate Services (9 January 2023) *2022 was a year of climate extremes, with record high temperatures and rising concentrations of greenhouse gases* (*last visited* 11 June 2023) ("2022 was the 5th warmest year – however, the 4th-8th warmest years are very close together. The last eight years have been the eight warmest on record. The annual average temperature was 0.3°C above the reference period of 1991-2020, which equates to approximately 1.2°C higher than the period 1850-1900. Atmospheric carbon dioxide concentrations increased by approximately 2.1 ppm, similar to the rates of recent years. Methane concentrations in the atmosphere increased by close to 12 ppb, higher than average, but below the last two years' record highs. La Niña conditions persisted during much of the year, for the third year in a row"); National Aeronautics and Space Administration (12 January 2023) *NASA Says 2022 Fifth Warmest Year on Record, Warming Trend Continues*; *and* National Oceanic and Atmospheric Administration (12 January 2022) *2022 was world's 6th-warmest year on record*. *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-6 ("The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 [11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is likely that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to 0.1°C, and internal variability changed it by –0.2°C to 0.2°C. It is very likely that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979, and extremely likely that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s."… Footnote 11: "The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C." Footnote 12: "Throughout this SPM, 'main driver' means responsible for more than 50% of the change.").

[9] Carbon Brief (4 August 2022) *Mapped: How climate change affects extreme weather around the world* (*last visited* 11 June 2023) ("Of the attribution studies included here, scientists found that human-caused climate change has altered the likelihood or severity of an extreme weather event in 80% of cases studied (71% made more severe or likely and 9% made less so).").

[10] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 24 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 832

(“Additional methane and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).”); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, Proc. Nat’l. Acad. Sci. 105(38): 14245–14250, 14248 (“Switching from coal to ‘‘cleaner’’ natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C).”); United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the near-term warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.”); *and* Wanser K., Wong A., Karspeck A., & Esguerra N. (2023) Near-term Climate Risk and Intervention: *A Roadmap for Research, U.S. Research Investment, and International Scientific Cooperation*, SilverLining, 12 (“Particles (i.e., aerosols) in the atmosphere generally increase the total amount of sunlight reflected to space by scattering incoming sunlight. Anthropogenic activities produce both GHGs and other particulate matter; while GHGs warm climate, aerosols have a cooling effect both by directly scattering sunlight (i.e., the aerosol direct effect) and indirectly as the aerosols interact with clouds, increasing their brightness and/or their duration (i.e., the cloud–aerosol effect) … The potential global cooling effect of all anthropogenic aerosols is estimated at 0.5–1.1℃ (see Figure 6). Thus, these effects are potentially very large while also serving as a large source of uncertainty, making reducing these uncertainties among the highest priorities for climate research, particularly in the context of assessing near-term climate risk. Particles from emissions produced by human activities are also associated with significant adverse health and environmental effects. Actions are ongoing around the world to substantially reduce them, including recent regulation to substantially reduce sulfate emissions from ships. As the world reduces these particulate emissions, the loss of this cooling “shield” could lead to rapid substantial warming.”).

[11] Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions*, Proc. Nat’l. Acad. Sci. 106(49): 20616–20621, 20616 (“Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of “dangerous anthropogenic interference” (DAI). Scientific and policy literature refers to the need for “early,” “urgent,” “rapid,” and “fast-action” mitigation to help avoid DAI and abrupt climate changes. We define “fast-action” to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO_2 GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO_2 emissions.”). *See also* Molina M., Ramanathan V. & Zaelke D. (2020) *Best path to net zero: Cut short-lived climate pollutants*, Bulletin of the Atomic Scientists (“And let us be clear: By “speed,” we mean

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measures—including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.”).

[12] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 (“The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement’s aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.”). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”); Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, Proc. Nat’l. Acad. Sci. 115(33): 8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System’s stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*).”; “The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

[13] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat’l. Acad. Sci. 114(39): 10319–10323, 10320 (“Box 2. Risk Categorization of Climate

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Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats."). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, Proc. Nat'l. Acad. Sci. 117(21): 11350–11355, 11350 ("Here, we demonstrate that for millennia, human populations have resided in the same narrow part of the climatic envelope available on the globe, characterized by a major mode around ~11 °C to 15 °C mean annual temperature (MAT). …We show that in a business-as-usual climate change scenario, the geographical position of this temperature niche is projected to shift more over the coming 50 y than it has moved since 6000 BP. … Specifically, 3.5 billion people will be exposed to MAT ≥29.0 °C, a situation found in the present climate only in 0.8% of the global land surface, mostly concentrated in the Sahara, but in 2070 projected to cover 19% of the global land (Fig. 3). … For instance, accounting for population growth projected in the SSP3 scenario, each degree of temperature rise above the current baseline roughly corresponds to one billion humans left outside the temperature niche, absent migration (*SI Appendix*, Fig. S14)."); Watts N., *et al.* (2021) *The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises*, The Lancet 397(10269): 129–170, 129 ("Vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019, which was, in turn, reflected in excess morbidity and mortality (indicator 1.1.2). During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296 000 deaths in 2018 (indicator 1.1.3). The high cost in terms of human lives and suffering is associated with effects on economic output, with 302 billion h of potential labour capacity lost in 2019 (indicator 1.1.4). India and Indonesia were among the worst affected countries, seeing losses of potential labour capacity equivalent to 4–6% of their annual gross domestic product (indicator 4.1.3)."); Atwoli L., *et al.* (2021) *Call for emergency action to limit global temperature increases, restore biodiversity, and protect health*, The Lancet 398(10304): 939–941, 939 ("Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems."); Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 ("In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*)."); *and* Berwyn B. (14 February 2023) *Sea Level Rise Could Drive 1 in 10 People from Their Homes, with Dangerous Implications for International Peace, UN Secretary General Warns*, Inside Climate News.

[14] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 15 ("With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than

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decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*)."). *See also* Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, Nat. Clim. Change 11: 689–695, 689 ("Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades.").

[15] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) Irrecoverable Carbon: *The Places We Must Protect to Avert Climate Catastrophe*, Conservation International, 7 ("'Irrecoverable carbon' refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change. There are high concentrations of irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves, Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Griscom B. W., *et al.* (2017) *Natural climate solutions*, Proc. Nat'l. Acad. Sci. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."); Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, Nat. Clim. Change 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth's ecosystems*, Nat. Sustain. 5: 37–46.

[16] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further

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emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)").

[17] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 23, 24 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century… Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*)").

[18] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 12 ("In model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range)…. Modelled pathways that limit global warming to 1.5 °C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010)."; "C.3. All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.").

[19] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("Abrupt change is defined as a change in the system that is substantially faster than the typical rate of the changes in its history (Chapter 1, Section 1.4.5). A related matter is a tipping point: a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly.").

[20] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, Proc. Nat'l. Acad. Sci. 112(43): E5777–E5786, E5777 ("Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61(e2021RG000757): 1–81, 48 ("Earth system elements that this review indicates are at higher risk of crossing critical thresholds or undergoing substantial changes in response to warming this century under moderate (RCP4.5) emissions scenarios include loss of Arctic summer sea ice, loss of portions of the GIS, loss of portions of the West Antarctic Ice-sheet, Amazon rainforest dieback, boreal forest ecosystem shifts, some permafrost carbon release, and coral reef loss (Figure 14). In contrast, methane release from marine methane hydrates and strato-cumulus cloud deck evaporation will likely require longer timescales and higher emissions forcing in order to occur at large scales, while disruptions of tropical monsoons may be contingent on large shifts in other Earth system components and are unlikely to occur as a direct response to changes in aerosol forcing or land cover (see Section 2.6). Critical

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thresholds for weakening of the AMOC remain unclear and a transition of this system to a different state may not occur this century (see Section 2.1). While the GIS and WAIS may transgress critical thresholds this century (see Section 2.3), timescales of ice loss may require many centuries to millennia to run to completion (Bakker et al., 2016; Clark et al., 2016; Golledge et al., 2015; Huybrechts & De Wolde, 1999)."); Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 593 ("A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic...."); Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-71–TS-72 ("It is *likely* that under stabilization of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850–1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries (*medium confidence*). At sustained warming levels between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*). At sustained warming levels between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over multiple millennia (*low confidence*). Early-warning signals of accelerated sea-level-rise from Antarctica, could possibly be observed within the next few decades. For other hazards (e.g., ice sheet behaviour, glacier mass loss and global mean sea level change, coastal floods, coastal erosion, air pollution, and ocean acidification) the time and/or scenario dimensions remain critical, and a simple and robust relationship with global warming level cannot be established (*high confidence*)... The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with climate change (*high confidence*). It is *very unlikely* that gas clathrates (mostly methane) in deeper terrestrial permafrost and subsea clathrates will lead to a detectable departure from the emissions trajectory during this century. Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century atmospheric GHG concentrations, but future anthropogenic emissions remain the dominant uncertainty (*high confidence*). There is potential for abrupt water cycle changes in some high-emission scenarios, but there is no overall consistency regarding the magnitude and timing of such changes. Positive land surface feedbacks, including vegetation, dust, and snow, can contribute to abrupt changes in aridity, but there is only *low confidence* that such changes will occur during the 21st century. Continued Amazon deforestation, combined with a warming climate, raises the probability that this ecosystem will cross a tipping point into a dry state during the 21st century (*low confidence*)."); *and* Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points).

[21] *See* Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 262 ("Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7."); *and* Abram N., *et al.* (2019) *Chapter 1: Framing and Context of the Report*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 1-81 ("While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally wh

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critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 ºC that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram et al., 2013; Trusel et al., 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al*. 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018).").

[22] Here we distinguish between abrupt shifts, as in Drijfhout *et al*. (2015), and the more restrictive definition of "core climate tipping points" defined by Armstrong McKay *et al.* (2022) as "when change in part of the climate system becomes (i) selfperpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks, leading to (iii) substantial and widespread Earth system impacts." *See* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS [West Antarctic Ice Sheet] and GrIS [Greenland Ice Sheet] tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF [low-latitude coral reefs], and North Atlantic subpolar gyre / Labrador-Irminger Sea convection abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST [Global Mean Surface Temperature] returns below 1.5°C within an uncertain overshoot time (likely decades) (94). … The chance of triggering CTPs [Climate tipping points] is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC [North Atlantic subpolar gyre / Labrador-Irminger Sea convection] collapse is crossed. The likelihood of triggering AMOC [Atlantic Meridional Overturning Circulation] collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESM [Earth System Models] at 1.5 to 2°C (19). Although not tipping elements, ASSI [Arctic Summer Sea Ice] loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[23] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, Earth Syst. Dyn. 12(2): 601–619, 614 ("In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole."); Klose A. K., Wunderling N., Winkelmann R., & Donges J. F. (2021) *What do we mean, `tipping cascade'?*, Environ. Res. Lett. 16(12): 125011, 1–12, 1 ("Here we illustrate how different patterns of

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multiple tipping dynamics emerge from a very simple coupling of two previously studied idealized tipping elements. In particular, we distinguish between a two phase cascade, a domino cascade and a joint cascade. A mitigation of an unfolding two phase cascade may be possible and common early warning indicators are sensitive to upcoming critical transitions to a certain degree. In contrast, a domino cascade may hardly be stopped once initiated and critical slowing down-based indicators fail to indicate tipping of the following element. These different potentials for intervention and anticipation across the distinct patterns of multiple tipping dynamics should be seen as a call to be more precise in future analyses of cascading dynamics arising from tipping element interactions in the Earth system."); Rocha J. C., Peterson G., Bodin Ö., & Levin S. (2018) *Cascading regime shifts within and across scales*, SCIENCE 362(6421): 1379–1383, 1383 ("A key lesson from our study is that regime shifts can be interconnected. Regime shifts should not be studied in isolation under the assumption that they are independent systems. Methods and data collection need to be further developed to account for the possibility of cascading effects. Our finding that ~45% of regime shift couplings can have structural dependence suggests that current approaches to environmental management and governance underestimate the likelihood of cascading effects."); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 16 ("Human influence has likely increased the chance of compound extreme events since the 1950s. Concurrent and repeated climate hazards have occurred in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Compound extreme events include increases in the frequency of concurrent heatwaves and droughts (*high confidence*); fire weather in some regions (*medium confidence*); and compound flooding in some locations (*medium confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Compound climate hazards can overwhelm adaptive capacity and substantially increase damage (*high confidence*).").

[24] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5784 ("Permafrost carbon release (51) and methane hydrates release (52) were not expected in CMIP5 simulations, because of missing biogeochemical components in those models capable of simulating such changes."). *See also* Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. CLIM. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the question whether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events (Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models."); Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength."); *and* Permafrost Pathways, *Course of Action: Mitigation Policy*, Woodwell Climate Research Center (*last visited* 14 February 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement.... Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature

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from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish.... 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.”).

[25] Molina M., Ramanathan V., & Zaelke D. (2018) *Climate report understates threat*, Bulletin of the Atomic Scientists (“These cascading feedbacks include the loss of the Arctic’s sea ice, which could disappear entirely in summer in the next 15 years. The ice serves as a shield, reflecting heat back into the atmosphere, but is increasingly being melted into water that absorbs heat instead. Losing the ice would tremendously increase the Arctic’s warming, which is already at least twice the global average rate. This, in turn, would accelerate the collapse of permafrost, releasing its ancient stores of methane, a super climate pollutant 30 times more potent in causing warming than carbon dioxide.”).

[26] Kemp L., Xu C., Depledge J., Ebi K. L., Gibbins G., Kohler T. A., Rockström J., Scheffer M., Schellnhuber H. J., Steffen W., & Lenton T. M. (2022) *Climate Endgame: Exploring catastrophic climate change scenarios*, Proc. Nat’l. Acad. Sci. 119(34): 1–9, 3 (“Third, climate change could exacerbate vulnerabilities and cause multiple, indirect stresses (such as economic damage, loss of land, and water and food insecurity) that coalesce into system-wide synchronous failures. This is the path of systemic risk. Global crises tend to occur through such reinforcing “synchronous failures” that spread across countries and systems, as with the 2007–2008 global financial crisis (44). It is plausible that a sudden shift in climate could trigger systems failures that unravel societies across the globe. The potential of systemic climate risk is marked: The most vulnerable states and communities will continue to be the hardest hit in a warming world, exacerbating inequities. Fig. 1 shows how projected population density intersects with extreme >29 °C mean annual temperature (MAT) (such temperatures are currently restricted to only 0.8% of Earth’sland surface area). Using the medium-high scenario of emissions and population growth (SSP3-7.0 emissions, and SSP3 population growth), by 2070, around 2 billion people are expected to live in these extremely hot areas. Currently, only 30 million people live in hot places, primarily in the Sahara Desert and Gulf Coast (43). Extreme temperatures combined with high humidity can negatively affect outdoor worker productivity and yields of major cereal crops. These deadly heat conditions could significantly affect populated areas in South and southwest Asia(47). Fig. 2 takes a political lens on extreme heat, overlapping SSP3-7.0 or SSP5-8.5 projections of >29 °C MAT circa 2070, with the Fragile States Index (a measurement of the instability of states). There is a striking overlap between currently vulnerable states and future areas of extreme warming. If current political fragility does not improve significantly in the coming decades, then a belt of instability with potentially serious ramifications could occur.”). *See also* Stern N., Stiglitz J., & Taylor C. (2022) *The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change*, J. Econ. Methodol. 29(3): 181–216, 182 (“Moreover, at the core of the standard IAM methodology is an analysis of intertemporal trade-offs; how much the current generation should sacrifice in order for future generations to be spared the devastation of climate change. Rising to the climate challenges does indeed involve deep normative questions, including how different generations’ welfare is to be compared and the rights of future generations. But the world has been much more focused than the IAMs on a different set of issues, the risks of catastrophic consequences. These potentially catastrophic risks are in large measure *assumed* away in the IAMs.”).

[27] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature, 575(7784): 592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 (“Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C

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by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94).").

[28] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Impacts, Adaptation, and Vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-19–20 ("SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3)… SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*).… SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*).").

[29] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (22 April 2022) *Global warming overshoots increase risk of triggering climate tipping points and cascades*, Nature (*preprint*), 1–31, 1, 11–12, 18 ("Climate tipping elements play a crucial role for the stability of the Earth system under human pressures and are potentially at risk of disintegrating within and partially even below the Paris temperature guardrails of 1.5-2.0°C above pre-industrial levels. However, current policies and actions make it very likely to, at least temporarily, transgress the Paris targets. This raises the question whether tipping points can still be avoided under such overshoot scenarios. Here, we investigate the associated risks for tipping under a range of temperature overshoot scenarios using a stylised network model of four interacting climate tipping elements: the Greenland and West Antarctic Ice Sheets, the Atlantic Meridional Overturning Circulation and the Amazon rainforest. Our results reveal that temporary overshoots can increase tipping risks by up to 72% compared to a soft landing without overshoots, even when the long-term equilibrium temperature stabilises within the Paris range."; "We compute that the risk for tipping events occurring at convergence temperatures within the limits of the Paris climate target ranges between slightly more than half (57.8%) to more than nine-tenths (91.4%) of all simulations (see Fig. 3). For small peak temperatures (T_{Peak} = 2.5 °C), overshoot tipping only accounts for as little as 9% of all tipping events but for intermediate peak temperature levels (T_{Peak} = 4.0 °C) this number can increase to as much as 42% (see pie charts in Fig. 3). Specifically, the risk of tipping increases between 10–72% in these scenarios for overshooting before stabilising at the convergence temperature than just approaching the convergence temperature with no overshoot. Note that in the special case, where the peak temperature equals the convergence temperature ($T_{\text{Peak}} = T_{\text{Conv}}$ = 2.0 °C), overshoot tipping events do not occur."; "Critically, to reduce the risk and prevent the negative impacts of interacting climate tipping elements on human societies and biosphere integrity, it is of utmost importance to ensure that temperature overshoot trajectories are limited in both magnitude and duration, while stabilising global warming at, or better, below the Paris agreement's targets. Concretely, avoiding a high climate risk zone aiming to limit the risk for tipping events would entail convergence temperatures of today's levels of global warming or below (< 1.2 °C, better $\lesssim$ 1.0 °C), while overshoot temperatures should not exceed 3.0 °C and convergence times should not exceed 300 years unless peak temperatures are significantly smaller than 2.5 °C. This would reduce the risk for one tipping event to occur to below 33% (see Fig. 2d).").

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[30] Vaughan A. (7 January 2022) *Record levels of greenhouse gas methane are a 'fire alarm moment'*, NEW SCIENTIST ("According to data compiled by the US National Oceanic and Atmospheric Administration (NOAA), average atmospheric concentrations of methane reached a record 1900 parts per billion (ppb) in September 2021, the highest in nearly four decades of records. The figure stood at 1638 ppb in 1983."). See also World Meteorological Organization (26 October 2022) *The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021*, WMO GREENHOUSE GAS BULLETIN, 1 ("In 2020 and 2021, the global network of the WMO Global Atmosphere Watch (GAW) Programme detected the largest within-year increases (15 and 18 ppb, respectively) of atmospheric methane (CH_4) since systematic measurements began in the early 1980s (Figure 1). The causes of these exceptional increases are still being investigated by the global greenhouse gas science community. Analyses of measurements of the abundances of atmospheric CH_4 and its stable carbon isotope ratio $^{13}C/^{12}C$ (reported as $\delta^{13}C(CH_4)$) (Figure 2) indicate that the increase in CH_4 since 2007 is associated with biogenic processes, but the relative contributions of anthropogenic and natural sources to this increase are unclear. While all conceivable efforts to reduce CH_4 emissions should be employed, this is not a substitute for reducing CO_2 emissions, whose impact on climate will continue for millennia."); United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 11 June 2023); *and* Allen G. H. (2022) *Cause of the 2020 surge in atmospheric methane clarified*, NATURE 612(7940): 413–414, 413 ("Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today[3] (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year… The concentration of atmospheric methane surged again (see go.nature.com/3xm1dx4) too 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded.").

[31] National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *Global carbon dioxide growth in 2018 reached 4th highest on record* (*last visited* 11 June 2023) ("In the last two decades, the rate of increase has been roughly 100 times faster than previous natural increases, such as those that occurred at the end of the last ice age 11,000-17,000 years ago.").

[32] National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *The NOAA Annual Greenhouse Gas Index (AGGI)* (*last visited* 11 June 2023) ("For example, the atmospheric abundance of CO_2 has increased by an average of 1.88 ppm per year over the past 42 years (1979-2021). This increase in CO_2 is accelerating — while it averaged about 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the growth rate increased to 2.4 ppm per year during the last decade (2011-2021).").

[33] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-10 ("It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006."). *See also* Kotz M., Wenz L., & Levermann A. (2021) *Footprint of greenhouse forcing in daily temperature variability*, PROC. NAT'L. ACAD. SCI. 118(32): 1–8, 1 ("Assessing historical changes to daily temperature variability in comparison with those from state-of-the-art climate models, we show that variability has changed with distinct global patterns over the past 65 years, changes which are attributable to rising concentrations of greenhouse gases. If these rises continue, temperature variability is projected to increase by up to 100% at low latitudes and decrease by 40% at northern high latitudes by the end of the century.").

[34] Philip S. Y., *et al.* (2021) *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada*, WORLD WEATHER ATTRIBUTION, 20 ("Results for current vs past climate, i.e. for 1.2°C of global warming vs pre-industrial conditions (1850-1900), indicate an increase in intensity of about 2.0 ˚C (1.2 ˚C to 2.8 ˚C) and a PR of at least 150. Model results for additional future changes if global warming reaches 2°C indicate another increase in intensity of about 1.3 ˚C (0.8 ˚C to 1.7 ˚C) and a PR of at least 3, with a best estimate of 175. This means that an event like the current one, that is currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.").

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[35] Philip S. Y., *et al.* (2021) *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada*, WORLD WEATHER ATTRIBUTION, 2 ("Also, this heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today."). *See also* Newburger E. (1 July 2021) *Historic heat wave linked to hundreds of deaths in Pacific Northwest and Canada*, CNBC ("Dr. Jennifer Vines, Multnomah County's health officer, said the preliminary cause of death was hyperthermia, an abnormally high body temperature resulting from an inability of the body to deal with heat. Many of the dead were found alone and without air conditioning…. "While it is too early to say with certainty how many of these deaths are heat related, it is believed likely that the significant increase in deaths reported is attributable to the extreme weather B.C. has experienced," Lapointe said in a statement.").

[36] Philip S. Y., *et al.* (2021) *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada*, WORLD WEATHER ATTRIBUTION, 1 ("Looking into the future, in a world with 2°C of global warming (0.8°C warmer than today which at current emission levels would be reached as early as the 2040s), this event would have been another degree hotter. An event like this -- currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.").

[37] First Street Foundation (2022) THE 6TH NATIONAL RISK ASSESSMENT: *HAZARDOUS HEAT*, 4 ("The results indicate that the incidence of extreme heat is growing across the country, both in absolute and relative terms. In absolute terms, the incidence of heat that exceeds the threshold of the National Weather Service's (NWS) highest category for heat, called "Extreme Danger" (Heat Index above 125°F) is expected to impact about 8 million people this year, increasing to about 107 million people in 2053, an increase of 13 times over 30 years. This increase in "Extreme Danger Days" is concentrated in the middle of the country, in areas where there are no coastal influences to mitigate extreme temperatures."); *discussed in* Kaufman L. (15 August 2022) *Much of the US Will Be an 'Extreme Heat Belt' by the 2050s*, BLOOMBERG.

[38] Vautard R., *et al.* (2020) *Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe*, ENVIRON. RES. LETT. 15(9): 094077, 1–9, 5 ("For the France average, the heatwave was an event with a return period estimated to be 134 years. As for the June case, except for HadGEM-3A, which has a hot and dry bias, the changes in intensity are systematically underestimated, as they range from 1.1 °C (CNRM-CM6.1) to 1.6 °C (EC-EARTH). By combining information from models and observations, we conclude that the probability of such an event to occur for France has increased by a factor of at least 10 (see the synthesis in figure 3). This factor is very uncertain and could be two orders of magnitude higher. The change in intensity of an equally probable heatwave is between 1.5 degrees and 3 degrees. We found similar numerical results for Lille, with however an estimate of change in intensity higher in the observations, and models predict trend estimates that are consistently lower than observation trends, a fact that needs further investigation beyond the scope of this attribution study. We conclude for these cases that such an event would have had an extremely small probability to occur (less than about once every 1000 years) without climate change in France. Climate change had therefore a major influence to explain such temperatures, making them about 100 times more likely (at least a factor of ten).").

[39] Copernicus Atmosphere Monitoring Service (4 August 2021) *Copernicus: Mediterranean region evolves into wildfire hotspot, while fire intensity reaches new records in Turkey*, Press Release ("With Southeast Europe currently experiencing heatwave conditions, the fire danger remains high in the area, especially across much of Turkey and around the Mediterranean. CAMS data show that the daily total Fire Radiative Power (FRP) for Turkey has reached unprecedented values in the entire dataset, which goes back to 2003.").

[40] Rousi E., Kornhuber K., Beobide-Arsuaga G., Luo F., & Coumou D. (2022) *Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia*, NAT. COMMUN. 13(3851): 1–11, 1 ("Persistent heat extremes can have severe impacts on ecosystems and societies, including excess mortality, wildfires, and harvest failures. Here we identify Europe as a heatwave hotspot, exhibiting upward trends that are three-to-four times faster compared to the rest of the northern midlatitudes over the past 42 years. This accelerated trend is linked to atmospheric dynamical changes via an increase in the frequency and persistence of double jet stream states over Eurasia. We find that double jet occurrences are particularly important for western European heatwaves, explaining up to 35% of temperature variability. The upward trend in the persistence of double jet events explains almost all of the accelerated heatwave trend in western Europe, and about 30% of it over the extended European region. Those findings provide evidence that in addition to thermodynamical drivers, atmospheric dynamical changes have contributed to the

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increased rate of European heatwaves, with implications for risk management and potential adaptation strategies.”); *discussed in* Fountain H. (18 July 2022) *Why Europe Is Becoming a Heat Wave Hot Spot*, The New York Times.

[41] World Weather Attribution (28 July 2022) *Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely* (“Combining the results based on observational and model analysis, we find that, for both event definitions, human-caused climate change made the event at least 10 times more likely. In the models, the same event would be about 2°C less hot in a 1.2°C cooler world, which is a much smaller change in intensity than observed.”).

[42] Climate Crisis Advisory Group (25 August 2022) *Record-breaking heatwave will be an average summer by 2035, latest Met Office Hadley Centre data shows*, Press Release (“The record-breaking heatwave experienced across Europe this summer will be considered an “average” summer by 2035, even if countries meet their current climate commitments so far agreed in negotiations under the 2015 Paris Agreement. That’s according to the latest data from the Met Office Hadley Centre, commissioned by the Climate Crisis Advisory Group (CCAG). The data (figure 1 below) looks at how rapidly temperatures are changing across Europe and tracks observed mean summer temperatures since 1850 against model predictions. It finds that, according to current predictions[1], an average summer in central Europe by 2100 will be over 4°C hotter than it was in the pre-industrial era.”); *discussed in* Mathers M. (25 August 2022) *UK’s record-breaking heatwave will be average summer by 2035, Met Office says*, Independent.

[43] Harrington L. J., Ebi K. L., Frame D. J., & Otto F. E. L. (2022) *Integrating attribution with adaptation for unprecedented future heatwaves*, Clim. Change 172(2): 1–7, 3 (“Thus, specifically resolving whether a recent heatwave — say, one which occurs once per decade in today’s climate — would have occurred either once in 100 generations or once in 1000 generations in a pre-industrial climate, is no longer useful. When the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison, other tools are needed to instead quantify future changes in exposure or the effectiveness of adaptation to changes in extreme weather seen over recent decades.”); *discussed in* Sengupta S. (3 May 2022) *An extraordinary heat wave exposes the limits of protecting people*, The New York Times (“For more than a month now, across much of the country (and in next door Pakistan), temperatures have soared and stayed there. The capital, Delhi, topped 46 degrees Celsius (114 degrees Fahrenheit) last week. West Bengal, in the muggy east of the country, where my family is from, is among those regions where the combination of heat and humidity could rise to a threshold where the human body is in fact at risk of cooking itself. That theoretical limit is a “wet bulb” temperature — when a thermometer is wrapped in a wet cloth, accounting for both heat and humidity — of 35 degrees Celsius. In neighboring Pakistan, the Meteorological Department warned last week that daily high temperatures were 5 to 8 degrees Celsius above normal, and that in the mountainous north, fast-melting snow and ice could cause glacial lakes to burst. How much of this extreme heat can be blamed on climate change? That’s now becoming an “obsolete question,” Friederike Otto, a leader in the science of attributing extreme weather events to climate change, said in a paper published Monday. The rise in the average global temperature has already intensified heat waves “many times faster than any other type of extreme weather,” the paper concluded. Get used to extremes. Adapt. As much as possible.”); *and* Tunio Z. (7 May 2022) *An unprecedented heat wave in India and Pakistan is putting the lives of more than a billion people at risk*, Inside Climate News.

[44] Balch J. K., Abatzoglou J. T., Joseph M. B., Koontz M. J., Mahood A. L., McGlinchy J., Cattau M. E., & Williams A. P. (2022) *Warming weakens the night-time barrier to global fire*, Nature 602: 442–448, 442 (“Night-time provides a critical window for slowing or extinguishing fires owing to the lower temperature and the lower vapour pressure deficit (VPD). However, fire danger is most often assessed based on daytime conditions[1,2], capturing what promotes fire spread rather than what impedes fire. Although it is well appreciated that changing daytime weather conditions are exacerbating fire, potential changes in night-time conditions—and their associated role as fire reducers—are less understood. Here we show that night-time fire intensity has increased, which is linked to hotter and drier nights. Our findings are based on global satellite observations of daytime and night-time fire detections and corresponding hourly climate data, from which we determine landcover-specific thresholds of VPD (VPD_t), below which fire detections are very rare (less than 95 per cent modelled chance). Globally, daily minimum VPD increased by 25 per cent from 1979 to 2020. Across burnable lands, the annual number of flammable night-time hours—when VPD exceeds VPD_t—increased by 110 hours, allowing five additional nights when flammability never ceases. Across nearly one-fifth of burnable lands, flammable nights increased by at least one week across this period. Globally, night fires have become 7.2 per cent more intense from 2003 to 2020, measured via a satellite record. These results reinforce the lack of night-time relief that wildfire suppression teams have experienced in recent years. We expect that continued night-time warming owing to anthropogenic climate change will promote more intense, longer-lasting and larger fires.”);

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discussed in Dickie G. (19 July 2022) *Steamy nights in European heatwave worsen health and fire risks – experts*, Reuters.

[45] Clarke B., Otto F., & Harrington L. (5 September 2022) *Pakistan floods: What role did climate change play?*, The Conversation ("Clues as to the role of climate change can also come from aspects that contributed to this disaster. There are three main factors. ¶ First, extreme rainfall. A warmer atmosphere holds more moisture. For every degree the atmosphere warms it can hold about 6%-7% more moisture, which often results in more rain falling during the most extreme events (south Asia has warmed around 0.7°C since 1900). Had this event happened in a world where carbon dioxide concentrations were instead at pre-industrial levels, the rains probably would have been less intense. ¶ Second, the monsoon itself, which is highly complex and variable. It forms in south Asia in the summer, when air over land warms faster than air over the sea, which creates a flow of air onto the land. The winds bring great volumes of moisture that precipitate into deluges when they meet higher ground, especially the Himalayas. ¶ Unusual monsoon rains over Pakistan have some predictability. They occur when multiple phenomena coincide, including a La Niña event in the Pacific and large meanders in the high-altitude jet stream, as was the case in both 2010 and this year. ¶ There is emerging evidence that this confluence of factors may occur more regularly as the climate changes. If such trends continue, then flooding in Pakistan and other simultaneous extremes across the northern Hemisphere will happen more often in the future. ¶ Pakistan also experienced extended and brutal heatwaves in May and June this year, which were amplified by climate change. This heat amplified the monsoonal "thermal low"—a low-pressure system created by hot air rising rapidly—which greatly enhanced the flow of moisture-laden air onto southern Pakistan. ¶ Third, Pakistan has more than 7,000 glaciers in its northern mountainous regions. As these glaciers melt, their waters contribute to the flooding. This melting is driven to a large degree by climate change and is especially prominent this year as a result of the heatwave."). *See also* Otto F. E. L., Zachariah M., Saeed F., Siddiqi A., & Shahzad K. (2022) *Climate change likely increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan*, World Weather Attribution, 3 ("However, for the 5-day rainfall extreme, the majority of models and observations we have analysed show that intense rainfall has become heavier as Pakistan has warmed. Some of these models suggest climate change could have increased the rainfall intensity up to 50% for the 5-day event definition."); *and* Trenberth K. (15 September 2022) *2022's supercharged summer of climate extremes: How global warming and La Niña fueled disasters on top of disasters*, The Conversation.

[46] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, Nat. Clim. Change 11: 689–685, 689 ("Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades. In 2051–2080, such events are estimated to occur about every 6–37 years somewhere in the northern midlatitudes.").

[47] National Oceanic and Atmospheric Administration National Centers for Environmental Information (2021) *State of the Climate: Global Climate Report for May 2021* ("The seven warmest years since 1880 have all occurred since 2014, while the 10 warmest years have occurred since 2005... The decadal global land and ocean surface average temperature anomaly for 2011–2020 was the warmest decade on record for the globe, with a surface global temperature of +0.82°C (+1.48°F) above the 20th century average. This surpassed the previous decadal record (2001–2010) value of +0.62°C (+1.12°F)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-5 ("Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-19009. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1ºC to the updated estimate of warming in AR6[10]."… Footnote 10: "Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have additionally increased the estimate of global surface temperature change by approximately 0.1 ºC, but this increase does not represent additional physical warming since the AR5.").

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[48] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Nature 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report."). *See also* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, Izv. Atmos. Ocean. Phys. (*preprint*): 1–62, 39 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate of at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 25)."; Figure 25 caption reads "Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade.").

[49] National Snow & Ice Data Center (15 September 2022) *Arctic Weather and Climate* ("Changes in the Arctic climate are important because the Arctic acts as a refrigerator for the rest of the world—it helps cool the planet. So changes in the Arctic climate could affect the climate in the rest of the world. Changes in the Arctic have effects that cascade through the food chain… Researchers say that the changes in the Arctic are worrisome, because they could lead to feedback effects that lead to further warming. For instance, when the white sea ice melts in summer, areas of dark open water are exposed which can absorb more heat from the sun. That extra heat then helps melt even more ice. The loss of sea ice is known to be one of the drivers of Arctic amplification. Permafrost may also be involved in feedbacks. As permafrost thaws, plants and animals that were frozen in the ground begin to decay. When they decay, they release carbon dioxide and methane back to the atmosphere that can contribute to further warming. The changing vegetation of the Arctic also affects the brightness of the surface, which then influences warming. As the Arctic atmosphere warms, it can hold more water vapor, which is an important greenhouse gas."). *See also* Jansen E., et al. (2020) *Past perspectives on the present era of abrupt Arctic climate change*, Nat. Clim. Change 10: 714–721, 714 ("Annual mean temperature trends over the Arctic during the past 40 years show that over this period, where satellite data are available, major portions have warmed by more than 1 °C per decade (Fig. 1a, red colours and outlined portion; a warming of 4 °C within 40 years is hereafter referred to as 1 °C per decade). … Using a criterion based on the speed of near-surface air temperature warming over the past four decades, we find that the current Arctic is experiencing rates of warming comparable to abrupt changes, or D–O events, recorded in Greenland ice cores during the last glacial period. [During the last glacial period (120,000–11,000 years ago), more than 20 abrupt periods of warming, known as Dansgaard–Oeschger (D–O) events, took place[18,19].] Both past changes in the Greenland ice cores and the ongoing trends in the Arctic are directly linked to sea-ice retreat—in the Nordic Seas during glacial times and in the Eurasian Arctic at present. Abrupt changes have already been experienced and could, according to state-of-the-art climate models, occur in the Arctic during the twenty-first century, but climate models underestimate current rates of change in this region.").

[50] *See* Drollette Jr. D. (30 August 2019) *What if the Arctic melts, and we lose the great white shield? Interview with environmental policy expert Durwood Zaelke*, Bulletin of the Atomic Scientists (article accessible here); Zaelke D. J. & Bledsoe P. (14 December 2019) *Our Future Depends on the Arctic*, The New York Times; *and* Molina M. & Zaelke D. (16 October 2020) *The Time Bomb at the Top of the World*, Project Syndicate.

[51] Pistone K., Eisenman I., & Ramanathan V. (2014) *Observational determination of albedo decrease caused by vanishing Arctic sea ice*, Proc. Nat'l. Acad. Sci. 111(9): 3322–3326, 3322 ("As per the Budyko–Sellers hypothesis, an initial warming of the Arctic due to factors such as CO$_2$ forcing will lead to decreased ice cover which exposes more of the underlying darker ocean and amplifies the warming. In 1975, this phenomenon was simulated in a 3D climate model by Manabe and Wetherald (9), who showed that under conditions of a doubling of CO$_2$, tropospheric warming in the polar regions was much larger than in the tropics, due in part to the albedo decrease from shrinking snow/ice area.").

[52] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, Commun. Earth Environ. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent

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research[44], and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea[44,45]. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area[46,47]. In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."); *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, The Hill; *and* Fountain H. (11 August 2022) *Arctic Warming Is Happening Faster Than Described, Analysis Shows*, The New York Times. *See also* Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 ("We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean."); *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, Science.

[53] Arctic Monitoring and Assessment Programme (2021) Arctic Climate Change Update 2021: Key Trends and Impacts, Summary for Policymakers, 6 ("The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s."). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S280 ("September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).").

[54] Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth Environ. 2(144): 1–8, 4, 6 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)"; "This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."). *See also* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8(15): 1–24, 17 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); *and* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.").

[55] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7477 ("This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO_2 into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO_2 have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO_2 per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic

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sea ice would be equivalent to 25 years of global CO_2 emissions at the current rate."). *See also* Institute for Governance & Sustainable Development (2019) *Plain Language Summary of Pistone K., et al*.

[56] Wadhams P. (2017) A Farewell to Ice: A Report from the Arctic, Oxford University Press, 107–108 ("Warm air over an ice-free Arctic also causes the snowline to retreat. … This of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water. Nobody has yet published the calculations for tundra as Pistone and her colleagues did for sea ice, but the similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming.").

[57] Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) *Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline*, Geophys. Res. Lett. 47(3): 1–10, 1, 8 ("The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic "Atlantification." … In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).").

[58] MacKinnon J. A., *et al*. (2021) *A warm jet in a cold ocean*, Nat. Commun. 12(2418): 1–12, 1 ("Unprecedented quantities of heat are entering the Pacific sector of the Arctic Ocean through Bering Strait, particularly during summer months. Though some heat is lost to the atmosphere during autumn cooling, a significant fraction of the incoming warm, salty water subducts (dives beneath) below a cooler fresher layer of near-surface water, subsequently extending hundreds of kilometers into the Beaufort Gyre. Upward turbulent mixing of these sub-surface pockets of heat is likely accelerating sea ice melt in the region. This Pacific-origin water brings both heat and unique biogeochemical properties, contributing to a changing Arctic ecosystem.").

[59] Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, Geophys. Res. Lett. 40(4): 720–726, 722 ("The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12×10^3 km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21×10^3 km^3 d^{-1} (or 0.17×10^3 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b)."). *See also* Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. Geophys. Res. Atmos. 126(12): 1–35, 20–21 ("We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season."); Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, Front. Earth Sci. 9(738497): 1–17, 15 ("The advective tendency of SIC due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011)."); *and* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea Ice Loss from Late Summer Cyclones in the New Arctic*, J. Clim. 35(23): 4151–4169, 4151 ("We compare the 1–7-day changes in sea ice area and thickness following days in each month with and without cyclones from two decades: 1991–2000 and 2009–18. Only in August do cyclones locally accelerate seasonal sea ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E–120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2°–0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea ice divergence that locally increase the

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likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea ice loss. Moreover, the 7-day sea ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0°–140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, Science.

[60] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, Commun. Earth Environ. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research[44], and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea[44,45]. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area[46,47]. In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."); *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, The Hill; *and* Fountain H. (11 August 2022) *Arctic Warming Is Happening Faster Than Described, Analysis Shows*, The New York Times. *See also* Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 ("We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean."); *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, Science; *and* Chylek P., Folland C., Klett J. D., Wang M., Hengartner N., Lesins G., & Dubey M. K. (2022) *Annual Mean Arctic Amplification 1970–2020: Observed and Simulated by CMIP6 Climate Models*, Geophys. Res. Lett. 49(13): 1–8, 1 ("While the annual mean Arctic Amplification (AA) index varied between two and three during the 1970–2000 period, it reached values exceeding four during the first two decades of the 21st century. The AA did not change in a continuous fashion but rather in two sharp increases around 1986 and 1999. During those steps the mean global surface air temperature trend remained almost constant, while the Arctic trend increased. Although the "best" CMIP6 models reproduce the increasing trend of the AA in 1980s they do not capture the sharply increasing trend of the AA after 1999 including its rapid step-like increase. We propose that the first sharp AA increase around 1986 is due to external forcing, while the second step close to 1999 is due to internal climate variability, which models cannot reproduce in the observed time…. Annual mean Arctic Amplification (AA) within the period 1970–2020 changed in steep steps around 1986 and 1999. It reached values over 4.0…"); *discussed in* Los Alamos National Laboratory (5 July 2022) *Arctic temperatures are increasing four times faster than global warming*, Phys.org.

[61] Cai Z., You Q., Wu F., Chen H., Chen D., & Cohen J. (2021) *Arctic Warming Revealed by Multiple CMIP6 Models: Evaluation of Historical Simulations and Quantification of Future Projection Uncertainties*, J. Clim. 34(12): 4871–4892, 4878 ("The Arctic's warming rate from 1986 to 2100 is much higher than that of the Northern Hemisphere and the global mean under the three different scenarios (You et al. 2021). Figure 8 shows the spatial patterns of annual mean near-surface temperature change in the Arctic according to the MMEM for the three periods relative to 1986–2005 under the three scenarios. Projections for the regionally averaged mean near-surface temperature increases in the Arctic under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios are +2.5°, +2.6°, and +2.8°C respectively in the near term (2021–40), +3.3°, +4.0°, and +5.1°C in the midterm (2014–60), and +3.5°, +5.8°, and +10.4°C in the long-term (2081–2100) relative to the reference period based on the CMIP6 MMEM.").

[62] Ciavarella A., *et al*. (2021) *Prolonged Siberian heat of 2020 almost impossible without human influence*, Clim. Change 166(9): 1–18, 1 ("Over the first half of 2020, Siberia experienced the warmest period from January to June since records began and on the 20th of June the weather station at Verkhoyansk reported 38 °C, the highest daily maximum temperature recorded north of the Arctic Circle… We show that human-induced climate change has dramatically increased the probability of occurrence and magnitude of extremes in both of these (with lower confidence for the probability for Verkhoyansk) and that without human influence the temperatures widely experienced in Siberia in the first half of 2020 would have been practically impossible."). *See also* DeGeorge K. (2

June 2021) *Siberia is seeing record heat — again*, ArcticToday ("On Monday, satellites with the European Union's Copernicus Earth observation program detected exceptionally high ground temperatures across much of the region, with a high reaching an astounding 48 degrees Celsius (118 degrees Fahrenheit) near Verkhoyansk, in the Sakha Republic, while other sites recorded highs of 43 degrees C (109.4 degrees F) and 37 degrees C (98.6 degrees F). It's important to note that those are ground temperatures, not air temperatures. For example, that latter figure was recorded in Saskylakh, also in the Sakha Republic, where air temperatures taken at the same time were a slightly cooler 31.9 degrees C (89.4 degrees F). That still set a record for Saskylakh, though, as the hottest pre-solstice temperature recorded there since measurements began in 1936. The news comes a month after the Arctic Council's Arctic Monitoring and Assessment working group issued a report confirming that the region is now warming three times faster than the global average, rather than twice as fast. And it comes almost exactly a year after the first 100-degree (Fahrenheit) temperature was recorded north of the Arctic Circle — also in Verkhoyansk.").

[63] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area*, Commun. Earth Environ. 2(122): 1–11, 2, 5–6 ("The Polarstern's route was guided by satellite images showing extensive areas of open water and sea ice concentration (SIC) as low as 70% at 87N (Figs. 1a, S1b). We define our WS study area by 81.5°N–85°N, 10°W–50°W, the same area where we saw signs of change in February 201810. Daily 2020 WS SIC drops below the 5th percentile of the 1979–2020 time series on July 25 and stays there almost until the end of August (Fig. 1b). August 14, 2020 constitutes a record low 52% SIC minimum (Fig. 1c). Several earlier years (e.g., 1985: 57%, 1990: 67%, and 1991: 62%) also show significant low SIC minima, although none as low as 2020."); 1 ("During spring 2020, ice accumulated in the WS (Fig. 4a, b) in response to anomalous advection (mostly in February; Fig. 4c, d). As a result, ice thickness was near its 1979–2020 mean value by June 1 according to PIOMAS; Fig. 2c), and actually thicker than in recent years (2011–2019) as confirmed by the combined CryoSat-2/SMOS satellite product… While primarily driven by unusual weather, climate change in the form of thinning sea ice contributed significantly to the record low August 2020 SIC in the WS. Several advection events, some relatively early in the melt season, transported sea ice out of the region and allowed the accumulation of heat from the absorption of solar radiation in the ocean. This heat was mixed upward and contributed to rapid melt during high wind events, notably between August 9 and 16. Ocean-forced melting in this area that is traditionally covered by thick, compact ice is a key finding of this study."; "These ensemble experiments underline the importance of both spring sea ice and summer atmospheric forcing to August SIC. In summary, we find that: Spring ice conditions were mostly responsible for the summer SIC anomaly through the end of July, while the atmosphere was mainly responsible for driving SIC to a record low during August. Partitioning the impact of 2020 spring initial sea ice conditions vs. summer atmospheric forcing on the sea ice anomaly at the time of the WS sea ice minimum on August 14 (see "Methods") attributes ~20% to the initial conditions while ~80% is the due to the atmospheric forcing.").

[64] Labe Z., Magnusdottir G., & Stern H. (2018) *Variability of Arctic Sea Ice Thickness Using PIOMAS and the CESM Large Ensemble,* J. Clim. 31(8): 3233–3247, 3243 (Figure 10. "While twenty-first-century sea ice thins substantially in all seasons, a large sea ice cover continues to reform during the cold season. A region of perennially thick ice north of Greenland also remains…. An area of perennially thick sea ice remains north of Greenland during all months of the year, but it significantly thins (especially in September) by the mid-twenty-first century. Average September SIT in all regions eventually falls below 0.5 m during the 21st century.").

[65] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area*, Commun. Earth Environ. 2(122): 1–11, 2 ("The LIA is considered to be a last refuge for ice-associated Arctic marine mammals, such as polar bears (Ursus maritimus), ice-dependent seals such as ringed seals (Pusa hispida) and bearded seals (Erignathus barbatus), and walrus (Odobendus rosmarus) throughout the 21st century.").

[66] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, Sci. Rep. 12(9371): 1–18, 11 ("The accelerated warming up to the latest decade is in agreement with the most recent assessments of instrumental observations in the Arctic[7,8]. Przybylak and Wyszyński[8] analyzed trends from 1951 to 2015 and showed that the strongest temperature increase in the Arctic in winter was observed over Svalbard, but no stations in north-eastern areas were then available. By including newly available SAT observations from northern and eastern Svalbard and from FJL, we were able to additionally study the regional SAT developments in the NBS. Our main findings are summarised in Fig. 7 and show that the warming in western Svalbard is large, but even larger in northern and eastern Svalbard and in FJL. From 1981 to 2020, we found an annual warming rate varying between 1.0 and 1.6 °C per decade, whereas, over the two periods

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1991–2020 and 2001–2020, the annual warming rates ranged from 1.1 to 2.7 °C per decade. These rates are stronger than hitherto known in this region. The increasing temperature rates for the Northern Barents Sea region are exceptional on the Arctic and global scale and correspond to 2 to 2.5 times the Arctic warming averages and 5 to 7 times the global warming averages (Fig. 7).”); *discussed in* Carrington D. (15 June 2022) *New data reveals extraordinary global heating in the Arctic*, The Guardian.

[67] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, Sci. Rep. 12(9371): 1–18, 3 (“Record-high warming was observed over the two periods 1991–2020 and 2001–2020, with annual values ranging from ~ 1.1 °C per decade in Ny-Ålesund to 2.7 °C per decade at Karl XII-øya (Table 1 and Fig. 3c). The annual warming was dominated by higher autumn and winter warming but enhanced warming occurred in all seasons (Table 1). In autumn (SON) we noticed an accelerated warming for 1991–2020 and 2001–2020, with up to 4.0 °C per decade for the latter period at Karl XII-øya.”); *discussed in* Carrington D. (15 June 2022) *New data reveals extraordinary global heating in the Arctic*, The Guardian.

[68] Arctic Monitoring and Assessment Programme (2021) Arctic Climate Change Update 2021: *Key Trends and Impacts, Summary for Policy-Makers*, 6 (“The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s.”). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S280 (“September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).”).

[69] Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth Environ. 2(144): 1–8, 4, 6 (“In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)”; “This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035.”). *See also* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8(15): 1–24, 17 (“Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations.”); *and* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.”).

[70] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7474 (“Here we use satellite observations to estimate the amount of solar energy that would be added in the worst-case scenario of a complete disappearance of Arctic sea ice throughout the sunlit part of the year. Assuming constant cloudiness, we calculate a global radiative heating of 0.71 W/m^2 relative to the 1979 baseline state. This is equivalent to the effect of one trillion tons of CO_2 emissions. These results suggest that the additional heating due to complete Arctic sea ice loss would hasten global warming by an estimated 25 years.”).

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[71] National Aeronautics and Space Administration, *Arctic Sea Ice Minimum Extent* (*last visited* 14 February 2023) ("Arctic sea ice reaches its minimum extent (the area in which satellite sensors show individual pixels to be at least 15% covered in ice) each September. September Arctic sea ice is now shrinking at a rate of 12.6% per decade, compared to its average extent during the period from 1981 to 2010.").

[72] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, REMOTE SENS. 14(8): 1846, 1–22, 19–20 ("Arctic AICA SIE was reduced 22% over the last four decades, mainly caused by PICA SIE reduction that declined at an annual rate of −1.105 × 105 km2 per year. The annual increase in SICA SIE, at a rate of 2.640 × 104 km2 per year, does not offset the decline in the PICA SIE, resulting in a net loss of AICA SIE at a rate of −7.871 × 104 km2 per year. The AICA SIE in September had a minimum extent of 4.32892 × 106 km2 in 2020 compared to the much larger SIE of 7.63860 × 106 km2 in 1982, resulting in a 43% decline over the past four decades.").

[73] U.S. Census Bureau, *State Area Measurements and Internal Point Coordinates* (*last visited* 19 July 2022).

[74] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, REMOTE SENS. 14(8): 1846, 1–22, 18 ("Over 1982–2020, AICA SIV decreased to 20,679.0 km3 in 2020 from 51,216.6 km3 in 1982, resulting in a 60% decrease at a rate of −859.2 km3 per year in March. In September, AICA SIV declined to 2462.0 km3 in 2020 from 8931.2 km3 in 1982, resulting in a 72% decrease at a rate of −170.2 km3 per year. Based on an annual average, AICA SIV decreased by 17,284.8 km3, which is 63% of the 27,590.4 km3 in 1982, resulting in 10,305.5 km3 SIV in 2020. PICA SIV and SICA SIV declined to 5766.0 km3 and 4522.8 km3 in 2020 from 20,313.0 km3 and 7271.0 km3 in 1982, respectively. In addition, the ratios of PICA SIV and SICA SIV to AICA SIV were declining in March, when Arctic sea ice reaches its maximum volume over 1982–2020 (Figure 14). It is around 2019 when the SICA SIV proportion started surpassing the PICA SIV proportion in March.").

[75] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, REMOTE SENS. 14(8): 1846, 1–22, 18 ("Over 1982–2020, AICA SIV decreased to 20,679.0 km3 in 2020 from 51,216.6 km3 in 1982, resulting in a 60% decrease at a rate of −859.2 km3 per year in March. In September, AICA SIV declined to 2462.0 km3 in 2020 from 8931.2 km3 in 1982, resulting in a 72% decrease at a rate of −170.2 km3 per year. Based on an annual average, AICA SIV decreased by 17,284.8 km3, which is 63% of the 27,590.4 km3 in 1982, resulting in 10,305.5 km3 SIV in 2020. PICA SIV and SICA SIV declined to 5766.0 km3 and 4522.8 km3 in 2020 from 20,313.0 km3 and 7271.0 km3 in 1982, respectively. In addition, the ratios of PICA SIV and SICA SIV to AICA SIV were declining in March, when Arctic sea ice reaches its maximum volume over 1982–2020 (Figure 14). It is around 2019 when the SICA SIV proportion started surpassing the PICA SIV proportion in March.").

[76] National Snow and Ice Data Center (21 September 2020) *Arctic sea ice decline stalls out at second lowest minimum* ("On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. …*Please note that this is a preliminary announcement. Changing winds or late-season melt could still reduce the Arctic ice extent, as happened in 2005 and 2010. NSIDC scientists will release a full analysis of the Arctic melt season, and discuss the Antarctic winter sea ice growth, in early October*. … The 14 lowest extents in the satellite era have all occurred in the last 14 years."). *See also* Richter-Menge J., Druckenmiller M. L. & Thoman R. L. (2020) *15 Years of Arctic Observation: A Retrospective*, *in* ARCTIC REPORT CARD 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 8 ("As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists and grabbed world-wide media attention with a new record minimum that was 23% below the previous record low set in 2005. Just five years later, in 2012, the 2007 record was overtaken by a September minimum sea ice extent that was 18% below 2007. The 2012 record low still stands as of 2020. However, in the 14 years since ARC2006 the late summer sea ice minimum extent has never returned to pre-2007 values.").

[77] National Snow and Ice Data Center (20 September 2022) *The sun sets on the melt season* ("As of September 19, 2022, Arctic sea ice extent stood at 4.68 million square kilometers (1.81 million square miles), placing it ninth lowest

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in the satellite record for the date. Between September 1 and September 19, the Arctic lost a total of 522,000 square kilometers (202,000 square miles) of ice, at an average rate of 27,500 square kilometers (10,600 square miles) per day. This was slightly faster than the average daily loss rate over this period. As of September 19, sea ice extent was tracking close to the levels observed in 2010, and the spatial pattern of sea ice extent is similar."). *See also* National Snow and Ice Data Center (22 September 2021) *Arctic Sea Ice at Highest Minimum Since 2014* ("On September 16, Arctic sea ice likely reached its annual minimum extent of 4.72 million square kilometers (1.82 million square miles). The 2021 minimum is the twelfth lowest in the nearly 43-year satellite record. The last 15 years are the lowest 15 sea ice extents in the satellite record. The amount of multi-year ice (ice that has survived at least one summer melt season), is one of the lowest levels in the ice age record, which began in 1984.").

[78] Perovich D., *et al.* (2020) *Sea Ice*, *in* Arctic Report Card 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 29–30, 48 ("The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km^2 in March 1985 to 0.09 million km^2 in March 2019. … First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s. Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents."; "The oldest ice (> 4 years old) was once a major component of the Arctic sea ice cover, but now makes up just a small fraction of the March Arctic Ocean ice pack (Fig. 3). In 1985, 33% of the ice pack was very old ice (> 4 years), but by March 2020 old ice only constituted 4.4% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.70 million km^2 in March 1985 to 0.34 million km^2 in March 2020. The March 2020 extent of > 4 year old ice increased from the record-low year in 2019 when it was only 1.2% (0.09 million km^2) of the ice cover. This increase was due to 3–4 year old ice surviving a year and aging into > 4 year old ice. The 3–4 year old cover dropped from 6.4% in 2019 to 3.7% in 2020. Overall the percentage of ice 3 years and older was effectively unchanged. Note that these percentages are relative to ice in the Arctic Ocean region (Fig. 3, bottom inset); areas in the peripheral seas outside of this region have little or no older ice and thus do not show any change over time."). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S282 ("The dominant ice type is now first-year ice (0–1 years old), which comprised about 70% of the March 2020 Arctic Ocean ice cover. The median ice age dropped from 2–3 years old in the mid-1980s to less than 1 year old by 2020. The total extent of the oldest ice (>4 years old) declined from 2.50 million km^2 in March 1985 to 0.34 million km^2 in March 2020."); World Meteorological Organization (2020) United in Science 2020, 9 ("Arctic (as well as sub-Arctic) sea ice has seen a long-term decline in all months during the satellite era (1979–present), with the largest relative losses in late summer, around the time of the annual minimum in September, with regional variations. The long-term trend over the 1979–2019 period indicates that Arctic summer sea-ice extent has declined at a rate of approximately 13% per decade (Figure 4). In every year from 2016 to 2020, the Arctic average summer minimum and average winter maximum sea-ice extent were below the 1981–2010 long term average. In July 2020, the Arctic sea-ice extent was the lowest on record for July. There is *very high confidence* that Arctic sea-ice extent continues to decline in all months of the year and that since 1979, the areal proportion of thick ice, at least 5 years old, has declined by approximately 90%."); National Snow & Ice Data Center (2 September 2020) *Tapping the brakes*, Arctic Sea Ice News & Analysis ("As of September 1, Arctic sea ice extent stood at 4.26 million square kilometers (1.64 million square miles), the second lowest extent for that date in the satellite passive microwave record that started in 1979."); *and* Bi H., Liang Y., Wang Y., Liang X., Zhang Z., Du T., Yu Q., Huang J., Kong M., & Huang H. (2020) *Arctic multiyear sea ice variability observed from satellites: a review*, J. Ocean. Limnol. 38(4): 962–984, 963 ("As the MY [multiyear] ice in the Arctic Ocean is declining at a significant rate, approximately -9%– -15%/decade in the past three decades (Comiso, 2012; Polyakov et al., 2012; Kwok, 2018), the MY ice area has declined from about two-thirds of the Arctic basin area to less than one third (Galley et al., 2016). Along with the significant decrease in the MY coverage and extent, there is also a clear transitioning trend in MY composition toward the thinner and younger components (Rigor and Wallace, 2004; Maslanik et al., 2007, 2011; Tschudi et al., 2016)."). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 ºN) was the lowest extent on record: *see* Zack Labe (@ZLabe), Twitter, 11 September 2020, 6:19pm ("Sea ice extent in the middle of the #Arctic Ocean is currently the lowest on record (e.g., high Arctic ~80°N+ latitude). This is a pretty impressive statistic.").

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[79] Osborne E., Richter-Menge J., & Jeffries M. (eds.) (2018) *Executive Summary*, *in* Arctic Report Card 2018, National Oceanic and Atmospheric Administration, 2 ("The disappearance of the older and thicker classes of sea ice are leaving an ice pack that is more vulnerable to melting in the summer, and liable to move unpredictably. When scientists began measuring Arctic ice thickness in 1985, 16% of the ice pack was very old (i.e., multiyear) ice. In 2018, old ice constituted less than 1% of the ice pack, meaning that very old Arctic ice has declined by 95% in the last 33 years."). *See also* Bi H., Liang Y., Wang Y., Liang X., Zhang Z., Du T., Yu Q., Huang J., Kong M., & Huang H. (2020) *Arctic multiyear sea ice variability observed from satellites: a review*, J. OCEAN. LIMNOL. 38(4): 962–984, 963 ("As the MY [multiyear] ice in the Arctic Ocean is declining at a significant rate, approximately -9%– -15%/decade in the past three decades (Comiso, 2012; Polyakov et al., 2012; Kwok, 2018), the MY ice area has declined from about two-thirds of the Arctic basin area to less than one third (Galley et al., 2016). Along with the significant decrease in the MY coverage and extent, there is also a clear transitioning trend in MY composition toward the thinner and younger components (Rigor and Wallace, 2004; Maslanik et al., 2007, 2011; Tschudi et al., 2016).").

[80] Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press, 107–108 ("Warm air over an ice-free Arctic also causes the snowline to retreat. … This of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water. Nobody has yet published the calculations for tundra as Pistone and her colleagues did for sea ice, but the similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming.").

[81] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 11 ("Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971– 2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%. The rate of ice sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006-2018. (*high confidence*).").

[82] Slater T., Lawrence I., Otosaka I. Shepherd A., Gourmelen N., Jacob L., Tepes P., Gilbert L., & Nienow P. (2021) *Earth's ice imbalance*, THE CRYOSPHERE 15: 233–246, 233 ("The rate of [global] ice loss has risen by 57 % since the 1990s – from 0.8 to 1.2 trillion tonnes per year – owing to increased losses from mountain glaciers, Antarctica, Greenland and from Antarctic ice shelves…. Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance [3.2 ± 0.3 %], it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017…. [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.").

[83] European Space Agency (25 January 2021) *Our world is losing ice at record rate* ("A paper, published today in The Cryosphere, describes how a team of researchers led by the University of Leeds in the UK used information from ESA's ERS, Envisat and CryoSat satellites as well as the Copernicus Sentinel-1 and Sentinel-2 missions to find that the rate at which Earth has lost ice has increased markedly within the past three decades, from 0.8 trillion tonnes per year in the 1990s to 1.3 trillion tonnes per year by 2017. To put this into perspective, one trillion tonnes of ice can be thought of as a cube of ice measuring 10x10x10 km, which would be taller than Mount Everest.").

[84] Slater T., Lawrence I., Otosaka I. Shepherd A., Gourmelen N., Jacob L., Tepes P., Gilbert L., & Nienow P. (2021) *Earth's ice imbalance*, THE CRYOSPHERE 15: 233–246, 233 ("The rate of [global] ice loss has risen by 57 % since the 1990s – from 0.8 to 1.2 trillion tonnes per year – owing to increased losses from mountain glaciers, Antarctica, Greenland and from Antarctic ice shelves…. Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance [3.2 ± 0.3 %], it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017…. [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.").

[85] Mallett R. D. C., Stroeve J. C., Tsamados M., Landy J. C., Willatt R., Nandan V., & Liston G. E. (2021) *Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover*, THE CRYOSPHERE 15(5): 2429–2450, 2429, 2441 ("When the sea ice thickness in the period 2002–2018 is calculated using new snow data with more realistic variability and trends, we find mean sea ice thickness in four of the seven marginal seas to be declining between 60 %–100 % faster than when calculated with the conventional climatology."; "We first assess regions where SIT was already in statistically significant decline when calculated with

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mW99. This is the case for all months in the Laptev and Kara seas and 4 of 7 months in the Chukchi and Barents sea. The rate of decline in these regions grew significantly when calculated with SnowModel-LG data (Fig. 10; green panels). Relative to the decline rate calculated with mW99, this represents average increases of 62% in the Laptev sea, 81% in the Kara Sea and 102% in the Barents Sea. The largest increase in an already statistically significant decline was in the Chukchi Sea in April, where the decline rate increased by a factor of 2.1. When analysed as an aggregated area and with mW99, the total marginal seas area exhibits a statistically significant negative trend in November, December, January and April. The East Siberian Sea is the only region to have a month of decline when calculated with mW99 but not with SnowModel-LG.”).

[86] Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) *Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline*, GEOPHYS. RES. LETT. 47(3): 1–10, 1 (“The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic “Atlantification.” … In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).”).

[87] MacKinnon J. A., *et al.* (2021) *A warm jet in a cold ocean*, NAT. COMMUN. 12(2418): 1–12, 1 (“Unprecedented quantities of heat are entering the Pacific sector of the Arctic Ocean through Bering Strait, particularly during summer months. Though some heat is lost to the atmosphere during autumn cooling, a significant fraction of the incoming warm, salty water subducts (dives beneath) below a cooler fresher layer of near-surface water, subsequently extending hundreds of kilometers into the Beaufort Gyre. Upward turbulent mixing of these sub-surface pockets of heat is likely accelerating sea ice melt in the region. This Pacific-origin water brings both heat and unique biogeochemical properties, contributing to a changing Arctic ecosystem.”).

[88] Barton B. I., Lenn Y.-D., & Lique C. (2018) *Observed Atlantification of the Barents Sea Causes the Polar Front to Limit the Expansion of Winter Sea Ice*, J. PHYS. OCEANOGR. 48(8): 1849–1866, 1866 (“Our results provide new evidence that, in addition to the natural multidecadal variability, the Barents Sea is currently undergoing Atlantification, with the corresponding temperature and salinity increases catalyzed by the observed PF constraint on the sea ice edge. The loss of winter sea ice south of the front represents a loss of freshwater input to BSW, a water mass that makes up 50%–80% of AIW. As the stationary PF, rather than the mobile sea ice edge, has become the limiting factor controlling the northern boundary of the surface area available for AW cooling in winter, the buffering effect to BSW temperature from the variations of sea ice conditions has decreased. Observations show a change in BSW properties over the same time period resulting in denser BSW, which could in turn result in a deeper settling depth of BSW once exported to the Arctic basin through St. Anna Trough (Dmitrenko et al. 2015), with potential far-reaching impacts for the dense water outflow through Fram Strait (Lique et al. 2010; Moat et al. 2014) or the density of the Denmark Strait overflow (Karcher et al. 2011), both of which are important for the deeper branch of the AMOC.”).

[89] Shu Q., Wang Q., Song Z., & Qiao F. (2021) *The poleward enhanced Arctic Ocean cooling machine in a warming climate*, NAT. COMMUN. 12(2966): 1–9, 6 (“Most of the CMIP6 models consistently show a poleward advance of the Arctic Ocean cooling machine and Arctic Atlantification (Supplementary Figs. 7–14). The significant model spreads in the simulated linear trends of sea ice concentration, sea surface heat flux, MLD, and sea surface stress (Supplementary Fig. 15) imply possible uncertainties in the predicted timing and strength of the changes in the cooling machine and Arctic Atlantification represented by the MMM. In particular, the underestimated trends in sea ice decline, ocean surface heat flux, and MLD in the CMIP6 MMM compared to observations and reanalysis as shown in Fig. 2 imply that the future development of the poleward expansion of the cooling machine and the strengthening of Arctic Atlantification are very possibly underestimated in the CMIP6 models on average.”).

[90] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, SCI. REP. 12(9371): 1–18, 1 (“Both the SAT analysis from instrumental records[8] and widely used reanalyses products, including ERA5, point to a maximum warming area in the Barents region (Fig. 1). This Arctic warming hotspot[10] is not constrained to the warming

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atmosphere; the Northern Barents Sea (NBS) region also hosts the most pronounced loss of Arctic winter sea ice[11] and has since the early 2000s experienced a sharp increase in both temperature and salinity in the entire water column. The decline in the Barents sea ice cover, increased ocean temperature and salinity are closely related to the higher temperatures in the Atlantic Water and increased ocean heat transport entering the region from the west[12,13,14]. In addition, the increase in salinity is larger towards the upper layers, leading to a weakened ocean stratification and hereby an increased upward heat flux[10]. These oceanographic processes strongly contribute to the amplified warming in the region and enable larger heat flux interaction between the ocean and the air. If the rise in ocean temperature and salinity continues, the originally cold and stratified Arctic shelf region may be transformed into an Atlantic-dominated climate regime with a warmer and more well-mixed water column strongly preventing sea ice formation[10].").

[91] Thomson J. & Rogers W. E. (2014) *Swell and sea in the emerging Arctic Ocean*, Geophys. Res. Lett. 41(9): 3136–3140, 3136 ("Ocean surface waves (sea and swell) are generated by winds blowing over a distance (fetch) for a duration of time. In the Arctic Ocean, fetch varies seasonally from essentially zero in winter to hundreds of kilometers in recent summers. Using in situ observations of waves in the central Beaufort Sea, combined with a numerical wave model and satellite sea ice observations, we show that wave energy scales with fetch throughout the seasonal ice cycle. Furthermore, we show that the increased open water of 2012 allowed waves to develop beyond pure wind seas and evolve into swells. The swells remain tied to the available fetch, however, because fetch is a proxy for the basin size in which the wave evolution occurs. Thus, both sea and swell depend on the open water fetch in the Arctic, because the swell is regionally driven. This suggests that further reductions in seasonal ice cover in the future will result in larger waves, which in turn provide a mechanism to break up sea ice and accelerate ice retreat.").

[92] Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, Front. Earth Sci. 9(738497): 1–17, 15 ("The advective tendency of SIC due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011). "). *See also* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea-Ice Loss from Late-Summer Cyclones in the New Arctic*, J. Clim.: 1–39, 1 ("We compare the 1-7 day changes in sea-ice area and thickness following days in each month with and without cyclones from two decades: 1991-2000 and 2009-2018. Only in August do cyclones locally accelerate seasonal sea-ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E-120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2-0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea-ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea-ice loss. Moreover, the 7-day sea-ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0-140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, Science.

[93] Mallett R. D. C., Stroeve J. C., Cornish S. B., Crawford A. D., Lukovich J. V., Serreze M. C., Barrett A. P., Meier W. N., Heorton H. D. B. S., & Tsamados M. (2021) *Record winter winds in 2020/21 drove exceptional Arctic sea ice transport*, Commun. Earth Environ. 2(149): 1–6, 2 ("The response of the sea ice to the wind forcing was such that four times as much MYI area was transported into the Beaufort Sea as was transported out, but the total ice area transported out was double that transported in (Fig. 2a, b). This transport acted to flush the Beaufort Sea of its first-year ice cover and fill it with MYI. Eight per cent of the Arctic's MYI cover was transported into the Beaufort Sea in winter 2020/2021 (Fig. 2e), contributing to a record fraction of the MYI cover residing in the Beaufort Sea (23.5%) in the last full week of February (Fig. 2f). This fraction has been historically increasing over the data period (1983–2020), however, this high concentration is well above the linear trend (by 2.06 standard deviations; Figs. S9 and S10). Because around two-thirds of the Beaufort Sea has been ice-free on the first of September over the last decade (Fig.2h), this unprecedented concentration of Arctic MYI in the Beaufort Sea puts it at a larger risk of melting."). *See also* Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (2021)

Chapter 2: Changing State of the Climate System, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 343 ("A reduction of survival rates of sea ice exported from the Siberian shelves by 15% per decade has interrupted the transpolar drift and affected the long-range transport of sea ice (Krumpen et al., 2019). The thinner and on average younger ice has less resistance to dynamic forcing, resulting in a more dynamic ice cover (Hakkinen et al., 2008; Spreen et al., 2011; Vihma et al., 2012; Kwok et al., 2013).").

[94] Mallett, R. (10 August 2021) *Record-breaking winter winds have blown old Arctic sea ice into the melt zone*, ArcticToday ("In the Arctic, the breakdown of the polar vortex produced an exceptional pattern of surface winds that swirled clockwise about the center of the Arctic Ocean like water around a plughole. These swirling winds spun the floating icepack like a spinning top. In doing so, they drove the Arctic's perennial ice from a relatively safe and cold position north of Greenland into an area where ice increasingly can't survive the summer: the Beaufort Sea. Over the winter, the Beaufort Sea filled with perennial ice such that in the last week of February 2021, it contained a record fraction (23.5 percent) of the Arctic Ocean's total perennial ice cover.").

[95] Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. Geophys. Res. Atmos. 126(12): 1–35, 20 ("One of the most intriguing results in our analysis of track counts was the strong positive trend in cyclone numbers from ∼2,000 onward in the cold season (Figure 3) and its connection to the decreasing SIC. Increased number of cyclones has also been observed in many other studies (Rudeva & Simmonds, 2015; Sepp & Jaagus, 2011; Zahn et al., 2018), but the positive trends found in Sepp and Jaagus (2011) and Zahn et al. (2018) were not spatially coherent, and some studies have also found negative or nonsignificant cyclone trends (e.g., Simmonds & Keay, 2009). The connection between cyclones and the changing sea ice surface has also remained unclear. The results presented here show a more coherent cold season increase in the cyclone counts than previous studies have. We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season. This was apparent in both the correlation tables and trend matrix figures (Tables 1 and A1, and Figures 3, 11, and A15). The negative correlation between the warm season SIC and cold season cyclones could be supported by the findings of Koyama et al. (2017), which connected low summer sea ice years with more favored conditions for cyclogenesis the following fall/winter. However, they did not find an increase in the number of cyclones associated with the declining sea ice, which our results clearly showed."). *See also* Day J. J. & Hodges K. I. (2018) *Growing Land-Sea Temperature Contrast and the Intensification of Arctic Cyclones*, Geophys. Res. Lett. 45: 3673–3681, 3680 ("In summary, we observed: 1. that 2m land temperatures near the Arctic coastline are warming at approximately twice the rate of sea surface temperatures in adjacent regions; 2. that significantly increased Arctic cyclone frequency and intensity, particularly in the Eastern part of the Arctic Ocean, are characteristic of years with high Arctic coastal temperature gradients, compared to low years; and 3. that the sign of this response is consistent with climate model projections, but the magnitude of change in cyclone numbers is higher, suggesting that CMIP models underestimate the sensitivity of the summer storm track to increasing land-sea contrast in the Arctic. Further, because climate change is increasing land-sea contrasts in the Arctic, it seems highly likely that the circulation patterns typical of years with strong AFZ will become more common as the climate warms. Indeed, strengthening of the mean temperature gradients in the AFZ is a robust feature of future climate projections as is an increase in the strength of the Arctic Front Jet (Mann et al., 2017; Nishii et al., 2014). This study shows that this linkage between surface temperature gradients and atmospheric circulation is important for Arctic cyclones, adding weight to previous studies.").

[96] Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, Geophys. Res. Lett. 40(4): 720–726, 722 ("The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12×10^3 km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21×10^3 km^3 d^{-1} (or 0.17×10^3 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b)."). *See also* Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. Geophys. Res. Atmos. 126(12): 1–35, 20 ("We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season."); *and* Finocchio

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M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea-Ice Loss from Late-Summer Cyclones in the New Arctic*, J. CLIM.: 1–39, 1 ("We compare the 1-7 day changes in sea-ice area and thickness following days in each month with and without cyclones from two decades: 1991-2000 and 2009-2018. Only in August do cyclones locally accelerate seasonal sea-ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E-120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2-0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea-ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea-ice loss. Moreover, the 7-day sea-ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0-140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface.").

[97] Kim Y.-H., Min S.-K., Gillett N. P., Notz D., & Malinina E. (2023) *Observationally-constrained projections of an ice-free Arctic even under a low emission scenario*, NAT. COMMUN. 14: 3139, 5 ("Based on the GHG+ scaling factors, we produce observationally-constrained future changes in Arctic SIA under four SSP scenarios. Results indicate that the first sea ice-free September will occur as early as the 2030s–2050s irrespective of emission scenarios. Extended occurrences of an ice-free Arctic in the early summer months are projected later in the century under higher emissions scenarios."). *See also* Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, COMMUN. EARTH ENVIRON. 2(144): 1–8, 4, 6 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)"; "This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."); Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, CLIMATE 8(15): 1–24, 17 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYS. RES. LETT. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two."); Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, NAT. CLIM. CHANGE 10: 928–932, 931 ("The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4). More broadly, multimodel CMIP3–6 mean predictions (and ranges) for a summer sea-ice-free Arctic are as follows: CMIP3, 2062 (2040–2086); CMIP5, 2048 (2020–2081); and CMIP6, 2046 (2029–2066) (Fig. 4 and Supplementary Table 3). We note that the latest year of sea-ice disappearance for CMIP6 models is 2066 and that 50% of the models predict sea-ice-free conditions between ~2030 and 2040. From this we can see that HadGEM3 is not a particular outlier, in terms of its ECS or projected ice-free year."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.8-b.

[98] Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, NAT. CLIM. CHANGE 10: 928–932, 929, 931, 932 ("Our study has demonstrated that the high-ECS HadGEM3 model yields a much-improved representation of Arctic summers during the warmer LIG climate compared with previous old-

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generation model simulations. We analysed simulated surface air temperatures and proxy reconstructions of LIG summer temperatures and showed a 95% agreement between the model and observations. Arctic surface temperatures and sea ice are strongly related. By simulating an ice-free summer Arctic, our LIG CMIP6 simulation provides (direct) modelling and (indirect) observational support that the summer Arctic could have been ice free during the LIG. This offers a unique solution to the long-standing puzzle of what occurred to drive the temperatures to rise during LIG Arctic summers. The ability of the HadGEM3 model to realistically simulate the very warm LIG Arctic climate provides independent support for predictions of ice-free conditions by summer 2035. This should be of huge concern to Arctic communities and climate scientists.”; “The LIG sea-ice decrease commences in June (when the LIG sea-ice extent is outside of the PI range of variability, Fig. 1a) and culminates in a complete loss of ice by the end of the melt season in August and September (Fig. 1a,f).”; “The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4).”).

[99] Crawford A., Stroeve J., Smith A., & Jahn A. (2021) *Arctic open-water periods are projected to lengthen dramatically by 2100*, COMMUN. EARTH ENVIRON. 2(109): 1–10, 4 (“The rate of increase in open-water period is comparable for all three emissions scenarios until the 2040s (Fig. 2), when the rate of change declines in SSP126 (blue), persists in SSP245 (orange), and accelerates in SSP585 (red). The most southerly regions (Sea of Okhotsk, Bering Sea, Gulf of St. Lawrence, and Labrador Sea) become ice-free year-round by the end of the century in SSP585, and some models also show the Greenland and Barents seas reach 365 days of open water for all grid cells by 2100.”). *See also* Årthun M., Onarheim I. H., Dörr J., & Eldevik T. (2021) *The seasonal and regional transition to an ice-free Arctic*, GEOPHYS. RES. LETT. 48: 1–10, 1 (“The Arctic sea ice cover is currently retreating and will continue its retreat in a warming world. However, the loss of sea ice is neither regionally nor seasonally uniform. Here we present the first regional and seasonal assessment of future Arctic sea ice loss in CMIP6 models under low (SSP126) and high (SSP585) emission scenarios, thus spanning the range of future change. We find that Arctic sea ice loss – at present predominantly limited to the summer season – will under SSP585 take place in all regions and all months. The summer sea ice is lost in all the shelf seas regardless of emission scenario, whereas ice-free conditions in winter before the end of this century only occur in the Barents Sea. The seasonal transition to ice-free conditions is found to spread through the Atlantic and Pacific regions, with change starting in the Barents Sea and Chukchi Sea, respectively.”); *and* Tor Eldevik (@TorEldevik), Twitter, 7 December 2020, 6:43AM (Co-author on the study sharing graphics and information about the ice-free conditions in the shelf seas).

[100] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, GEOPHYS. RES. LETT. 48(18): 1–12, 1 (“Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the “likely” date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.”).

[101] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7477 (“This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO_2 into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO_2 have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO_2 per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic sea ice would be equivalent to 25 years of global CO_2 emissions at the current rate.”). *See also* Institute for Governance & Sustainable Development (2019) *Plain Language Summary of Pistone K., et al*.

[102] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7479 (“The estimate of one trillion tons of CO_2 emissions is computed using the following approximate formula: $f = (5.35\ W/m^2) \ln[x/R]$ (Myhre et al., 1998). Here f is the radiative forcing relative to an arbitrary reference value R, x is the atmospheric CO_2 concentration, and ln indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO_2 causes a radiative forcing of 3.71 W/m^2. Considering a radiative forcing of 0.71 W/m^2, this translates to an increase in the atmospheric CO_2 concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO_2 is equivalent to 7.77 Gt (Le Quéré et al., 2018), this increase of 56.7 ppm weighs 441 Gt. The mean airborne fraction of CO_2 (i.e., fraction of CO_2 emissions that remain in the atmosphere) is estimated to be 0.44 ± 0.06 (section 6.3.2.4 of Ciais et al., 2013). This implies that the emissions needed to increase atmospheric CO_2 enough to cause 0.71 W/m^2 of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44).”).

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[103] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7476 ("Hence, we focus on the baseline estimate scenario in which cloud conditions remain unchanged from the present. We find that the complete disappearance of Arctic sea ice throughout the sunlit part of the year in this scenario would cause the average planetary albedo of the Arctic Ocean (poleward of 60 ºN) to decrease by 11.5% in absolute terms. This would add an additional 21 W/m^2 of annual-mean solar heating over the Arctic Ocean relative to the 1979 baseline state. Averaged over the globe, this implies a global radiative heating of 0.71 W/m^2 (Figure 2)."). *See also* Wunderling N., Willeit M., Donges J. F., & Winklemann R. (2020) *Global warming due to loss of large ice masses and Arctic summer sea ice*, Nat. Commun. 11(5177): 1–8, 6 ("On shorter time scales, the decay of the Arctic summer sea ice would exert an additional warming of 0.19 °C (0.16–0.21 °C) at a uniform background warming of 1.5 °C (=400 ppm) above pre-industrial. On longer time scales, which can typically not be considered in CMIP projections, the loss of Greenland and West Antarctica, mountain glaciers and the Arctic summer sea ice together can cause additional GMT warming of 0.43°C (0.39–0.46 °C). This effect is robust for a whole range of CO_2 emission scenarios up to 700 pm and corresponds to 29% extra warming relative to a 1.5 °C scenario."). If the Greenland Ice Sheet, West Antarctic Ice Sheet, and mountain glaciers were also completely ice-free, the planet could see an additional 0.43 ºC of warming, with 55% of that coming from the loss of albedo.

[104] Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7-49 (Table 7.8 gives Effective Radiative Forcings (ERF) for CO_2 of 2.16 (1.90 to 2.41)). *See also* National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *The NOAA Annual Greenhouse Gas Index (AGGI)* (*last visited* 14 February 2023) (Table 2 shows that the radiative forcing from CO_2 was 2.079 W/m^2 in 2019, 2.111 W/m^2 in 2020, and 2.140 W/m^2 in 2021.)

[105] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7477 ("We examine two perhaps unrealistically extreme future Arctic cloud scenarios: at one extreme, an ice-free Arctic Ocean that is completely cloud free and at the other extreme, an ice-free Arctic Ocean that is completely overcast. For simplicity, in the latter scenario we use distributions of cloud optical thickness based on present-day observations (see Appendix A). Both of these extreme scenarios are shown in Figure 2. The cloud-free, ice-free Arctic scenario results in a global radiative heating of 2.2 W/m^2 compared with the 1979 baseline state, which is 3 times more than the 0.71 W/m^2 baseline estimate derived above for unchanged clouds. The completely overcast ice-free Arctic scenario results in a global radiative heating of 0.37 W/m^2, which is approximately half as large as the 0.71 W/m^2 baseline estimate (Figure 2b). This suggests that even in the presence of an extreme negative cloud feedback, the global heating due to the complete disappearance of the Arctic sea ice would still be nearly double the already-observed heating due to the current level of ice loss.").

[106] United States Environmental Protection Agency (2015) U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council, 2, 9 (Figure 1 shows BC emissions north of the 40th parallel in 2011 amounting to 0.51 million metric tons, with 39% from open biomass burning, and 51% of that number [19.89% or ~0.10 MMT] due to wildfires; "In 2011, 51 percent of black carbon emissions from open biomass burning were from wildfires, 43 percent from prescribed burning, with the remainder from agricultural field burning."). *See also* Kim J.-S., Kug J.-S., Jeong S.-J., Park H., & Schaepman-Strub G. (2020) *Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation*, Sci. Adv. 6(2): 1–7, 2, 4 ("Strictly speaking, the fire activity–related high-pressure pattern extends further into southeastern Siberia than the typical AO pattern. This suggests that the AO provides preferable conditions for strong fire activity (i.e., high-temperature anomalies), but the positive pressure anomaly extending westward from the North Pacific to southeastern Siberia explains more southeastern Siberian fire activity variability."; "In contrast, we found a significant negative relationship between March to April snow cover and total annual fire activity, as positive temperature anomalies related to a positive AO in February and March drive early snowmelt in March and April with a time lag of 1 to 2 months (Fig. 3, B and C, and fig. S6) (*18*, *19*). This is consistent with results from a snow water equivalent dataset (fig. S7). Accumulated positive temperature anomalies in late winter lead to earlier melting in snow cover's seasonal evolution. Once snow cover is reduced, a positive snow-albedo feedback accelerates surface warming and snowmelt (fig. S8). Thus, significant negative snowmelt is observed in March and April as a result (Fig. 3, B and C). Earlier snowmelt leads to faster exposure of the ground surface and litter, which, in turn, allows favorable conditions for fire spreading because this region consists mostly of larch (*Larix*

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gmelinii) forests with a high amount of litter that can act as fire fuel (*22*)…. This analysis shows a generally negative relation between burned area and P/PET, meaning that more arid regions have stronger fire activity."); *and* Environmental Protection Agency (2012) *Report to Congress on Black Carbon*, EPA-450/R-12-001.

[107] Schuur E. A. G., *et al*. (2008) *Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle*, BioScience 58(8): 701–714, 710 ("Model scenarios of fire in Siberia show that extreme fire years can result in approximately 40% greater C emissions because of increased soil organic C consumption (Soja et al. 2004). In combination with dry conditions or increased water infiltration, thawing and fires could, given the right set of circumstances, act together to expose and transfer permafrost C to the atmosphere very rapidly"). *See also* McCarty J. L., Smith T. E. L., & Turetsky M. R. (2020) *Arctic fires re-emerging*, Nat. Geosci. 13(10): 658–660, 659 ("Evidence from 2019 and 2020 suggests that extreme temperatures accompanied by drying are increasing the availability of surface fuels in the Arctic. New tundra vegetation types, including dwarf shrubs, sedges, grasses and mosses, as well as surface peats, are becoming vulnerable to burning, and what we typically consider to be 'fire-resistant' ecosystems, such as tundra bogs, fens and marshes, are burning (Fig. 1). While wildfires on permafrost in boreal regions of Siberia are not uncommon[7], 2020's fires are unusual in that more than 50% of the detected fires above 65° N occurred on permafrost with high ice content. Ice-rich permafrost is considered to contain the most carbon-rich soils in the Arctic[8] and burning can accelerate thaw and carbon emission rates[9]").

[108] Holzworth R. H., Brundell J. B., McCarthy M. P., Jacobson A. R., Rodger C. J., & Anderson T. S. (2021) *Lightning in the Arctic*, Geophys. Res. Lett. 48(7): 1–6, 1 ("The ratio of strokes occurring above a given latitude, compared to total global strokes, increases with time, indicating that the Arctic is becoming more influenced by lightning. We compare the increasing fraction of strokes with the NOAA global temperature anomaly, and find that the fraction of strokes above 65°N to total global strokes increases linearly with the temperature anomaly and grew by a factor of 3 as the anomaly increased from 0.65°C to 0.95°C."); *discussed in* DeGeorge K. (5 January 2022) *The high Arctic saw a huge spike in lightning last year,* ArcticToday ("In 2021 there were 7,238 lightning events north of 80 degrees North latitude, the company said. That's almost twice as many as in the preceding nine years combined. Even further north — north of 85 degrees — the company recorded a record high 634 events. (Areas of the Arctic further south, where lightning is a little more common, didn't see such dramatic increases.).").

[109] Chen Y., Romps D. M., Seeley J. T., Veraverbeke S., Riley W. J., Mekonnen Z. A., & Randerson J. T. (2021) *Future increases in Arctic lightning and fire risk for permafrost carbon*, Nat. Clim. Chang. 11(5): 404–410, 407–408 ("Lightning-driven increases in fire may trigger a positive fire–vegetation–soil feedback that promotes shrub expansion, northward displacement of the treeline and changes in tree species composition8,25,51,52. A dynamic vegetation feedback may develop over a longer timescale than the atmospheric processes that regulate lightning flash rate and fire ignition. … Together, the vegetation dynamics and changes in fire weather may contribute to a higher ratio of burned area to lightning flash rate north of the treeline than what is currently observed (Extended Data Fig. 8a). After we add this amplifying effect from a vegetation feedback into our simple fire model (by assuming that the ratio of burned area to lightning flash rate in the Arctic tundra will change to the present-day value in boreal forests 480 km south of the treeline, referred to as the 'dynamic vegetation' approach), the model predicts a 570 ± 480% enhancement in burned area and carbon release by the end of this century in Arctic tundra. Increases in burned area within Arctic tundra, in turn, may increase the vulnerability of the permafrost carbon reservoir in at least two ways (Fig. 4b). First, more frequent fires have the potential to damage or remove the surface insulating layer of organic matter in areas that have moderate or high fire severity59. The loss of this layer through wildfire combustion will expose the underlying permafrost to substantial warming and degradation8 and lead to thermokarst development in ice-rich permafrost60. …Second, with the expansion of shrubs and northern forests in fire-disturbed areas, surface albedo will probably decline in spring and summer, and the extra energy absorbed by the land surface may further amplify regional climate warming63. … Extra warming and productivity from a fire-driven northward expansion of forests could thus accelerate permafrost thaw and decomposition in areas not currently affected by fire."). *See also* Witze A. (10 September 2020) *The Arctic is burning like never before — and that's bad news for climate change*, Nature News ("Wildfires blazed along the Arctic Circle this summer, incinerating tundra, blanketing Siberian cities in smoke and capping the second extraordinary fire season in a row. By the time the fire season waned at the end of last month, the blazes had emitted a record 244 megatonnes of carbon dioxide — that's 35% more than last year, which also set records. One culprit, scientists say, could be peatlands that are burning as the top of the world melts.").

[110] Scholten R. C., Jandt R., Miller E. A., Rogers B. M., & Veraverbeke S. (2021) *Overwintering fires in boreal forests,* Nature 593(7859): 399–404, 404 (We estimated that large overwintering fires in Alaska and the Northwest

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Territories emitted 3.5 (standard deviation, 1.1) Tg of carbon between 2002 and 2018, 64% of which occurred during the 2015 Northwest Territories and 2010 Alaska fire seasons. The contribution of smouldering combustion is generally underestimated in carbon emission estimates from boreal fires. Thus, our estimate is likely to be conservative, because overwintering fires exhibit a substantial smouldering phase and may burn deeper than our emissions model currently predicts. In addition, smouldering fires emit relatively more methane and less carbon dioxide in comparison to flaming fires41, yet methane has a much larger global warming potential.”).

[111] Comer B., Olmer N., Mao X., Roy B., & Rutherford D. (2017) *Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025*, International Council on Clean Transportation, 3, 4 (“Studies have analyzed the amount of HFO used and carried in the Arctic. Between 2011 and 2013, Det Norske Vertitas completed a series of reports for the AC’s Protection of the Arctic Marine Environment (PAME) working group to help it understand the use and carriage of HFO in the Arctic (Det Norske Veritas [DNV], 2011, 2013). In these studies, DNV found that only 20% of vessels sailing in the IMO Arctic from August to November 2010, and 28% from January to December 2012, operated on HFO. However, roughly 78%, or 400,000 tonnes, of the bunker fuel mass on board vessels in the IMO Arctic was HFO. DNV found that fishing vessels dominated the Arctic fleet in terms number of ships, operating hours, and fuel consumption in the Arctic; however, they assumed that most of these vessels operated on lighter and cleaner distillate fuels, rather than HFO, a reasonable assumption according to the results presented here. Bulk carriers, passenger vessels, and oil tankers had the most HFO fuel on board by mass because of their larger bunker tank capacity. A recent International Council on Clean Transportation (ICCT) working paper (Comer, Olmer, & Mao, 2016) found that whereas less than half of ships operating in the IMO Arctic used HFO in 2015, the mass of fuel onboard all ships in the IMO Arctic was dominated by HFO (76% HFO; 23% distillate; less than 1% LNG, nuclear, and gas boil of), because ships operating on HFO tend to be larger ships with large bunker fuel tanks. That paper reported that ships in the IMO Arctic in 2015 had more than 830,000 t of HFO onboard, more than twice the amount estimated by DNV for the year 2012. A portion of this substantial increase in fuel carriage is attributable to greater carriage of HFO; however, the bulk of this diference is likely as a result of having more complete ship position and ship characteristics data in the 2016 ICCT study than in the 2013 DNV study. Comer et al. (2016) found that the carriage of HFO as bunker fuel in the IMO Arctic in 2015 was dominated by bulk carriers (247,800 t), container vessels (112,900 t), oil tankers (110,600 t), general cargo vessels (76,600 t), and fishing vessels (76,200 t).”; “Several studies have estimated BC emissions in the Arctic, although the geographical definitions of the Arctic are inconsistent across studies. Corbett et al. (2010) estimated that ships operating in the AMSA area1 emitted 0.88 kilotonnes (kt) of BC in 2004,2 growing to 1.20 kt in 2020, 1.50 kt in 2030, and 2.70 kt in 2050 under a BAU scenario. Similarly, Peters et al. (2011) estimated that ships operating within the AMAP boundary3 emitted 1.15 kt of BC emissions in 2004, growing to 2.16 kt in 2030 and 2.96 kt in 2050. Both studies assumed a BC emission factor (EF) of 0.35 g/kg fuel. Two more recent studies—DNV (2013) and Winther et al. (2014)—better match the geospatial extents of the Arctic found in this report. DNV (2013) estimated that ships operating within the IMO Arctic emitted 0.052 kt of BC in 2012, assuming a BC EF of 0.18 g/kg fuel. Winther et al. (2014) estimated ships operating at or above 58.95°N emitted 1.585 kt of BC in 2012, assuming a BC EF of 0.35 g/kg fuel.”). *See also* Anselmi E. (6 April 2020*) A new report shows that more ships are visiting the Arctic*, ArcticToday; *and* McVeigh K. (10 April 2022) *‘Black carbon’ threat to Arctic as sea routes open up with global heating*, The Guardian.

[112] O’Rourke R., Leggett J. A., Comay L. B., Ramseur J. L., Frittelli J., Sheikh P. A., Keating-Bitonti C., & Tracy B. S. (*updated* 24 March 2022) Changes in the Arctic: Background and Issues for Congress, Congressional Research Service R41153, 19 (“While there continues to be significant international cooperation on Arctic issues, the emergence of great power competition (also called strategic competition) between the United States, Russia, and China, combined with the increase in human activities in the Arctic resulting from the diminishment of Arctic ice, has introduced elements of competition and tension into the Arctic’s geopolitical environment,[77] and the Arctic is viewed by some observers as an arena for geopolitical competition among the three countries.[78]”). *See also* Gricius G. (18 March 2021) *Geopolitical Implications of New Arctic Shipping Lanes*, The Arctic Institute; *and* Spohr K. & Hamilton D. S. (eds.) (2020) The Arctic and World Order, Foreign Policy Institute & Henry A. Kissinger Center for Global Affairs, Johns Hopkins University SAIS: Washington, DC.

[113] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 (“This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata

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et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC ºC^{-1}. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} ºC^{-1} (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2).”). *See also* Lawrence D. M., Slater A. G., Tomas R. A., Holland M. M., & Deser C. (2008) *Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss*, Geophys. Res. Lett. 35(L11506): 1–6, 5 (“We find that rapid sea ice loss forces a strong acceleration of Arctic land warming in CCSM3 (3.5-fold increase, peaking in autumn) which can trigger rapid degradation of currently warm permafrost and may increase the vulnerability of colder permafrost for subsequent degradation under continued warming. Our results also suggest that talik formation may be a harbinger of rapid subsequent terrestrial change. This sea ice loss – land warming relationship may be immediately relevant given the record low sea ice extent in 2007.”); *and* Vaks A., Mason A., Breitenbach S., Kononov A., Osinzev A., Rosensaft M., Borshevsky A., Gutareva O., & Henderson G. (2020) *Palaeoclimate evidence of vulnerable permafrost during times of low sea ice*, Nature 577(7789): 221–225, 221 (“The robustness of permafrost when sea ice is present, as well as the increased permafrost vulnerability when sea ice is absent, can be explained by changes in both heat and moisture transport. Reduced sea ice may contribute to warming of Arctic air, which can lead to warming far inland. Open Arctic waters also increase the source of moisture and increase autumn snowfall over Siberia, insulating the ground from low winter temperatures. These processes explain the relationship between an ice-free Arctic and permafrost thawing before 0.4 Ma. If these processes continue during modern climate change, future loss of summer Arctic sea ice will accelerate the thawing of Siberian permafrost.”).. For more on impacts of melting permafrost to climate and water supply, *see* Taillant J. D. (2021) *Chapter 5. A Thawing Earth*, *in* Meltdown: The Earth Without Glaciers, Oxford University Press: Oxford, United Kingdom; *and* Taillant J. D. (2015) *Chapter 4. Invisible Glaciers*, *in* Glaciers: The Politics of Ice, Oxford University Press: Oxford, United Kingdom.

[114] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, Environ. Res. Lett. 9(085003): 1–9, 2 (“If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO_2 into organic matter and freeze it back into the permafrost.”). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, Tellus B 63(2): 165–180, 166 (“The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO_2 and methane concentrations increase, surface air temperatures will increase, causing permafrost degradation and thawing some portion of the permafrost carbon. Once permafrost carbon thaws, microbial decay will resume, increasing respiration fluxes to the atmosphere and atmospheric concentrations of CO_2 and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b).”); *and* Chen Y., Liu A., & Moore J.C. (2020) *Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering*, Nat. Commun. 11(2430): 1–35, 2, 3 (“Between 2020 and 2069, PInc-Panther simulations of soil C change, driven by outputs of 7 ESMs for the RCP4.5 projection, varied from 19.4 Pg C gain to 52.7 Pg C loss (mean 25.6 Pg C loss), while under G4 the ensemble mean was 11.9 Pg C loss (range: 29.2 Pg C gain to 44.9 Pg C loss). Projected C losses are roughly linearly proportional to changes in soil temperature, and each 1 °C warming in the Arctic permafrost would result in ~13.7 Pg C loss; the yintercept indicates that the Arctic permafrost, if maintained in current state, would remain a weak carbon sink. MIROC-ESM and MIROC-ESM-CHEM, with simulations of warming above 3°C, produce severe soil C losses, while GISS-E2-R with minor soil temperature change produces net soil C gains under both scenarios before 2070.”; “PIncPanTher simulations of the anoxic respiration rates over the period 2006–2010 are 1.2–1.7 Pg C year−1, and so the estimated range of CH_4 emissions is 28–39 Tg year−1, which is very close to the 15–40 Tg CH4 year−1 estimates of current permafrost wetland CH_4 emissions.”).

[115] Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, Atmos. Chem. Phys. 19(7): 4257–4268, 4257 (“The microbial by-product nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with ever

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known in situ study focused on permafrost N_2O fluxes, have used chambers to examine small areas (< 50 m^2). In late August 2013, we used the airborne eddy-covariance technique to make in situ N_2O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km^2. We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N_2O m^{-2} d^{-1} with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions.").

[116] Biskaborn B. K., *et al.* (2019) *Permafrost is warming at a global scale*, Nat. Commun. 10(264): 1–11, 1 ("During the reference decade between 2007 and 2016, ground temperature near the depth of zero annual amplitude in the continuous permafrost zone increased by 0.39 ± 0.15 °C. Over the same period, discontinuous permafrost warmed by 0.20 ± 0.10 °C. Permafrost in mountains warmed by 0.19 ± 0.05 °C and in Antarctica by 0.37 ± 0.10 °C. Globally, permafrost temperature increased by 0.29 ± 0.12 °C."). *See also* Smith S. L., O'Neill H. B., Isaksen K., Noetzli J., & Romanovsky V. E. (2022) *The changing thermal state of permafrost*, Nat. Rev. Earth Environ. 3: 10–23, 10 ("In warmer permafrost (temperatures close to 0 °C), rates of warming are typically less than 0.3 °C per decade, as observed in sub-Arctic regions. In colder permafrost (temperatures less than −2 °C), by contrast, warming of up to about 1 °C per decade is apparent, as in the high-latitude Arctic. Increased active-layer thicknesses have also been observed since the 1990s in some regions, including a change of 0.4 m in the Russian Arctic.").

[117] Miner K. R., Turetsky M. R., Malina E., Bartsch A., Tamminen J., McGuire A. D., Fix A., Sweeney C., Elder C. D., & Miller C. E. (2022) *Permafrost carbon emissions in a changing Arctic*, Nat. Rev. Earth Environ. 3: 55–67, 55 ("Permafrost underlies ~25% of the Northern Hemisphere land surface and stores an estimated ~1,700Pg (1,700Gt) of carbon in frozen ground, the active layer and talik[1,2]. Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores[3,4], potentially increasing atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4), and converting the Arctic from a carbon sink to a carbon source."). *See also* Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, Nature 520: 171–179, 171 ("The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting."); *and* World Bank & International Cryosphere Climate Initiative (2013) On Thin Ice: How Cutting Pollution Can Slow Warming and Save Lives, 44.

[118] Smith S. L., O'Neill H. B., Isaksen K., Noetzli J., & Romanovsky V. E. (2022) *The changing thermal state of permafrost*, Nat. Rev. Earth Environ. 3: 10–23, 10 ("In warmer permafrost (temperatures close to 0 °C), rates of warming are typically less than 0.3 °C per decade, as observed in sub-Arctic regions. In colder permafrost (temperatures less than −2 °C), by contrast, warming of up to about 1 °C per decade is apparent, as in the high-latitude Arctic. Increased active-layer thicknesses have also been observed since the 1990s in some regions, including a change of 0.4 m in the Russian Arctic."). *See also* Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (2021) *Chapter 2: Changing State of the Climate System*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 348 ("Recent (2018–2019) permafrost temperatures in the upper 20–30 m layer (at depths where seasonal variation is minimal) were the highest ever directly observed at most sites (Romanovsky et al., 2020), with temperatures in colder permafrost of northern North America being more than 1°C higher than they were in 1978. Increases in temperature of colder Arctic permafrost are larger (average 0.4°C–0.6°C per decade) than for warmer (temperature >–2° C) permafrost (average 0.17°C per decade) of sub-Arctic regions (Figures 2.25, 9.22).").

[119] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $°C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and

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assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} ºC^{-1} (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2).... Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period... Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH4 from 2100–2300 (Turetsky et al., 2020).”).

[120] Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G., & Westermann S. (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NAT. CLIM. CHANGE 7: 340–344, 340 (“The estimated permafrost area is 15.5 million km^2 using this technique (12.0–18.2 million km^2 using minimum/maximum curves), which compares well to 15.0 million km^2 from observations (12.6–18.4 million km^2).”). *See also* Obu J., *et al.* (2019) *Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale*, EARTH-SCI. REV. 193: 299–316, 305 (“The best estimate of the permafrost area in the Northern Hemisphere is 13.9 × 10^6 km^2 (14.6% of the exposed land area), representing the total area with where MAGT <0 °C (Fig. 3). The borehole temperature comparison can be used to incorporate uncertainty into this estimate, giving a minimum permafrost extent of 10.1 × 10^6 km^2 (10.5% of exposed land area; the area within MAGT < −2 °C) and a maximum extent of 19.6 × 10^6 km^2 (20.6% of exposed land area; the area within MAGT < +2 °C). The extent of the permafrost region (i.e. all permafrost zones) inferred from permafrost occurrence probabilities is 20.8 × 10^6 km^2 (21.8% of exposed land area). The continuous permafrost zone occupies about half of this area, underlying 10.7 × 10^6 km^2 (11.2% of exposed land area), while the discontinuous (3.1 × 10^6 km^2; 3.3% of exposed land area), sporadic (3.5 × 10^6 km^2; 3.6% of exposed land area), and isolated patches zones (3.5 × 10^6 km^2; 3.6% of exposed land area) almost equally divide the remainder.”); *and* Obu J. (2021) *How Much of the Earth’s Surface is Underlain by Permafrost?*, J. GEOPHYS. RES. EARTH SURF. 126(5): e2021JF006123, 1–5, 5 (”Globally, permafrost underlies between 14 and 15.7 × 106 km^2 of the exposed land area (Gruber, 2012; Obu, Westermann, Bartsch, et al. (2019)), which equates to approximately 11% of the exposed land surface with around 2% uncertainty. No subglacial, relict, or subsea permafrost is included in the above estimates. Circum-Arctic subsea permafrost extent was estimated to be 2.5 × 106 km^2 (Overduin et al., 2019). Thus, the permafrost area including Circum-Arctic subsea permafrost can be estimated to be around 17 × 106 km^2.”).

[121] Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G., & Westermann S. (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NAT. CLIM. CHANGE 7: 340–344, 340 (“Under a 1.5 °C stabilization scenario, 4.8 (+2.0, -2.2) million km^2 of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2 °C stabilization we would lose 6.6 (+2.0, -2.2) million km^2, over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km^2 of permafrost from thawing.”). *See also* Burke E.J., Zhang Y., & Krinner G. (2020) *Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change*, THE CRYOSPHERE 14(9): 3155–3174, 3173 (“The CMIP6 models project a loss of permafrost under future climate change of between 1.7 and 2.7×10^6 km$^{2\circ}$C^{-1}. A more impact-relevant statistic is the decrease in annual mean frozen volume (3.0 to 5.3×103 km3°C−1) or around 10 %–40 %∘C−1.”); *and* Wang X., *et al.* (2022) *Contrasting characteristics, changes, and linkages of permafrost between the Arctic and the Third Pole*, EARTH SCI. REV. 230(104042): 1–21, 9 (“The future reduction in near-surface permafrost (permafrost in the topmost ground layers, < 10–15 m depth, Hjort et al., 2022) area exhibits different magnitudes in the two regions. In the Arctic, the near-surface permafrost area is projected to gradually decline, from 22% (28%) in 2041–2060 to 29% (49%) in 2061–2080 under the RCP 4.5 (RCP 8.5) scenarios relative to the baseline (Table 3). This means that almost one-half of the near-surface permafrost would be lost by the end of the 21st century under the high emission scenario. In western Siberia, permafrost is projected by the CMIP6 models to disappear under SSP5–8.5 because of the MAAT 0 °C isocline moving toward the north (Alexandrov et al., 2021). On the TP, near-surface permafrost exhibits more rapid thaw than in the Arctic, especially under RCP 8.5: 58% in 2041–2060 and 84% in 2061–2080 (Table 3), indicating that near-surface permafrost on the TP is more susceptible to rising air temperatures than the Arctic near-surface

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permafrost. The near-surface permafrost area on the TP is projected to decrease to 0.54 × 106 km2 in 2099 under a future air temperature increase of 2.9 °C (warming magnitude under RCP 4.5) using an "altitude model" (Li and Cheng, 1999), which is close to the projection under RCP 4.5 (Table 3).").

[122] Gasser T., Kechiar M., Ciais P., Burke E.J., Kleinen T., Zhu D., Huang Y., Ekici A., & Obersteiner M. (2018) *Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release*, NAT. GEOSCI. 11(11): 830–835, 833 ("The OSCAR v2.2.1 model, with its new permafrost carbon emulator, estimates future carbon release from thawing permafrost within the range of existing studies (Table 1). A cumulative 60 (11–144)PgC [220 (40–528) $GtCO_2$] is projected to be released by 2100 under RCP8.5, slightly lower than the 37–174PgC [136–638 $GtCO_2$] reviewed by Schuur et al.14, and close to the 28–113PgC [103–414 $GtCO_2$] obtained with a data-constrained model by Koven et al.30"). *Compare with* Rogelj J., *et al.* (2018) *Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 96 ("This assessment suggests a remaining budget of about 420 $GtCO_2$ for a two-third chance of limiting warming to 1.5°C.").

[123] Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13: 138–143, 138–139 ("The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km^2 of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost..... Our simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80±19PgC by 2300 (Fig. 2a). For context, a recent modelling study found that gradual vertical thaw could result in permafrost carbon losses of 208PgC by 2300 under RCP8.5 (multimodel mean), although model projections ranged from a net carbon gain of 167PgC to a net loss of 641PgC (ref. 2). Thus, our results suggest that abrupt thaw carbon losses are equivalent to approximately 40% of the mean net emissions attributed to gradual thaw. Most of this carbon release stems from newly formed features that cover <5% of the permafrost region").

[124] *Compare* 43 $GtCO_2e$ in 2100 with 220 $GtCO_2$ from Gasser *et al.* (2018) for 20% additional emissions. *See* Sayedi S. S., *et al.* (2020) *Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment*, ENVIRON. RES. LETT. 15(12): 124075, 1–13, 1 ("We performed a structured expert assessment with 25 permafrost researchers to combine quantitative estimates of the stocks and sensitivity of organic carbon in the subsea permafrost domain (i.e. unglaciated portions of the continental shelves exposed during the last glacial period). Experts estimated that the subsea permafrost domain contains ~560 gigatons carbon (GtC; 170–740, 90% confidence interval) in OM and 45 GtC (10–110) in CH_4. Current fluxes of CH_4 and carbon dioxide (CO_2) to the water column were estimated at 18 (2–34) and 38 (13–110) megatons C yr^{-1}, respectively. Under Representative Concentration Pathway (RCP) RCP8.5, the subsea permafrost domain could release 43 Gt CO_2-equivalent (CO_2e) by 2100 (14–110) and 190 Gt CO_2e by 2300 (45–590), with ~30% fewer emissions under RCP2.6."); *discussed in* (15 February 2021) *Submarine Permafrost Has Been Overlooked as a Major Source of Greenhouse Gases, Scientists Warn*, YALE ENVIRONMENT 360.

[125] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT'L. ACAD. SCI. 118(21): e2100163118, 1–3, 1 ("These nonlinear processes are particularly relevant when considering the pathway to 2 °C—that is, whether mitigation keeps global average temperature increase below 2 °C ("avoidance") or causes an "overshoot" in temperature before stabilizing. Permafrost emissions from gradual thaw alone are highly dependent on both the extent and duration of the temperature overshoot (12). For example, for a 1.5 °C or 2 °C target, an overshoot of 0.5 °C leads

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to a twofold increase in permafrost emissions, and an overshoot of 1.5 °C leads to a fourfold increase.”). *See also* Gasser T., Kechiar M., Ciais P., Burke E. J., Kleinen T., Zhu D., Huang Y., Ekici A., & Obersteiner M. (2018) *Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release*, Nat. Geosci. 11(11): 830–835, 833 (“In the case of an overshoot amplitude of 0.5 °C, emissions from permafrost thaw reduce the net emission budgets by 130 (30–300) $GtCO_2$ for the 1.5 °C long-term target (that is for a peak temperature of 2 °C, a case that corresponds to the Paris Climate Agreement), and by 190 (50–400)$GtCO_2$ for the 2 °C target (Fig. 2a). For an overshoot amplitude of 1 °C, permafrost-induced reductions reach 210 (50–430)$GtCO_2$ for the 1.5 °C target, and 270 (70–530)$GtCO_2$ for 2 °C target. (Budgets for other targets and other levels of overshoot are provided in Fig. 2 and Supplementary Table 1.)”).

[126] Schuur E. A. G., *et al.* (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, Annu. Rev. Environ. Resour. 47: 343–371, 362 (“The recent appearance of “craters” with high concentrations of CH_4 in some parts of Siberia have raised new questions (133). This phenomenon is a surprise to the permafrost community and appears to be connected with potential CH_4 emissions. Each crater does not contain exceptional levels of CH_4 but could represent new pathways from deep fossil methane that have previously been capped by permafrost. Sources of geologic methane have been observed where ice and permafrost are retreating (116), including subsea (25, 134), and could be new sources to the atmosphere at levels that are only poorly constrained by the projections synthesized in this review.”) *See also* Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, Proc. Nat’l. Acad. Sci. 118(32): 1–3, 1 (“In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future.”); *discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, The Guardian (“The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas.”), *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia’s permafrost. What they found is ‘much more dangerous’*, Washington Post.

[127] Permafrost Pathways, *Course of Action: Mitigation Policy* (*last visited* 13 June 2023) (“Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement…. Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish…. 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.”). Annual U.S. CO_2 emissions from Figure 1 in United States Environmental Protection Agency, *Climate Change Indicators: U.S. Greenhouse Gas Emissions* (*last visited* 13 June 2023).

[128] Hjort J., Streletskiy D., Doré G., Wu Q., Bjella K., & Luoto M. (2022) *Impacts of permafrost degradation on infrastructure*, Nat. Rev. Earth Environ. 3: 24–38, 24 (“Permafrost change imposes various threats to infrastructure, namely through warming, active layer thickening and thaw-related hazards such as thermokarst and mass wasting. These impacts, often linked to anthropogenic warming, are exacerbated through increased human activity. Observed infrastructure damage is substantial, with up to 80% of buildings in some Russian cities and ~30% of some road surfaces in the Qinghai–Tibet Plateau reporting damage. Under anthropogenic warming, infrastructure

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damage is projected to continue, with 30–50% of critical circumpolar infrastructure thought to be at high risk by 2050. Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billions of US dollars by the second half of the century.”). *See also* Hjort J., Karjalainen O., Aalto J., Westermann S., Romanovsky V. E., Nelson F. E., Etzelmüller B., & Luoto M. (2018) *Degrading permafrost puts Arctic infrastructure at risk by mid-century*, Nat. Commun. 9(5147): 1–9, 1 (“Here we identify at unprecedentedly high spatial resolution infrastructure hazard areas in the Northern Hemisphere’s permafrost regions under projected climatic changes and quantify fundamental engineering structures at risk by 2050. We show that nearly four million people and 70% of current infrastructure in the permafrost domain are in areas with high potential for thaw of near-surface permafrost. Our results demonstrate that one-third of pan-Arctic infrastructure and 45% of the hydrocarbon extraction fields in the Russian Arctic are in regions where thaw-related ground instability can cause severe damage to the built environment. Alarmingly, these figures are not reduced substantially even if the climate change targets of the Paris Agreement are reached.”).

[129] Staalesen A. (29 June 2021) *The looming Arctic collapse: More than 40% of north Russian buildings are starting to crumble*, Arctic Today (“Aleksandr Kozlov, Russia’s Minister of Natural Resources, told a minister’s council in May that more than 40% of the northern region’s buildings are starting to deform. Nearly 30% of oil and gas installations are inoperable. By 2050, Russian researchers estimate that the melting permafrost will inflict damages worth about $69 billion, about a quarter of the current Russian federal budget.”).

[130] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, Nature 499(7459): 401–403, 401–403 (“We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher… The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see ‘Arctic methane’). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added…. These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. … The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ….”). *See also* Wadhams P. (2017) A Farewell to Ice: A Report from the Arctic, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, Geosci. 9(6): 251, 1–23.

[131] Watts J. (27 October 2020) *Arctic methane deposits ‘starting to release’, scientists say*, The Guardian (“‘At this moment, there is unlikely to be any major impact on global warming, but the point is that this process has now been triggered. This East Siberian slope methane hydrate system has been perturbed and the process will be ongoing,’ said the Swedish scientist Örjan Gustafsson, of Stockholm University, in a satellite call from the vessel.”); *discussing* the International Siberian Shelf Study (ISSS) 2020 Arctic Ocean Expedition. *See also* Smith E. (18 February 2020) *NASA Flights Detect Millions of Arctic Methane Hotspots*, National Aeronautics and Space Administration.

[132] Steinbach J., Holmstrand H., Shcherbakova K., Kosmach D., Brüchert V., Shakhova N., Salyuk A., Sapart C. J., Chernykh D., Noormets R., Semiletov I., & Gustafsson Ö. (2021) *Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf*, Proc. Nat’l. Acad. Sci. 118(10): 1–9, 7 (“Taken together, the triple-isotope data presented here, in combination with other system data and indications from earlier studies, suggest that deep thermogenic reservoirs are key sources of the elevated methane concentrations in the outer Laptev Sea. This finding is essential in several ways: The occurrence of elevated levels of radiocarbon-depleted methane in the water column may be an indication of thawing subsea permafrost in the study area (see also ref. 8). The triple-isotope fingerprinting suggests, however, that methane may not primarily originate directly from the subsea

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permafrost; the continuous leakage of an old geological reservoir to the water column suggests the existence of perforations in the subsea permafrost, serving as conduits of deeper methane to gas-charged shallow sediments. Second, the finding that methane is released from a large pool of preformed methane, as opposed to methane from slow decomposition of thawing subsea permafrost organic matter, suggests that these releases may be more eruptive in nature, which provides a larger potential for abrupt future releases.”). *See also* Wild B., Shakhova N., Dudarev O., Ruban A., Kosmach D., Tumskoy V., Tesi T., Grimm H., Nybom I., Matsubara F., Alexanderson H., Jakobsson M., Mazurov A., Semiletov I., & Gustafsson Ö. (2022) *Organic matter composition and greenhouse gas production of thawing subsea permafrost in the Laptev Sea*, NAT. COMMUN. 13(5057): 1–12, 7 (“The lower rates of CH_4 production by subsea permafrost decomposition estimated here, and the likely oxidation of part of this CH_4, do not point to a dominant contribution of organic matter decomposition in thawed subsea permafrost to the high emissions observed in the area. We emphasize, however, the high variability of observed CH_4 production rates, and the limitations of upscaling from incubations to natural environments. Taken together, the high CH_4 emissions ubiquitously observed in the field likely stem from other sources such as preformed CH_4 in gas pockets in the subsea permafrost, collapsing CH_4 hydrates, or venting of a deep thermogenic CH_4 pool.”).

[133] Dyonisius M. N., *et al.* (2020) *Old carbon reservoirs were not important in the deglacial methane budget*, SCIENCE 367(6480): 907–910, 908–909 (“Resulting CH_4 emissions from old permafrost carbon range from 0 to 53 Tg CH_4 per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH_4 emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)…. The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH…. Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH_4 emissions from old carbon reservoirs, such CH_4 emissions in response to anthropogenic warming also appear to be unlikely.”). *See also* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-80 (“The present-day methane release from shelf clathrates is <10 $TgCH_4$ yr^{-1} (Kretschmer et al., 2015; Saunois et al., 2020). Despite polar amplification (Chapter 7), substantial releases from the permafrost-embedded subsea clathrates is very unlikely (Minshull et al., 2016; Malakhova and Eliseev, 2017, 2020). This is consistent with an overall small release of methane from the shelf clathrates during the last deglacial despite large reorganisations in climate state (Bock et al., 2017; Petrenko et al., 2017; Dyonisius et al., 2020). The long timescales associated with clathrate destabilisation makes it unlikely that CH_4 release from the ocean to the atmosphere will deviate markedly from the present-day value through the 21st century (Hunter et al., 2013), corresponding to no more than additional 20 ppb of atmospheric methane (i.e. <0.2 ppb yr^{-1} 52).”).

[134] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 (“Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94).”). *See also* Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2023) *Global warming overshoots increase risks of climate tipping cascades in a network model*, NAT. CLIM. CHANG. 13: 75–82, 75 (“Current policies and actions make it very likely, at least temporarily, to overshoot the Paris climate targets of 1.5–<2.0 °C above pre-industrial levels. If this global warming range is exceeded, potential tipping elements such as the Greenland Ice Sheet and Amazon rainforest may be at increasing risk of crossing critical thresholds. This raises the question of how much this risk is amplified by increasing overshoot magnitude and duration. Here we investigate the danger for tipping under a range of temperature overshoot scenarios using a stylized network model of four interacting climate tipping elements. Our model analysis reveals that temporary overshoots can increase tipping risks by up to 72% compared with non-overshoot scenarios, even when the long-term equilibrium temperature stabilizes within the Paris range. Our results suggest that avoiding high-end climate risks is possible only for low-temperature overshoots and if long-term temperatures stabilize at or below today’s levels of global warming.”); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE

Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[135] DeConto R. M., Pollard D., Alley R. B., Velicogna I., Gasson E., Gomez N., Sadai S., Condron A., Gilford D. M., Ashe E. L., Kopp R. E., Li D., & Dutton A. (2021) *The Paris Climate Agreement and future sea-level rise from Antarctica*, Nature 593(7857): 83–89, 88 ("We find that without future warming beyond 2020, Antarctica continues to contribute to 21st-century sea-level rise at a rate roughly comparable to today's, producing 5 cm of GMSL (Global Mean Sea Level) rise by 2100 and 1.34 m by 2500 (Fig. 3, Table 1). Simulations initially following the +3 °C pathway, but with subsequent CDR (carbon dioxide reduction/negative emissions) delayed until after 2060, show a sharp jump in the pace of 21st-century sea-level rise (Fig. 3b). Every decade that CDR mitigation is delayed has a substantial long-term consequence on sea level, despite the fast decline in CO$_2$ and return to cooler temperatures (Fig. 3c). Once initiated, marine-based ice loss is found to be unstoppable on these timescales in all mitigation scenarios (Fig. 3). The commitment to sustained ice loss is caused mainly by the onset of marine ice instabilities triggered by the loss of ice shelves that cannot recover in a warmer ocean with long thermal memory (Fig. 3c)."). *See also* Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 °C global warming*, Nat. Clim. Change 8(12): 1053–1061, 1053 ("On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.").

[136] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BioSci. 71(9): 894–898, 896 ("Greenland and Antarctica recently showed new year-to-date alltime record low levels of ice mass (figure 2f, 2g). In 2020, the minimum summer Arctic sea ice was at its second smallest extent on record, and glacier thickness also set a new all-time low (figure 2e, 2h). Glaciers are melting much faster than previously believed; they are losing 31% more snow and ice per year than they did just 15 years ago (Hugonnet et al. 2021).").

[138] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, Nat. Clim. Change: 808–818, 809, 812 ("Application of the average 2000–2019, hereafter 'recent', climatology to Greenland's entire glacierized area of 1,783,090 km^2 gives an AAR/AAR$_0$ (α) disequilibrium with the current ice configuration corresponding with a $3.3 \pm 0.8\%$ committed area and volume loss. Taken in perpetuity, this imbalance with recent climate results in $59 \pm 15 \times 10^3$ km^2 of committed retreat of Greenland's ice area, equivalent to $110 \pm 27 \times 10^3$ km^3 of the ice sheet volume or 274 ± 68 mm of global eustatic SLR."; "Given the breadth and potency of those processes, we contend that known physical mechanisms can deliver most of the committed ice volume loss from Greenland's disequilibrium with its recent climate within this century. Nevertheless, we underscore that a SLR of at least 274 ± 68 mm is already committed, regardless of future climate warming scenarios."); *discussed in* Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, The Washington Post; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet's Terrifying Future*, Atmos.

[139] Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1308–1309 , 1302 ("[T]he main uncertainty related to high-end sea-level rise is "when" rather than "if" it arises: the upper limit of 1.02 m of *likely* sea-level range by 2100 for the SSP 5-8.5 scenario will be exceeded in any future warming scenario on time scales of centuries to millennia (*high confidence*), but it is uncertain how quickly the long-term committed sea level will be reached (Section 9.6.3.5). Hence, global-mean sea level might rise well above the *likely* range before 2100, which is reflected by assessments of ice-sheet contributions based on structured expert judgment (Bamber et al., 2019) leading to a 95th percentile of projected future sea-level rise as high as 2.3 m in 2100 (Section 9.6.3.3)… High-end sea-level rise can therefore occur if one or two processes related to ice-sheet collapse in Antarctica result in an additional sea-level rise at the maximum of their plausible ranges (Sections 9.4.2.5, 9.6.3.3; Table 9.7) or if several of the processes

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described in this box result in individual contributions to additional sea-level rise at moderate levels. In both cases, global-mean sea-level rise by 2100 would be substantially higher than the assessed *likely* range, as indicated by the projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile (Section 9.6.3.3).”; “While ice-sheet processes in whose projection there is *low confidence* have little influence up to 2100 on projections under SSP1-1.9 and SSP1-2.6 (Table 9.9), this is not the case under higher emissions scenarios, where they could lead to GMSL rise well above the *likely* range. In particular, under SSP5-8.5, *low confidence* processes could lead to a total GMSL rise of 0.6-1.6 m over this time period (17th-83rd percentile range of p-box including SEJ- and MICI-based projections), with 5th-95th percentile projections extending to 0.5-2.3 m (*low confidence*).”). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 19–20 (“As mentioned above, reduction of the GIS will likely require a millennium. Yet the weakening of ice shelf buttressing directly accelerates ice flow and discharge independent of MISI and MICI processes, with immediate implications for observed rates of sea-level rise. Consequently, under our current best understanding, Greenland and Antarctic ice-sheet collapse cannot be considered an abrupt or fast phenomenon in which most sea level impacts manifest within decades. Nevertheless, ice-sheet losses may contribute to regional sea level rise under RCP8.5 and worst-case scenarios that reaches 1–2 m for many cities globally by 2100, seriously threatening existing communities and infrastructure (Trisos et al., 2022). Over longer timescales, sustained high rates of global sea-level rise (>1 cm/yr by 2200, with further acceleration to up to a couple centimeters per year beyond) may broadly strain coastal adaptation efforts (Oppenheimer et al., 2019). At the same time, models indicate that strong climate mitigation may avert significant fractions of potential sea-level rise and prevent ice-sheet collapse across large regions. In several modeling studies the RCP2.6 scenario prevents collapse of the WAIS (Bulthuis et al., 2019; DeConto & Pollard, 2016) and may reduce the Antarctic contribution to global sea level rise by 2100 to 13 cm (Edwards et al., 2021).... Although significant uncertainties remain regarding the precise temperature thresholds that could trigger ice-sheet collapse, research to date suggests that aggressive climate mitigation could limit risks from ice-sheet instabilities (Table 4).”).

[140] Boers N. & Rypdal M. (2021) *Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point*, PROC. NAT'L. ACAD. SCI. 118(21): 1–7, 1 (“A crucial nonlinear mechanism for the existence of this tipping point is the positive melt-elevation feedback: Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. We reveal early-warning signals for a forthcoming critical transition from ice-core-derived height reconstructions and infer that the western Greenland Ice Sheet has been losing stability in response to rising temperatures. We show that the melt-elevation feedback is likely to be responsible for the observed destabilization. Our results suggest substantially enhanced melting in the near future.”). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 (“Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).”).

[141] Robinson A., Calov R., & Ganopolski A. (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NAT. CLIM. CHANGE 2(6): 429–432, 429 (“Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 ºC (1.9–5.1 ºC, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet’s ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold.”). *See also* Overland J., Dunlea E., Box J. E., Corell R., Forsius M., Kattsov V., Olsen M. S., Pawlak J., Reiersen L.-O., & Wang M. (2019) *The urgency of Arctic change*, POLAR SCI. 21: 6–13, 9 (“The summer air temperature “viability threshold” that triggers irreversible wastage of the Greenland ice sheet was previously estimated

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to be for an annual global temperature increase of 2–5 °C (Gregory and Huybrechts, 2006; Huybrechts et al., 2011). An updated estimate based on a higher resolution simulation that explicitly incorporates albedo and elevation feedbacks suggests a lower loss threshold: 0.8–3.2°C (95% confidence range) (Robinson et al., 2012) with 1.6 °C above pre-industrial conditions as a best estimate. It is likely that the Greenland ice sheet enters a phase of irreversible loss under the RCP 4.5 scenario."); Schleussner C.-F., Lissner T. K., Fischer E. M., Wohland J., Perrette M., Golly A., Rogelj J., Childers K., Schewe J., Frieler K., Menge M., Hare W., & Schaeffer M. (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, Earth Syst. Dynam. 7(2): 327–351, 342 ("In addition to that, Levermann et al. (2013) report a steep increase in long-term SLR between 1.5°C and 2°C as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson et al., 2012). The disintegration process that would lead to 5–7m global SLR, however, is projected to happen on the timescale of several millennia."); *and* Kopp R. E., Shwon R. L., Wagner G., & Yuan J. (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, Earth's Future 4(8): 346–372, 354–355 ("For the Greenland Ice Sheet, for example, feedbacks between ice sheet topography and atmospheric dynamics and between ice area and albedo give rise to multiple stable states [*Ridley et al*., 2009; *Robinson et al*., 2012; *Levermann et al*., 2013]. *Robinson et al*. [2012]'s coupled ice-sheet/regional climate model indicated that, at a temperature of 1ºC above pre-Industrial temperatures, the stable states are at 100%, 60%, and 20% of present ice volume. At 1.6ºC, however, their model produced only one stable configuration, at ~15% of the Greenland ice sheet's present volume; thus, 1.6°C warming would represent a commitment to ~6 m of sea-level rise from the Greenland Ice Sheet. The rate of ice sheet mass loss is, however, limited by the flux at the ice sheet margins [e.g., *Pfeffer et al*., 2008], leading to a disconnect between committed and realized change that could persist for millennia, particularly for levels of warming near the threshold [*Applegate et al*., 2015]."). If warming is limited to 2 °C, Greenland could contribute 5 cm of sea-level rise by 2050 and 13 cm by 2100, but if emissions are unabated and warming rises to 5 °C, Greenland could contribute 6 cm of sea-level rise by 2050 and 23 cm by 2100: *see* Bamber J. L., Oppenheimer M., Kopp R. E., Aspinall W. P., & Cooke R. M. (2019) *Ice sheet contributions to future sea-level rise from structured expert judgment*, Proc. Nat'l. Acad. Sci. 116(23): 11195–11200, 11197 (Table 1).

[142] Trusel L. D., Das S. B., Osman M. B., Evans M. J., Smith B. E., Fettweis X., McConnell J. R., Noël B. P. Y., & van den Broeke M. R. (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, Nature 564: 104–108, 104 ("Our results show a pronounced 250% to 575% increase in melt intensity over the last 20 years, relative to a pre-industrial baseline period (eighteenth century) for cores NU and CWG, respectively (Fig. 2). Furthermore, the most recent decade contained in the cores (2004– 2013) experienced a more sustained and greater magnitude of melt than any other 10-year period in the ice-core records. For GrIS cores, 2012 melt is unambiguously the strongest melt season on record. Both NU and CWG annual ice-core-derived melt records significantly ($P < 0.01$) correlate with one another over their 339 years of overlap, and both also with summer air temperatures from the Ilulissat region (Extended Data Table 2; Methods), relationships that improve after applying a 5-year moving average, probably reflecting the noise inherent to melt records owing to variability in meltwater percolation and refreezing. These empirically derived results revealing coherence between independent melt and temperature records emphasize broad-scale GrIS melt forcing, and suggest that summer warming (see Fig. 2) is an important component of the observed regional melt intensification.").

[143] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, Comm. Earth & Env't.: 1–7, 1 ("The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain. Here we combine more than three decades of remotely sensed observational products of outlet glacier velocity, elevation, and front position changes over the full ice sheet. We compare decadal variability in discharge and calving front position and find that increased glacier discharge was due almost entirely to the retreat of glacier fronts, rather than inland ice sheet processes, with a remarkably consistent speedup of 4–5% per km of retreat across the ice sheet. We show that widespread retreat between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt."). When compared to the projections of the IPCC Fifth Assessment Report, the associated sea-level rise from the recent ice sheet melting of both Greenland and Antarctica is most like the upper range projections: *see* Slater T., Hogg A. E., & Mottram R. (2020) *Ice-sheet losses track high-end sea-level rise projections*, Comment, Nat. Clim. Change 10: 879–881, 881 ("In AR5, the ice-sheet contribution by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming. Driven by the century-scale increase in temperature forced by representative

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concentration pathways (RCPs), global mean SLR estimates range from 280–980 mm by 2100 (Fig. 1). Of this, the ice-sheet contribution constitutes 4–420 mm (ref. 3). The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Fig. 1). During 2007–2017, satellite observations show total ice-sheet losses increased the global sea level by 12.3 ± 2.3 mm and track closest to the AR5 upper range (13.7–14.1 mm for all emissions pathways) (Fig. 1). Despite a reduction in ice-sheet losses during 2013–2017 — when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall2 — the observed average SLR rate (1.23 ± 0.24 mm per year) is 45% above central predictions (0.85 ± 0.07 mm per year) and closest to the upper range (1.39 ± 0.14 mm per year) (Fig. 2).”). In mid-September 2020, consistent warming over northeast Greenland contributed to a large chunk of a glacier breaking away from the Arctic’s largest remaining ice shelf: *see* Amos J. (14 September 2020) *Climate change: Warmth shatters section of Greenland ice shelf*, BBC NEWS (“A big chunk of ice has broken away from the Arctic's largest remaining ice shelf - 79N, or Nioghalvfjerdsfjorden - in north-east Greenland. The ejected section covers about 110 square km; satellite imagery shows it to have shattered into many small pieces. The loss is further evidence say scientists of the rapid climate changes taking place in Greenland. … At its leading edge, the 79N glacier splits in two, with a minor offshoot turning directly north. It's this offshoot, or tributary, called Spalte Glacier, that has now disintegrated. The ice feature was already heavily fractured in 2019; this summer's warmth has been its final undoing. Spalte Glacier has become a flotilla of icebergs.”).

[144] Ramirez R. (30 July 2021) *The amount of Greenland ice that melted on Tuesday could cover Florida in 2 inches of water*, CNN (“Greenland is experiencing its most significant melting event of the year as temperatures in the Arctic surge. The amount of ice that melted on Tuesday alone would be enough to cover the entire state of Florida in two inches of water.”).

[145] Robinson A., Calov R., & Ganopolski A. (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NAT. CLIM. CHANGE 2(6): 429–432, 429 (“Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 ºC (1.9–5.1 ºC, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet’s ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold.”).

[146] National Snow & Ice Data Center (18 August 2021) *Rain at the summit of Greenland*, GREENLAND ICE SHEET TODAY (“On August 14, 2021, rain was observed at the highest point on the Greenland Ice Sheet for several hours, and air temperatures remained above freezing for about nine hours. This was the third time in less than a decade, and the latest date in the year on record, that the National Science Foundation’s Summit Station had above-freezing temperatures and wet snow. There is no previous report of rainfall at this location (72.58°N 38.46°W), which reaches 3,216 meters (10,551 feet) in elevation.”).

[147] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, NAT. CLIM. CHANGE: 808–816, 808 (“Ice loss from the Greenland ice sheet is one of the largest sources of contemporary sea-level rise (SLR). While process-based models place timescales on Greenland’s deglaciation, their confidence is obscured by model shortcomings including imprecise atmospheric and oceanic couplings. Here, we present a complementary approach resolving ice sheet disequilibrium with climate constrained by satellite-derived bare-ice extent, tidewater sector ice flow discharge and surface mass balance data. We find that Greenland ice imbalance with the recent (2000–2019) climate commits at least 274 ± 68 mm [10.8 ± 2.7 in] SLR from 59 ± 15 × 103 km^2 ice retreat, equivalent to 3.3 ± 0.9% volume loss, regardless of twenty-first-century climate pathways. This is a result of increasing mass turnover from precipitation, ice flow discharge and meltwater run-off. The high-melt year of 2012 applied in perpetuity yields an ice loss commitment of 782 ± 135 mm [30.8 ± 5.3 in] SLR, serving as an ominous prognosis for Greenland’s trajectory through a twenty-first century of warming.”); *discussed*

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in Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, The Washington Post; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet's Terrifying Future*, Atmos.

[148] Smeed D. A., Josey S. A., Beaulieu C., Johns W. E., Moat B. I., Frajka-Williams E., Rayner D., Meinen C. S., Baringer M. O., Bryden H. L., & McCarthy G. D. (2018) *The North Atlantic Ocean Is in a State of Reduced Overturning*, Geophys. Res. Lett. 45(3): 1527–1533, 1527 ("Using data from an array of instruments that span the Atlantic at 26°N, we show that the AMOC has been in a state of reduced overturning since 2008 as compared to 2004–2008. This change of AMOC state is concurrent with other changes in the North Atlantic such as a northward shift and broadening of the Gulf Stream and altered patterns of heat content and sea surface temperature. These changes resemble the response to a declining AMOC predicted by coupled climate models.").

[149] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 5, 7, 8 ("Model simulations of the abovementioned paleoclimate changes indicate that the AMOC may have transitioned rapidly between different modes during past climates, including potentially bistable behaviors. Driven by the salt-advection feedback (Stommel, 1961), the AMOC could switch between "on" and "off" states under natural perturbations such as deglacial meltwater pulses when the ocean system passes certain tipping points.…The AMOC also may have shifted between different modes during Dansgaard-Oeschger events in response to changes in freshwater forcing, rapidly transitioning to a marginally unstable "warm" mode associated with a northward shift of the deep-water formation site and more intense convection, in contrast to flip-ping between an "on" and "off" state (Ganopolski & Rahmstorf, 2001). Moreover, based on an AMOC stability indicator (de Vries & Weber, 2005; W. Liu & Liu, 2013; Rahmstorf, 1996), analyses of modern observations suggest that the current AMOC resides in a bi-stable regime. The circulation may be at risk of an eventual collapse under future anthropogenic warming, as the possibility of an AMOC collapse could be downplayed currently by most coupled climate models due largely to a ubiquitous model bias toward AMOC stability (W. Liu et al., 2014, 2017)."; "("Troublingly, defining particular critical temperature thresholds expected to contribute to committed weakening of the overturning circulation also represents a challenge (Weijer et al., 2019). Hoegh-Guldberg et al. (2018) determined a higher likelihood of more intense weakening for >2°C of warming based on model predictions. Committed loss of the GIS is more likely than not to occur beyond a 2°C warming threshold (Pattyn et al., 2018), with the IPCC expressing *medium confidence* regarding long-term near-complete loss of Greenland ice for sustained warming of 3°C or more (IPCC, 2021). As loss of significant volumes of Greenland ice carries important implications for buoyancy dynamics in deep water formation regions, the IPCC's assessment of a 2°C threshold seems a plausible lower bound above which the risks of significant weakening of the AMOC increase. A recent paper suggests that even small, incremental changes in freshwater forcing could drive AMOC collapse if the rate of forcing is sufficiently rapid (Lohmann & Ditlevsen, 2021). However, the current ability of models to accurately represent the AMOC and predict its response to climate change remains low, leaving the proximity of today's AMOC to potential critical thresholds uncertain (Weijer et al., 2019)."; "Taken together, the possibility that the overturning circulation is currently weakening and may weaken further with continuing warming is sufficiently backed by recent research to justify the degree of past and ongoing attention devoted to this potential tipping element."); Boers N. (2021) *Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation*, Nat. Clim. Change 11(8): 680–688, 687 ("The results presented here hence show that the recently discovered AMOC decline during the last decades is not just a fluctuation related to low-frequency climate variability or a linear response to increasing temperatures. Rather, the presented findings suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that the AMOC could be close to a critical transition to its weak circulation mode."); *and* Ritchie P. D. L., Clarke J. J., Cox P. M., & Huntingford C. (2021) *Overshooting tipping point thresholds in a changing climate*, Nature 592(7855): 517–523, 522 ("Our analysis reveals that for many climate tipping points it is possible to cross a threshold temporarily without triggering tipping to a different system state. This finding is particularly relevant for potential slow-onset tipping elements such as ice-sheet melt or collapse of the AMOC. Hence, the point of no return for a slow-onset tipping element is not the threshold but some point beyond the threshold. How far this point is beyond the threshold is determined by three factors: (1) the effective timescale of the system, (2) how fast global warming can be reduced and (3) the level at which warming stabilizes.").

[150] Douville H., *et al*. (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1055–1210, 1148 ("These patterns of past hydroclimatic change are relevant for future projections because it is *very likely* that AMOC will weaken by 2100 in response to increased

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greenhouse gas emissions (Weaver et al., 2012; Drijfhout et al., 2015; Bakker et al., 2016; Reintges et al., 2017) (See also Section 9.2.3.1). Furthermore, there is *medium confidence* that the decline in AMOC will not involve an abrupt collapse before 2100 (Section 9.2.3.1).”). *See also* Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 73 (“While there is *medium confidence* that the projected decline in the Atlantic Meridional Overturning Circulation (AMOC) (TS.2.4) will not involve an abrupt collapse before 2100, such a collapse might be triggered by an unexpected meltwater influx from the Greenland Ice Sheet. If an AMOC collapse were to occur, it would *very likely* cause abrupt shifts in the weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons.”); Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1211–1261, 1239 (“Both the AR5 (Collins et al., 2013) and the SROCC (Collins et al., 2019) assessed that an abrupt collapse of the AMOC before 2100 was *very unlikely*, but the SROCC added that by 2300 an AMOC collapse was *as likely as not* for high-emission scenarios. The SROCC also assessed that model-bias may considerably affect the sensitivity of the modelled AMOC to freshwater forcing. Tuning towards stability and model biases (Valdes, 2011; Liu et al., 2017; Mecking et al., 2017; Weijer et al., 2019) provides CMIP models a tendency toward unrealistic stability (*medium confidence*). By correcting for existing salinity biases, Liu et al. (2017) demonstrated that AMOC behaviour may change dramatically on centennial to millennial timescales and that the probability of a collapsed state increases. None of the CMIP6 models features an abrupt AMOC collapse in the 21st century, but they neglect meltwater release from the Greenland ice sheet and a recent process study reveals that a collapse of the AMOC can be induced even by small-amplitude changes in freshwater forcing (Lohmann and Ditlevsen, 2021). As a result, we change the assessment of an abrupt collapse before 2100 to *medium confidence* that it will not occur.”); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 1-85, 43 (“The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities.”).

[151] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1148–1149 (“As with the paleoclimate events, AMOC collapse results in a southward shift in the ITCZ that is most pronounced in the tropical Atlantic. This could cause drying in the Sahel region (Defrance et al., 2017) as well as Mesoamerica and northern Amazonia (Parsons et al., 2014; Chen et al., 2018c). AMOC collapse also causes the Asian monsoon systems to weaken (Liu et al., 2017b) (Figure 8.27b) counteracting the strengthening expected in response to elevated greenhouse gases (see Section 8.4.2). Europe is projected to experience moderate drying in response to AMOC collapse (Jackson et al., 2015)”); *discussed in* Velasquez-Manoff M. & White J. (3 March 2021) *In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers*, The New York Times (“The consequences could include faster sea level rise along parts of the Eastern United States and parts of Europe, stronger hurricanes barreling into the Southeastern United States, and perhaps most ominously, reduced rainfall across the Sahel, a semi-arid swath of land running the width of Africa that is already a geopolitical tinderbox.”).

[152] Sweet W. V., *et al.* (2022) Global and Regional Sea Level Rise Scenarios for the United States: *Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*, National Oceanic and Atmospheric Administration Technical Report NOS 01, 40 (“By 2050, moderate HTF frequencies nationally are projected to increase by more than a factor of 10, with about a factor of 5 increase in major HTF frequencies. In short, assuming continuation of current trends and summarized at the national level, a flood regime shift is projected by 2050, with moderate HTF occurring a bit more frequently than minor HTF events occur today and major HTF events occurring about as frequently as moderate HTF frequencies occur today”).

[153] Orihuela-Pinto B., England M. H., & Taschetto A. S. (2022) *Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation*, Nat. Clim. Chang. 12(6): 558–565, 558 (“We find that an AMOC collapse drives

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a complex rearrangement of the global atmospheric circulation that affects all latitudes, from the tropics to the polar circulation of both hemispheres. We find that changes in the tropical Pacific involve a robust intensification of the Walker circulation, a weakening of the subtropical highs in the Southern Hemisphere and an intensification of the Amundsen Sea Low over west Antarctica."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 43 ("The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 5, 32–33 ("A slowdown or shutdown of the AMOC system would significantly affect regional and global climate patterns (L. C. Jackson et al., 2015; W. Liu et al., 2020). Paleoclimate evidence and numerical simulations have identified AMOC transitions and/or latitudi-nal shift of deep-water formation sites as potential drivers of multiple large, rapid shifts in past climate, including fast or abrupt changes occurring on timescales as short as a few decades (Alley et al., 2001; Bozbiyik et al., 2011; Brovkin et al., 2021; Clark et al., 2001; Ganopolski & Rahmstorf, 2001; Rahmstorf, 2002). The impacts of past AMOC shifts affected climate globally, significantly altering tropical rainfall patterns and causing heat redis-tribution between the northern and southern hemispheres (S. Li & Liu, 2022; Masson-Delmotte et al., 2013). Changes to the overturning circulation could also affect the ocean's strength as a heat and carbon sink (X. Chen & Tung, 2018; Fontela et al., 2016; Nielsen et al., 2019; Romanou et al., 2017) and heat redistribution (S. Li & Liu, 2022; W. Liu & Fedorov, 2019; X. Ma et al., 2020)."; "In Heinrich events, for example, large discharges of fresh ice from the Laurentide ice sheet into the North Atlantic are hypothesized to have been associated with slowing of the AMOC and cooling of the entire north-ern hemisphere, resulting in a shift of tropical precipitation maxima southward to dry and weaken the West African and South Asian summer monsoons while enhancing South American monsoon precipitation (Chiang & Bitz, 2005; Deplazes et al., 2013; Schneider et al., 2014; X. Wang et al., 2004). In these sorts of scenarios, monsoons may be responding predictably and even linearly to the abrupt forcing of extratropical climate; synchronous changes in insolation may "pace" or "trigger" these changes (Cheng et al., 2016), but the nonlinear response may originate in midlatitude ocean-atmosphere dynamics. Such scenarios bear important lessons for the possible response of monsoons to abrupt changes in the Greenland or Antarctic ice sheets or the Atlantic Meridional Overturning Circulation.").

[154] Scambos T. & Weeman K. (13 December 2021) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("The glacier is the size of Florida or Britain and currently contributes four percent of annual global sea level rise. If it does collapse, global sea levels would rise by several feet—putting millions of people living in coastal cities in danger zones for extreme flooding. 'Thwaites is the widest glacier in the world,' said Ted Scambos, a senior research scientist at the Cooperative Institute for Research in Environmental Sciences (CIRES). 'It's doubled its outflow speed within the last 30 years, and the glacier in its entirety holds enough water to raise sea level by over two feet. And it could lead to even more sea-level rise, up to 10 feet, if it draws the surrounding glaciers with it.'"). *See also* Rignot E., Mouginot J., Scheuchl B., van den Broeke M., van Wessem M. J., & Morlighem M. (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*, Proc. Nat'l. Acad. Sci. 116(4): 1095–1103, 1096 (Table 1 gives 65 cm sea-level equivalent (SLE) for Thwaites glacier).

[155] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, Nat. Geosci. 13: 132–137, 134 ("We do not find major bumps in bed topography upstream of the current grounding line that could stop the grounding line retreat, except for two prominent ridges ~35 and 50 km upstream (red lines, Fig. 2a). Ice sheet numerical models indicate that once the glacier retreats past the second ridge, the retreat of Thwaites Glacier would become unstoppable[18,19,20]."). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, Science Alert.

[156] Graham A. G. C., Wåhlin A., Hogan K. A., Nitsche F. O., Heywood K. J., Totten R. L., Smith J. A., Hillenbrand C.-D., Simkins L. M., Anderson J. B., Wellner J. S., & Larter R. D. (2022) *Rapid retreat of Thwaites Glacier in the pre-satellite era*, Nat. Geosci. 15: 706–713, 706 ("Understanding the recent history of Thwaites Glacier, and the processes controlling its ongoing retreat, is key to projecting Antarctic contributions to future sea-level rise. Of

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particular concern is how the glacier grounding zone might evolve over coming decades where it is stabilized by sea-floor bathymetric highs. Here we use geophysical data from an autonomous underwater vehicle deployed at the Thwaites Glacier ice front, to document the ocean-floor imprint of past retreat from a sea-bed promontory. We show patterns of back-stepping sedimentary ridges formed daily by a mechanism of tidal lifting and settling at the grounding line at a time when Thwaites Glacier was more advanced than it is today. Over a duration of 5.5 months, Thwaites grounding zone retreated at a rate of >2.1 km per year—twice the rate observed by satellite at the fastest retreating part of the grounding zone between 2011 and 2019. Our results suggest that sustained pulses of rapid retreat have occurred at Thwaites Glacier in the past two centuries. Similar rapid retreat pulses are likely to occur in the near future when the grounding zone migrates back off stabilizing high points on the sea floor."); *discussed in* University of South Florida (5 September 2022) *Faster in the Past: New seafloor images of West Antarctic Ice Sheet upend understanding of Thwaites Glacier retreat*, SCIENCEDAILY.

[157] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, NAT. GEOSCI. 13: 132–137; *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 14 February 2023) ("**7. Thwaites Glacier ice loss currently contributes around 4% of all global sea-level rise** (assuming 3.5 mm annual sea-level rise) and has the potential to contribute significantly more.").

[158] Groh A., & Horwath M. (2021) *Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels*, REMOTE SENS. 13(9): 1736, 1–25; *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 13 June 2023) ("**10. Since 2000, the glacier has had a net loss of more than 1000 billion tons of ice.** … **11. The amount of ice loss has doubled over the last 30 years** by Thwaites and its neighbouring glaciers.").

[159] Witze A. (11 January 2022) *Giant cracks push imperilled Antarctic glacier closer to collapse*, NATURE NEWS ("The fractures are propagating through the ice at speeds of several kilometres per year. They are heading into weaker and thinner ice, where they could accelerate and lead to the demise of this part of the ice shelf within five years, Pettit estimates."). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, SCIENCE ALERT ("But scientists have just confirmed that this ice shelf is becoming rapidly destabilized. The eastern ice shelf now has cracks crisscrossing its surface and could collapse within ten years, according to Erin Pettit, a glaciologist at Oregon State University. This work supports research published in 2020 which also noted the development of cracks and crevasses on the Thwaites ice shelf. These indicate that it is being structurally weakened. This damage can have a reinforcing feedback effect because cracking and fracturing can promote further weakening, priming the ice shelf for disintegration."); Scambos T. & Weeman K. (13 December 2021, updated 31 January 2022) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("Thwaites sits in West Antarctica, flowing across a 120km stretch of frozen coastline. A third of the glacier, along its eastern side, flows more slowly than the rest—it's braced by a floating ice shelf, a floating extension of the glacier that is held in place by an underwater mountain. The ice shelf acts like a brace that prevents faster flow of the upstream ice. But the brace of ice slowing Thwaites won't last for long, said Erin Petitt, an associate professor at Oregon State University. Beneath the surface, warmer ocean water circulating beneath the floating eastern side is attacking this glacier from all angles, her team has found. This water is melting the ice directly from beneath, and as it does so, the glacier loses its grip on the underwater mountain. Massive factures have formed and are growing as well, accelerating its demise, said Pettit. This floating extension of the Thwaites Glacier will likely survive only a few more years."; "The "chain reaction," beginning with the potential collapse of Thwaites' Eastern Ice Shelf would set in motion a long-term process which would eventually result in global sea level rise. While the initial steps of ice shelf collapse, glacier speed-up, and increased ice-cliff failure might happen within a couple of decades, the "2 to 10 feet" of sea level rise will require centuries to unfold—and impacts can still be mitigated depending on how humans respond in coming decades. Risk of multiple feet of sea level rise will not happen this decade (and likely not even in the next few decades)."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 6: 1–81, 16 ("The observational record has established the predominant role of ocean-driven subsurface melt at the base of ice shelves, leading to the thinning and retreat of Antarctic ice shelves (Khazendar et al., 2016; Y. Liu et al., 2015; Wouters et al., 2015). Shifts in atmospheric circulation have driven increased intrusions of warm Circumpolar Deep Water (CDW) onto the continental shelf at depths of several hundred meters, promoting the melt of basal ice (Jenkins et al., 2016). As ice shelves also provide a supportive "buttressing" effect that opposes and slows the rate of ice flux to sea, loss of ice shelf mass itself accelerates flow from ice streams and enhances

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discharge of ice into the ocean (Schoof, 2007). Ocean warming in combination with physical stresses can also drive an ice shelf damage feedback in which crevasses and fractures develop within the ice shelves buttressing outlet glaciers of the AIS, accelerating ice loss and further exacerbating damage (Lhermitte et al., 2020). Patterns of ice loss have been influenced partly by natural tropical variability (Jenkins et al., 2016) but are also driven by anthropogenically forced shifts in regional winds and positive feedbacks from the ungrounding of ice sheets (P. R. Holland et al., 2019).").

[160] Cheng L., Abraham J., Hausfather Z., & Trenberth K. E. (2019) *How fast are the oceans warming?*, Science 363(6423): 128–129, 128 ("About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 11 ("It is virtually certain that the global upper ocean (0-700m) has warmed since the 1970s and extremely likely that human influence is the main driver. Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*)."); von Schuckmann K., *et. al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?,* Earth System Science Data 15(4): 1675–1709, 1677 ("Here we show that the Earth system has continued to accumulate heat, with 381±61 ZJ accumulated from 1971 to 2020. This is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2}. The majority, about 89 %, of this heat is stored in the ocean, followed by about 6 % on land, 1 % in the atmosphere, and about 4 % available for melting the cryosphere. Over the most recent period (2006–2020), the EEI amounts to 0.76±0.2 W m^{-2}. The Earth energy imbalance is the most fundamental global climate indicator that the scientific community and the public can use as the measure of how well the world is doing in the task of bringing anthropogenic climate change under control. Moreover, this indicator is highly complementary to other established ones like global mean surface temperature as it represents a robust measure of the rate of climate change and its future commitment.").

[161] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, Proc. Nat'l. Acad. Sci. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions."). *See also* MacDougall A. H., *et al.* (2020) *Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from* CO_2, Biogeosci. 17(11): 2987–3016, 3003 ("Overall, the most likely value of ZEC on decadal timescales is assessed to be close to zero, consistent with prior work. However, substantial continued warming for decades or centuries following cessation of emissions is a feature of a minority of the assessed models and thus cannot be ruled out purely on the basis of models."); Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 55 (Figure 16); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).").

[162] Cheng L., Foster G., Hausfather Z., Trenberth K. E., & Abraham J. (2022) *Improved Quantification of the Rate of Ocean Warming*, J. Clim. 35(14): 4827–4840, 4836 ("A robust increase of ocean warming for the upper 2000 m has occurred since 1958 from about 0 to 0.06 ± 0.08 W m^{-2} for 1958–73 to 0.58 ± 0.08 W m^{-2} in 2003–18. With the new methods, the rates of OHC change and EEI since 1958 have been recalculated and updated. The total ocean warming for the upper 2000 m is 341.3 ± 21.0 ZJ from 1958 to 2020 (with the 95% confidence interval). The new estimate suggests a dramatic increase of ocean heat uptake and EEI from 1980s to early 2000s. For the most recent period with

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better data quality (2005–19) and another estimate of land–ice–atmosphere heat content (Trenberth 2022), the EEI is estimated to 153.9 ZJ (10.99 ZJ yr^{-1}) with the ocean heat uptake of 139.7 ZJ (9.98 ZJ yr^{-1}) for 2005–19. This estimate is slightly lower than that using von Schuckmann et al. (2020) in Fig. 8, indicating uncertainty in land–ice–atmosphere heat content.").

[163] Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 74 ("It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory (TS.3.1). The ocean is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*), with warming extending to depths well below 2000 m (*very high confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*), and will *likely* continue until at least to 2300 even for low CO_2 emissions scenarios. Ocean warming is irreversible over centuries to millennia (*medium confidence*), but the magnitude of warming is scenario-dependent from about the mid-21st century (*medium confidence*)... Global mean SST has increased since the beginning of the 20th century by 0.88 [0.68 to 1.01] °C, and it is *virtually certain* it will continue to increase throughout the 21st century with increasing hazards to marine ecosystems (*medium confidence*). Marine heatwaves have become more frequent over the 20th century (*high confidence*), approximately doubling in frequency (*high confidence*) and becoming more intense and longer since the 1980s (*medium confidence*).").

[164] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 24 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."); Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8822 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, Proc. Nat'l. Acad. Sci. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); *and* United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld

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2009), although most of the nearterm warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.”).

[165] Climate scientist and IPCC author Joeri Rogelj, *as quoted in* Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, Inside Climate News (“James Hansen, a climate scientist who shook Washington when he told Congress 33 years ago that human emissions of greenhouse gases were cooking the planet, is now warning that he expects the rate of global warming to double in the next 20 years. While still warning that it is carbon dioxide and methane that are driving global warming, Hansen said that, in this case, warming is being accelerated by the decline of other industrial pollutants that they’ve cleaned from it…. In Hansen’s latest warning, he said scientists are dangerously underestimating the climate impact of reducing sulfate aerosol pollution. ‘Something is going on in addition to greenhouse warming,’ Hansen wrote, noting that July’s average global temperature soared to its second-highest reading on record even though the Pacific Ocean is in a cooling La Niña phase that temporarily dampens signs of warming. Between now and 2040, he wrote that he expects the climate’s rate of warming to double in an ‘acceleration that can be traced to aerosols.’ That acceleration could lead to total warming of 2 degrees Celsius by 2040, the upper limit of the temperature range that countries in the Paris accord agreed was needed to prevent disastrous impacts from climate change. What’s more, Hansen and other researchers said the processes leading to the acceleration are not adequately measured, and some of the tools needed to gauge them aren’t even in place…. A doubling of the rate of global warming would put the planet in the fast lane of glacial melting, sea level rise and coral reef ecosystem die-offs, as well as escalating heatwaves, droughts and floods. But that future is not yet set in stone, said Michael Mann, a climate scientist at Penn State. He said Hansen’s prediction appears inconsistent with the scientific literature assessed by the Intergovernmental Panel on Climate Change. The IPCC’s latest report advises “that reductions of carbon emissions by 50 percent over the next decade and net-zero by 2100, along with a ramp-down in both aerosols and other short-term agents, including black carbon and other trace anthropogenic greenhouse gases, stabilizes warming well below 2 degrees Celsius,” Mann said. But the IPCC report also highlighted that declining aerosol pollution will speed warming. “The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO2, will result in an increase in the resulting rate of warming,” said climate scientist and IPCC report author Joeri Rogelj, director of research at the Imperial College London’s Grantham Institute. There’s a fix for at least some of this short-term increase in the rate of warming, he said. “The only measures that can counteract this increased rate of warming over the next decades are methane reductions,” Rogelj said. “I just want to highlight that methane reductions have always been part of the portfolio of greenhouse gas emissions reductions that are necessary to meet the goals of the Paris Agreement. This new evidence only further emphasizes this need.”).

[166] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, Proc. Nat’l. Acad. Sci. 116(15): 7192–7197, 7194 (“Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO_2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22).”). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7 (Figure SPM.2c shows that Sulphur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900); Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestvedt J. S., Osprey S., & Schleussner C.-F. (2018) *Climate impacts from a removal of anthropogenic aerosol emissions*, Geophys. Res. Lett. 45(2): 1020–1029, 1020 (“Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission with GHG, and measures to improve air quality. … Removing aerosols induces a global mean surface heating of 0.5–

1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. … "Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there."); *and* Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in CO_2 and non-CO_2 forcing*, Environ. Res. Lett. 14(4): 1–11.

[167] Bodansky D. & Pomerance R. (2021) *Sustaining the Arctic in Order to Sustain the Global Climate System*, Sustainability 13(19): 1–5, 3 ("Volcanic eruptions provide proof-of-concept that stratospheric aerosols cool the planet. The sulfur aerosols injected into the stratosphere by the eruption of Mount Pinatubo in 1991 cooled the planet by about 0.5 °C."). *See also* NASA Earth Observatory (2001) *Global Effects of Mount Pinatubo* ("Pinatubo injected about 15 million tons of sulfur dioxide into the stratosphere, where it reacted with water to form a hazy layer of aerosol particles composed primarily of sulfuric acid droplets. Over the course of the next two years strong stratospheric winds spread these aerosol particles around the globe.… In the case of Mount Pinatubo, the result was a measurable cooling of the Earth's surface for a period of almost two years. Because they scatter and absorb incoming sunlight, aerosol particles exert a cooling effect on the Earth's surface. The Pinatubo eruption increased aerosol optical depth in the stratosphere by a factor of 10 to 100 times normal levels measured prior to the eruption. ("Aerosol optical depth" is a measure of how much light airborne particles prevent from passing through a column of atmosphere.) Consequently, over the next 15 months, scientists measured a drop in the average global temperature of about 1 degree F (0.6 degrees C)."); *and* Dutton E. G. & Christy J. R. (1992) *Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo*, Geophys. Res. Lett. 19(23): 2313–2316, 2313 ("By September 1992 the global and northern hemispheric lower tropospheric temperatures had decreased 0.5°C and 0.7°C, respectively compared to pre-Pinatubo levels.").

[168] Quaas J., *et al.* (2022) *Robust evidence for reversal of the trend in aerosol effective climate forcing*, Atmos. Chem. Phys. 22(18): 12221–12239, 12231 ("In conclusion, there are clear, robust and consistent signals for net declining anthropogenic aerosol influence on climate in the period since 2000, i.e. the period, for which high-quality satellite retrievals of all relevant quantities are available. The regions in which aerosol emissions declined (in particular North America, Europe and East Asia) dominate over regions with increasing trends. …The overall climate-relevant signal is a decline in negative [aerosol effective radiative forcing] by about 0.1 to 0.3 W $m^{-2,}$ i.e. between 15 and 50% of the 0.6 W m^{-2} increase in CO_2 ERF (Forster et al., 2021) in the same time period. This signal will most likely continue in the future, increasing the urgency for strong measures on reducing greenhouse gas emissions (McKenna et al., 2021).").

[169] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

[170] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10320, Table S1 ("Hence, the CO_2 measures implemented in 2020 will unmask some of the aerosol cooling (red lines in SI Appendix, Fig. S5) and offset the warming reduction by CO_2 and SLCP mitigation. In the baseline scenarios of this study, the cooling aerosols are regulated gradually between 2020 and 2100 (SI Appendix, Fig. S6), whereas in the mitigation scenario examined here, CO_2 mitigation is implemented starting from 2020 and CO_2 emission is brought to net zero in about three decades (SI Appendix, Fig. S2B). As a result, the unmasking of coemitted aerosol cooling (a net warming effect) is more rapid in the decreasing CO_2 emissions beginning in 2020 (CN2020) mitigation scenario (SI Appendix, Fig. S5B vs. S7)."; Table S1 [graph depicting warming potential based on cumulative emissions from CO_2 only, aerosols only, and short-lived climate pollutants only from the 1970's into the 2090's]). *See also* Xu Y. (2020, personal communication). The baseline-fast warming scenario against which these mitigation scenarios are compared includes "unmasking" as emissions of cooling aerosols are reduced in the baseline-fast (RCP6.0) scenarios. If these aerosol emissions continued at current emission levels, undesired from air quality perspective, the warming in 2100 would be 0.6°C smaller.

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[171] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39): 10315–10323, Supplemental Information, 1 (“In the Baseline-default scenario for CO_2, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO_2 (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO_2 (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a).”).

[172] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39): 10315–10323, Supplemental Information, 1 (“In the Baseline-default scenario for CO_2, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO_2 (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO_2 (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a). The CN2020 scenario is the same as CN2030, except that the peak of emission is reached at 2020 (Fig. S2b).”). *See also Id.* Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

[173] Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, 409–410, Addendum “Methods” (“These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of the reduction in CO_2, SO_2 and CH_4 roughly balance one another until about 2035. After this, the cooling effects of reduced CO_2 continue to increase, whereas the warming induced by a reduction in SO_2 and the cooling induced by the reduction in CH_4 taper off, such that the cooling induced by the reduction in CO_2 dominates (Fig. 3). Examining the effects of CO_2 and SO_2 alone (Fig. 3d), the faster response of SO_2 to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO_2) during the gradual fossil phase-out, as well as the response to historical emissions.”; “We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.”). *See also* Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT’L. ACAD. SCI. 116(15): 7192–7197, 7194 (“Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH_4), O_3, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH_4 emissions constitute nearly 20% of the total source, and removing all anthropogenic CH_4 (nearly 60% of the source), in addition to anthropogenic O_3, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals.”)

[174] Intergovernmental Panel on Climate Change (2023) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 27 (“Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality. (Figure SPM.10, Table SPM.2)”. *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden

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M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 59 ("Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near-term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*) The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*).").

[175] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013)).") . *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, Nature 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.").

[176] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): 1–8, 5 ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[177] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10321 ("The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface

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temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).").

[178] Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, Science 335(6065): 183–189, 183–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. …Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases.… BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic)."). *See also* United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."; "Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.").

[179] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 17 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)").

[180] Allen M. R., Dube O. P., Solecki W., Aragón-Durand F., Cramer W., Humphreys S., Kainuma M., Kala J., Mahowald N., Mulugetta Y., Perez R., Wairiu M., & Zickfeld K. (2018) *Chapter 1: Framing and Context*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 61 ("If emission reductions do not begin until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO_2 emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO_2 forcing and these pathways also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year's delay before initiating emission reductions decreases by approximately two years the remaining time available to reach zero emissions on a pathway still remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018)."). *See also* United Nations Environment Programme & Climate

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& Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 20 ("For the 2015 United Nations (UN) Paris Agreement to succeed, reducing anthropogenic methane in addition to carbon dioxide is paramount. Currently the largest contributor to the departure from an idealized path to the 2°C target used in the IPCC's Fifth Assessment Report is the growth in methane amounts (Figure 1.3). Achieving the more stringent 1.5°C target requires even larger decreases in methane. The IPCC's 2018 Special Report concluded that reaching a sustainable mitigation pathway to 1.5˚ C can only be achieved with deep and simultaneous reductions of carbon dioxide and all non-carbon dioxide climate forcing emissions, including short-lived climate pollutants such as methane.").

[181] Shindell D. T., Borgford-Parnell N., Brauer M., Haines A., Kuylenstierna J. C. I., Leonard S. A., Ramanathan V., Ravishankara A., Amann M., & Srivastava L. (2017) *A climate policy pathway for near- and long-term benefits*, Science 356(6337): 493–494.

[182] Ripple W. J., Wolf C., Newsome T. M., Barnard P., & Moomaw W. R. (2020) *World Scientists' Warning of a Climate Emergency*, BioSci. 70: 8–12.

[183] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BioSci. 71(9): 894–898, 897 ("Given the impacts we are seeing at roughly 1.25 degrees Celsius (°C) warming, combined with the many reinforcing feedback loops and potential tipping points, massive-scale climate action is urgently needed. The remaining carbon budget for 1.5°C was recently estimated to have a 17% chance of being negative, indicating that we may already have lost the opportunity to limit warming to this level without overshoot or risky geoengineering (Matthews et al. 2021). Because of the limited time available, priorities must shift toward immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane (UNEP/CCAC 2021).").

[184] Parties to the United Nations Framework Convention on Climate Change are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶47 (2019) ("47. Each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the GHG inventory throughout the reported period on a gas-by-gas basis in units of mass at the most disaggregated level, in accordance with the IPCC guidelines referred to in paragraph 20 above, using the common reporting tables, including a descriptive summary and figures underlying emission trends, with emissions by sources listed separately from removals by sinks, except in cases where it may be technically impossible to separate information on emissions and removals in the LULUCF sector, and noting that a minimum level of aggregation is needed to protect confidential business and military information."). *See also* Allen M. R., *et al.* (2022) *Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets*, npj Clim. Atmos. Sci. 5(5): 1–4, 1 ("As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO_2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO_2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties' Decision (4/CMA.1)1 to provide 'information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSs).'").

[185] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, Environ. Res. Lett. 17(2): 1–10, 7 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C}$ = 75 and $GTP_{1.5\ °C}$ = 41."); *discussed in* McKenna P. (

February 2022) *To Counter Global Warming, Focus Far More on Methane, a New Study Recommends*, Inside Climate News ("The Environmental Protection Agency is drastically undervaluing the potency of methane as a greenhouse gas when the agency compares methane's climate impact to that of carbon dioxide, a new study concludes. The EPA's climate accounting for methane is "arbitrary and unjustified" and three times too low to meet the goals set in the Paris climate agreement, the research report, published Wednesday in the journal Environmental Research Letters, found."); *and* Rathi A. (15 February 2022) *The Case Against Methane Emissions Keeps Getting Stronger*, Bloomberg.

[186] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶ 37 (2019) ("37. Each Party shall use the 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as agreed upon by the CMA, to report aggregate emissions and removals of GHGs, expressed in CO_2 eq. Each Party may in addition also use other metrics (e.g., global temperature potential) to report supplemental information on aggregate emissions and removals of GHGs, expressed in CO_2 eq. In such cases, the Party shall provide in the national inventory document information on the values of the metrics used and the IPCC assessment report they were sourced from.").

[187] Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 7.SM.7.

[188] Lynch J., Cain M., Pierrehumbert R., & Allen M. (2020) *Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants*, Environ. Res. Lett. 15(4): 044023, 1–13, 2 ("Following these behaviours, sustained emissions of an SLCP therefore result in a similar impact to a one-off release of a fixed amount of CO_2: both lead to a relatively stable long-term increase in radiative forcing. Thus an alternative means of equivalence can be derived, relating a change in the rate of emissions of SLCPs to a fixed quantity of CO_2…"). See also Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, Environ. Sci. Policy 134: 127–136, 132 ("However, this practice of assigning "equivalence" belies the physical reality, namely that CH_4's impact on climate is distinct from CO_2's in several important ways, as described in Section 3. In effect, only the long-term climate impact of CH_4 (i.e., its radiative forcing over a 100-year time horizon) is robustly taken into account under the Kyoto Protocol and the Paris Agreement. Among other things, this means that CH_4's outsized contribution to near-term climate warming is overlooked…. The focus on CO_2 equivalence under the UNFCCC also leads to an information and transparency gap. The common practice of expressing mitigation targets in terms of aggregate CO_2e, without specifying which reductions come from which GHGs, compromises the ability of modelers to evaluate in detail how the climate will respond to pledged emission reductions; this is because the climate responds differently to the different climate forcers (Fig. 2).").

[189] Cain M., Lynch J., Allen M. R., Fuglestvedt J. S., Frame D. J., & Macey A. H. (2019) *Improved calculation of warming-equivalent emissions for short-lived climate pollutants*, npj Clim. Atmos. Sci. 2(29): 1–7, 4 ("We have used an empirical method to find a definition of GWP* that preserves the link between an emission and the warming it generates in the medium term up to 2100. The physical interpretation of equation 1 is that the flow term (with coefficient *r*) represents the fast climate response to a change in radiative forcing, generated by the atmospheric and ocean mixed-layer response.[30] The timescale of this response is about 4 years here.[31] The stock term (with coefficient *s*) represents the slower timescale climate response to a change in radiative forcing, due to the deep ocean response. This effect means that the climate responds slowly to past changes in radiative forcing, and is why the climate is currently far from equilibrium. We have approximated this response by treating a quarter of the climate response to a SLCP as "cumulative".").

[190] Rogelj J. & Schleussner C.-F. (2021) *Reply to Comment on `Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'*, Environ. Res. Lett. 16(6): 1–8, 2 ("These ethical issues arise from moving away from an emissions centered metric like GWP-100—where every unit of emissions of a certain GHG is treated equally and independent of the emitter or timing of emissions—to metrics like GWP*—which focus

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on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history… Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady 2020)."); *citing* Cady R. (2020) *A Literature Review of GWP*: A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane*, GLOBAL DAIRY PLATFORM; *discussed in* Elgin B. (19 October 2021) *Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math*, BLOOMBERG GREEN.

[191] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

[192] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 128–129 ("Methane is a GHG and thereby a direct climate forcer; that is, it absorbs and re-radiates thermal radiation, contributing directly to the greenhouse effect. Unlike CO_2, CH_4 is chemically active, with atmospheric oxidation accounting for approximately 95% of its loss. Among other things, reactions of CH_4 lead to the production of tropospheric O_3 and stratospheric water vapor, and the end product of CH_4 oxidation is CO_2 itself (Forster et al., 2021). In this way, CH_4 also acts as an indirect climate forcer because it leads to the production of other GHGs (Fig. 1). A quantitative overview of radiative forcing due to CH_4 and its associated photochemical products is provided in Table 1. The chemical reactions of CH_4 also alter the atmospheric concentration of oxidants, especially the OH radical. This in turn has an indirect effect on the abundance of other trace gases and aerosols in the troposphere. In particular, increased atmospheric CH_4 provides an increased sink for OH [hydroxy radical], reducing the formation of sulfate aerosol (via SO_2 +OH). Since sulfate aerosol has a cooling effect on the climate (see also (Fig. 2) its reduction can be seen as an additional, indirect positive radiative forcing attributable to CH_4 (Shindell et al., 2009) calculate that this effect is equivalent to a radiative forcing of approximately + 0.1 W m^{-2} (Table 1), comparable to the CH_4-induced radiative forcing due to stratospheric water vapor.").

[193] White House (18 September 2021) *Joint US-EU Press Release on the Global Methane Pledge*, Statements and Releases ("Methane is a potent greenhouse gas and, according to the latest report of the Intergovernmental Panel on Climate Change, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era. Rapidly reducing methane emissions is complementary to action on carbon dioxide and other greenhouse gases, and is regarded as the single most effective strategy to reduce global warming in the near term and keep the goal of limiting warming to 1.5 degrees Celsius within reach.").

[194] Yahoo Finance (8 November 2021) *LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland*, YOUTUBE (from 23:12–23:19).

[195] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."). *See also* Ross K., Waskow D., & Ge M. (17 September 2021) *How Methane Emissions Contribute to Climate Change*, WORLD RESOURCES INSTITUTE ("Methane is the second most abundant human-caused greenhouse gas (GHG), and is 86 times more powerful than carbon dioxide over 20 years in the atmosphere (34 times more powerful over 100 years). Because it exists for a relatively short time in the atmosphere, cutting methane provides a quick benefit in terms of limiting near-term temperature rise. Studies estimate that ambitious actions to reduce methane can avoid 0.3 degrees C of warming by 2050.").; *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33, 57 ("Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end of century (*high confidence*)."; "All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH

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emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). (CrossSection Box.2).”).

[196] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 8 (“Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5°C. Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts. It would also, each year, prevent 255 000 premature deaths, 775 000 asthma related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally.”).

[197] United Nations Environment Programme & Climate & Clean Air Coalition (2022) Global Methane Assessment: 2030 Baseline Report, 11 (“Using the results from the 2021 Global Methane Assessment, we calculate that Global Methane Pledge would provide additional benefits worldwide through 2050, beyond keeping the planet cool, including: - Prevention of roughly 200,000 premature deaths per year due to ozone exposure - Avoidance of ~580 million tonnes of yield losses to wheat, maize (corn), rice and soybeans per year - Avoidance of ~$500 billion (2018 US$) per year in losses per year due to non-mortality health impacts, forestry and agriculture - Avoidance of ~1,600 billion lost work hours per year due to heat exposure.”).

[198] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 78 (“The total valuation per tonne of methane for all market and non-market impacts assessed here is roughly US$ 4 300 using a cross-nation income elasticity for WTP of 1.0 and US$ 7 900 using an elasticity of 0.4 (Figure 3.19) – values are ~US$ 150 per tonne larger for fossil-related emissions. This value is dominated by mortality effects, of which US$ 2 500 are due to ozone and ~US$ 700 are due to heat using the more conservative 500 deaths per million tonnes of methane of this analysis’ two global-scale estimates and a WTP income elasticity of 1.0, followed by climate impacts.”).

[199] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 21 (“The short lifetime of methane, and the quick response of methane abundance to reduced emissions described earlier, mean that any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production. Observations over the past few decades have shown that decreased emissions lead quickly to lower methane levels relative to those that could be expected in the absence of the decreases. That is, there are no mechanisms that offset the decreases even though there are significant natural sources. Simply put, natural emissions do not make up for the decrease in anthropogenic emission. Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane.”).

[200] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 21 (“This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013)).”). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, Environ. Res. Lett. 16(5): 1–11, 1 (“Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative

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to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action).”).

[201] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254, 262 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2).”); “Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

[202] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, Figure 5.1.

[203] Sun T., Ocko I. B., & Hamburg S. P. (2022) *The value of early methane mitigation in preserving Arctic summer sea ice*, Environ. Res. Lett. 17(4): 1–11, 1 (“While drastic cuts in carbon dioxide emissions will ultimately control the fate of Arctic summer sea ice, we show that simultaneous early deployment of feasible methane mitigation measures is essential to avoiding the loss of Arctic summer sea ice this century. In fact, the benefit of combined methane and carbon dioxide mitigation on reducing the likelihood of a seasonally ice-free Arctic can be greater than the simple sum of benefits from two independent greenhouse gas policies. The extent to which methane mitigation can help preserve Arctic summer sea ice depends on the implementation timeline. The benefit of methane mitigation is maximized when all technically feasible measures are implemented within this decade, and it decreases with each decade of delay in implementation due to its influence on end-of-century temperature. A key insight is that methane mitigation substantially lowers the risk of losing Arctic summer sea ice across varying levels of concomitant carbon dioxide mitigation.”).

[204] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 10 (“The levels of methane mitigation needed to keep warming to 1.5°C will not be achieved by broader decarbonization strategies alone. The structural changes that support a transformation to a zero-carbon society found in broader strategies will only achieve about 30 per cent of the methane reductions needed over the next 30 years. Focused strategies specifically targeting methane need to be implemented to achieve sufficient methane mitigation. At the same time, without relying on future massive-scale deployment of unproven carbon removal technologies, expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5°C. (Sections 4.1, 4.2 and 4.3)”).

[205] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 23, 24 (“Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.1)”).

[206] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 17 (“C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%]

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in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)"). *See also* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 57 ("All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*).").

[207] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, Earth Syst. Sci. Data 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %).").

[208] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 25 ("Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.").

[209] Shindell D. (25 May 2021) *Benefits and Costs of Methane Mitigation*, Presentation at the CCAC Working Group Meeting. *Updating* Figure 3d from Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, Nature 573: 408–411. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions.

[210] Jackson R. B., *et al.* (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, Environ. Res. Lett. 15(7): 1–7, 6 ("Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner *et al* 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.").

[211] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Fortunately, most leaks are straightforward to repair (and fixing leaks is paid for by the value of the gas that is saved by repairing them). Further, finding leaks has become efficient with modern technology. The standard approach today is to use special cameras that can detect infrared light (think of night-vision goggles) which are tuned to make methane, which is invisible to our eyes, visible. They allow inspectors to directly image leaking gas in real time, with the ability to inspect entire components (not just connections and other areas most likely to leak) and pinpoint the precise source, making repair more straightforward. And, technology promises to make this process even more efficient (and cheaper) over the coming years. These technologies can be utilized to reduce harmful leak emissions, by using regular inspections

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the lynchpin of rigorous “leak detection and repair” (LDAR) programs. These programs require operators to regularly survey all of their facilities for leaks and improper emissions, and repair all the leaks they identify in a reasonable time. For example, California requires operators to survey all sites four times a year. Colorado has a different approach, requiring operators of the largest sites to survey them monthly, but requiring less frequent inspections for site with smaller potential emissions.”).

[212] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) (Listing pneumatic equipment venting, compressor seal venting, tank venting, well completion venting, oil well venting and flaring, and dehydrator venting as sources of the “biggest mitigation opportunities.”).

[213] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) (“Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%.”).

[214] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) (“Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off — wasting energy and producing large amounts of carbon dioxide and other pollutants — some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other technologies that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%.”). *See also* World Bank, *Zero Routine Flaring by 2030 Initiative Text* (*last visited* 13 June 2023) (“This “**Zero Routine Flaring by 2030” initiative** (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030.”).

[215] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT, 13 (“Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions. Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits.”). *See also* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 13–14 (“The technical abatement potential for agricultural sources is assessed at 21 percent below baseline emissions in year 2050. This includes relatively limited abatement potentials for livestock of 12 percent due to applicability limitations (see section S3.4. in the SI for details). Large farms with more than 100 LSU contribute about a third of global CH_4 emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric

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fermentation emissions through animal feed changes (Gerberetal 2013, Hristov et al 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett et al 2006, Berglund 2008, Bell et al 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (ADs) with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson et al 2018).”); *and* Borgonovo F., *et al.* (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, Sustainability 11(18): 1–14, 8 (“N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.”).

[216] Höglund-Isaksson L., Gómez-Sanabria A., Zbigniew K., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, Environ. Res. Comm. 2(2): 1–21, 16–17 (“An additional almost 10 percent of baseline emissions in 2050 could be removed at a marginal cost below 20 €/t CO_2eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.”).

[217] United States Climate Alliance (2018) From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement, 15 (“Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities.”). *See also* Geyik Ö., Hadjikakou M., & Bryan B. A. (2022) *Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions*, Nat. Food. 4: 61–73, 61 (“Here, we estimate the non-CO_2 greenhouse gas emissions resulting from closing the world’s dietary nutrient gap—that between country-level nutrient supply and population requirements—for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate under five climate-friendly intervention scenarios in 2030. We show that improving crop and livestock productivity and halving food loss and waste can close the nutrient gap with up to 42% lower emissions (3.03 Gt CO_2eq yr^{-1}) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO_2eq yr^{-1}).”).

[218] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, Philos. Trans. R. Soc. A 379(2210): 1–17, 3–4 (“Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal.”). *See also* Abernethy S., O’Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379(2210): 1–13, 6 (“Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE,

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0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.").

[219] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, Earth Syst. Sci. Data 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ∼ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %).").

[220] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E."); *discussed in* Jordan R. (26 September 2021) *Stanford-led research reveals potential of an overlooked climate change solution*, Stanford Woods Institute for the Environment ("The analyses, published Sept. 27 in Philosophical Transactions of the Royal Society A, reveal that removing about three years-worth of human caused emissions of the potent greenhouse gas would reduce global surface temperatures by approximately 0.21 degrees Celsius while reducing ozone levels enough to prevent roughly 50,000 premature deaths annually. The findings open the door to direct comparisons with carbon dioxide removal – an approach that has received significantly more research and investment – and could help shape national and international climate policy in the future. […] Under a high emissions scenario, the analysis showed that a 40 percent reduction in global methane emissions by 2050 would lead to a temperature reduction of approximately 0.4 degrees Celsius by 2050. Under a low emissions scenario where temperature peaks during the 21st century, methane removal of the same magnitude could reduce the peak temperature by up to 1 degree Celsius.").

[221] O'Grady C. (2 November 2021) *To slow global warming, some researchers want to pull methane out of the air*, Science ("At a side event at the summit, researchers with the advocacy group Methane Action argued that so-called negative emissions technologies—alongside every trick in the book to reduce emissions—could restore methane to pre-industrial levels and trim an estimated 0.4°C to 0.6°C of warming.").

[222] Secretariat of the United Nations Framework Convention on Climate Change, *External Press Release, World Leaders Kick Start Accelerated Climate Action at COP26* (2 November 2021) ("Today is also the first time a COP in recent history has hosted a major event on methane, with 103 countries, including 15 major emitters including Brazil, Nigeria and Canada, signing up to the Global Methane Pledge.").

[223] White House (11 October 2021) *Joint US-EU Press Release on the Global Methane Pledge*, Press Release ("At the Major Economies Forum on Energy and Climate (MEF) on September 17, 2021, President Biden and European Commission President Ursula von der Leyen announced, with support from seven additional countries, the Global Methane Pledge—an initiative to be launched at the World Leaders Summit at the 26th UN Climate Change Conference (COP-26) this November in Glasgow, United Kingdom.").

[224] For a list of Global Methane Pledge participants, *see* https://www.globalmethanepledge.org/#pledges.

[225] United States Department of State (2 November 2021) *United States, European Union, and Partners Formally Launch Global Methane Pledge to Keep 1.5°C Within Reach*, Press Release ("Today, the United States, the Europe

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Union, and partners formally launched the Global Methane Pledge, an initiative to reduce global methane emissions to keep the goal of limiting warming to 1.5 degrees Celsius within reach. A total of over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions have now signed onto the pledge.”).

[226] William + Flora Hewlett Foundation (11 October 2021, updated 2 November 2021) *Leading Philanthropic Organizations Partner and Commit to Over $328M to Reducing Methane Emissions*, Press Release.

[227] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge* (“Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.”).

[228] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 9 (“Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1).”).

[229] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 8 (“Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts.”).

[230] United States Department of State (17 June 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release (“Today, the United States, the European Union, and 11 countries launched the Global Methane Pledge Energy Pathway to catalyze methane emissions reductions in the oil and gas sector, advancing both climate progress and energy security…. **Countries and supporting organizations announced nearly $60 million in dedicated funding to support implementation of the Pathway.** Countries and supporting organizations have announced $59 million in dedicated funding and in-kind assistance in support of the GMP Energy Pathway that was announced at today’s MEF, including: **$4 million** to support the **World Bank Global Gas Flaring Reduction Partnership (GGFR)**. The United States intends to support the transfer by the World Bank of at least $1.5 million in funding to the GGFR. **Germany** intends to provide $1.5 million, and **Norway** intends to provide approximately $1 million to GGFR. **$5.5 million** to support the **Global Methane Initiative (GMI)**. The **United States** will provide $3.5 million. Guided by the recommendations of the GMI, **Canada** will contribute $2 million over the next four years, as part of its global climate finance commitment, to support methane mitigation projects in developing countries including in the oil and gas sector. Up to **$9.5 million** from the UNEP **International Methane Emissions Observatory** to support scientific assessments of methane emissions and mitigation potential in the oil and gas sector that are aligned with the Global Methane Pledge Energy Pathway. Up to **$40 million** annually from the philanthropic **Global Methane Hub** to support methane mitigation in the fossil energy sector. These funds will be critical to improve methane measurements in the oil and gas sector, identify priority areas for methane mitigation, develop technical assessments for project development, strengthen regulator and operator capacity, support policy development and enforcement, and other essential activities to achieve reductions in methane emissions.”).

[231] *See* Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); *and* United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *discussed in* Friedman L. & Plumer B. (28 July 2022) *Surprise Deal Would Be Most Ambitious Climate Action Undertaken by U.S.*, The New York Times (“The bill would also crack down on leaks of methane, a powerful greenhouse gas, from oil and gas wells, pipelines and other infrastructure. By 2026, polluters would face a penalty of $1,500 per ton of methane that escaped into the atmosphere in excess of federal limits. The methane fee will raise $6.3 billion from the oil and gas industry over a decade, much of which will be reinvested in measures to help prevent methane leaks.”). For further information on what is in the 2022 Inflation Reduction Act, *see* Paris F., Parlapiano A., Sanger-Katz M.

& Washington E. (13 August 2022, *updated* 16 August 2022) *A Detailed Picture of What's in the Democrats' Climate and Health Bill*, THE NEW YORK TIMES.

[232] Analyses by Princeton's REPEAT Project, Energy Innovation, and the Rhodium Group confirm the 40% GHG reductions capability of the 2022 Inflation Reduction Act. *See* Jenkins J. D., Mayfield E. N., Farbes J., Jones R., Patankar N., Xu Q., & Schivley G. (August 2022) *Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022*, REPEAT Project, Princeton University ZERO Lab, 6 (Figure. Historical and Modeled Net U.S. Greenhouse Gas Emissions (Including Land Sinks); Mahajan M., Ashmoore O., Rissman J., Orvis R., & Gopal A. (August 2022) *Modeling the Inflation Reduction Act Using the Energy Policy Simulator*, Energy Innovation, 1 ("We find that the IRA is the most significant federal climate and clean energy legislation in U.S. history, and its provisions could cut greenhouse gas (GHG) emissions 37-41 percent below 2005 levels. If the IRA passes, additional executive and state actions can realistically achieve the U.S. nationally determined commitments (NDCs) under the Paris Agreement."); *and* Larsen J., King B., Kolus H., Dasari N., Hiltbrand G., & Herndon W. (12 August 2022) *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*, The Rhodium Group ("The IRA is a game changer for US decarbonization. We find that the package as a whole drives US net GHG emissions down to 32-42% below 2005 levels in 2030, compared to 24-35% without it. The long-term, robust incentives and programs provide a decade of policy certainty for the clean energy industry to scale up across all corners of the US energy system to levels that the US has never seen before. The IRA also targets incentives toward emerging clean technologies that have seen little support to date. These incentives help reduce the green premium on clean fuels, clean hydrogen, carbon capture, direct air capture, and other technologies, potentially creating the market conditions to expand these nascent industries to the level needed to maintain momentum on decarbonization into the 2030s and beyond."); *discussed in* Hirji Z. (4 August 2022) *How the Senate's Big Climate Bill Eliminates 4 Billion Tons of Emissions*, BLOOMBERG.

[233] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 51–57 ("Long-term exposure to ozone can cause inflammation and allergic responses leading to respiratory mortality, as well as the development of a systemic oxidative, proinflammatory environment that can increase the risk of cardiovascular diseases. … It should be noted that the larger impact of ozone on health has been reported in several previous studies. Malley et al. (2017) used the new health exposure relationships (Turner et al. 2016) along with modelled ozone distributions, and found a 125 per cent increase in respiratory deaths attributable to ozone exposure in 2010 compared to previous estimates – 1.04–1.23 million deaths compared to 0.40–0.55 million. … Further to this, a bias-adjusted model recently reported total worldwide ozone-related premature deaths of 1.0 ± 0.3 million (Shindell et al. 2018). The value for respiratory-related premature deaths due to ozone was 0.6 ± 0.2 million for 2010, and 1.0 ± 0.3 million without bias adjustment, the latter being consistent with the value reported by Malley et al. (2017).").

[234] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, NAT. FOOD 3: 47–56, 47 ("East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 68 ("Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills et al. 2018; Shindell et al. 2016; Avnery et al. 2011a)"); *and* Shindell D., Faluvegi G., Kasibhatla P., & Van Dingenen R. (2019) *Spatial Patterns of Crop Yield Change by Emitted Pollutant*, EARTH'S FUTURE 7(2): 101–112, 101 ("Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone).").

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[235] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 129 ("Methane is an important contributor to the formation of tropospheric O_3. In addition to acting as a greenhouse gas and being directly harmful to human health (see Section 3.3), it also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore, 2005, Sitch et al., 2007). This results in an estimated $11-$18 billion worth of global crop losses annually (Avnery et al., 2011). Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007, Ciais et al., 2013, Arneth et al., 2010, Ainsworth et al., 2012).").

[236] Butler T., Lupascu A., & Nalam A. (2020) *Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model*, ATMOS. CHEM. PHYS. 20(17): 10707–10731, 10726 ("As a reactive carbon precursor, methane contributes 35 % of the tropospheric ozone burden and 41 % of the Northern Hemisphere annual average surface mixing ratio, which is more than any other source of reactive carbon.").

[237] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVT'L. SCIENCE & POL'Y 134: 127–136, 130 ("Importantly, the role of methane's contribution to O_3 production is expected to increase in the future, as emissions of other anthropogenic precursors (primarily NO_x and VOCs) are anticipated to decrease as a result of current and planned air quality regulations across much of the globe. For instance, Young et al. (2013) showed that rising CH_4 concentrations could be a major driver of increased surface O_3 by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Turnock et al. (2018) showed that increased O_3 production from rising CH_4 concentrations could offset the reduction in surface O_3 due to reductions in emissions of shorter-lived O_3 precursors.").

[238] Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (2005) (Entered into force in accordance with article 17 which reads as follows: "1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.").

[239] 1979 Convention on Long-Range Transboundary Air Pollution, 11302 U.N.T.S 217, Art. 2 (1983).

[240] Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (2005) (Entered into force in accordance with article 17 which reads as follows: "1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.").

[241] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 27 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface

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temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).").

[242] The Climate & Clean Air Coalition to Reduce Short-Lived Climate Pollutants (The CCAC identifies solutions to reduce SLCP emissions, conducts relevant scientific research, and promotes policy development. It is the only institution focusing solely on SLCP mitigation, although it does not have any regulatory authority.).

[243] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. Geophys. Res. Atmos. 118(11): 5380–5552, 5420 ("Major sources of BC are also major sources of PM$_{2.5}$, but the converse is not always true; major sources of PM$_{2.5}$ may produce little BC if their emissions are primarily inorganic. Sources that are BC and OC emitters are shown in the table. Resuspended dust, secondary pollutants like sulfate and nitrate, or sea salt, could also be contributors to PM2.5 at some locations but are not included in Table 11."); major sources in Table 11 include (in order of decreasing importance): transport (vehicle exhaust including gasoline and diesel); IN = industry including coal and oil and biomass burning; coal burning power plants; RE = residential energy; OB= open burning of biomass and refuse; SA = secondary aerosols; O= Others.

[244] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, Proc. Nat'l. Acad. Sci. 116(15): 7192–7197, 7193 ("We find that the global total excess mortality rate is 8.79 million per year, with a 95% confidence interval of 7.11–10.41 million per year."). *See also* Vohra K., Vodonos A., Schwartz J., Marais E. A., Sulprizio M. P., & Mickley L. J. (2021) *Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem*, Environ. Res. 195: 1–33, 2 ("We used the chemical transport model GEOS-Chem to estimate global exposure levels to fossil-fuel related PM$_{2.5}$ in 2012. Relative risks of mortality were modeled using functions that link long-term exposure to PM$_{2.5}$ and mortality, incorporating nonlinearity in the concentration response. We estimate a global total of 10.2 (95% CI: -47.1 to 17.0) million premature deaths annually attributable to the fossil-fuel component of PM$_{2.5}$. The greatest mortality impact is estimated over regions with substantial fossil fuel related PM$_{2.5}$, notably China (3.9 million), India (2.5 million) and parts of eastern US, Europe and Southeast Asia. The estimate for China predates substantial decline in fossil fuel emissions and decreases to 2.4 million premature deaths due to 43.7% reduction in fossil fuel PM$_{2.5}$ from 2012 to 2018 bringing the global total to 8.7 (95% CI: -1.8 to 14.0) million premature deaths.").

[245] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 193, 201 ("Implementing all measures could avoid 2.4 million premature deaths (within a range of 0.7–4.6 million) associated with reductions in PM$_{2.5}$, associated with 5.3–37.4 million years of life lost (YLL), based on the 2030 population."; "Total global production gains of all crops ranges between 30 and 140 million tonnes (model mean: 52 million tonnes). The annual economic gains for all four crops in all regions ranges between US$4billion and US$33 billion, of which US$2–28 billion in Asia.").

[246] Climate & Clean Air Coalition, *Black Carbon* (*last visited* 13 June 2023) (Listing solutions to reach 70% reduction in black carbon by 2030).

[247] 1999 Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg Protocol), Decision 2012/8: Adoption of guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM$_{10}$, PM$_{2.5}$, and black carbon) from stationary sources. *See also* Matthews B. & Paunu V.-V. (2019) *Review of Reporting Systems for National Black Carbon Emissions Inventories*, EU Action on Black Carbon in the Arctic - Technical Report 2, 1–2 ("Emissions reporting systems are thus in need of further improvement. In evaluating needs for improvement, the EU Action on Black Carbon in the Arctic review identified the following priority areas . . . 4. Enhanced cooperation between CLRTAP and the Arctic Council to expand and harmonise black carbon emissions reporting by countries whose black carbon emissions impact the Arctic."). *Compare with* Expert Group on Black Carbon and Methane (2019) *Summary of Progress and Recommendations*, Arctic Council Secretariat, 32 (Table 5, *showing* U.S. with 9.5bcm of flaring based on World Bank satellite observations); *and* Energy Information Administration, *Natural Gas Gross Withdrawals and Production* (*last visited* 10 June 2023) (showing combined flaring and venting volumes of 255bcm for 2017).

[248] World Bank (2014) Reducing Black Carbon Emissions from Diesel Vehicles: Impacts, Control Strategies, and Cost-Benefit Analysis, 17 ("A vehicle emissions reduction program often focuses on three areas

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new vehicles, fuels, and the in- use fleet. In some countries it may make sense to start with the in-use fleet and transportation demand management. In certain cases, fiscal policies can be effective tools to complement mandatory regulatory requirements. The order or priority in approach should be dictated by the baseline technology, the rate of growth of the fleet, the feasibility of available options, the institutional capacity to support the intervention, and other local considerations. Successful strategies tend to take a holistic approach that integrates all maximum feasible and cost-effective emissions reduction strategies."). *See also* Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYS. RES. ATMOS. 118(11): 5380–5552, 5525 ("Diesel sources of BC appear to offer the most promising mitigation opportunities in terms of near-term forcing and maturity of technology and delivery programs. Although some options, such as diesel retrofits, may be costly relative to other BC mitigation options, they may also deliver significant health benefits. Mitigating emissions from residential solid fuels may yield a reduction in net positive forcing. The near-term net effect remains uncertain because of uncertain knowledge regarding the impacts of co-emitted species on clouds, but longer-term forcing by co-emitted species interacting with the methane budget is positive. Furthermore, the evolution of feasibility is still in the emerging phase for these sources.").

[249] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off — wasting energy and producing large amounts of carbon dioxide and other pollutants — some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other technologies that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%."). *See also* World Bank, *Zero Routine Flaring by 2030 Initiative Text* (*last visited* 13 June 2023) ("This "**Zero Routine Flaring by 2030" initiative** (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030."); *and* Saunier S., Bergauer M-A., & Isakova I. (2019) *Best Available Techniques Economically Achievable to Address Black Carbon from Gas Flaring*, EU Action on Black Carbon in the Arctic Technical Report 3, 3 ("Although the effectiveness of BATEA largely depends on site-specific economic and technical parameters, they have a substantial potential to achieve meaningful and measurable environmental and financial benefits. Quantifying resultant reductions in BC emissions as a result of mitigation strategies remains challenging, however, implementing BATEA should still be considered a best practice for reducing flaring-associated BC emissions. Along with other newly available technologies, use of the BATEA described herein will support existing efforts to mitigate short-term climate change, as well as address other energy, environmental, and safety issues that are likely to result from gas flaring in Arctic regions.").

[250] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, & World Health Organization (2020) TRACKING SDG 7: THE ENERGY PROGRESS REPORT, 6 ("The share of the global population with access to clean fuels and technologies for cooking increased from 56 percent in 2010 (uncertainty interval 52–61 percent) to 63 percent in 2018 (56–68), leaving approximately 2.8 billion people without access.[1] That number has been largely unchanged over the past two decades owing to population growth outpacing the number of people gaining access to clean cooking solutions."). Cleaner cookstoves must also be reliable for interventions to succeed: *see* Ramanathan T., Molin Valdés H., & Coldrey O. (7 September 2020) *Reliability matters: Achieving affordable, reliable, sustainable and modern energy for all by 2030*, SUSTAINABLE ENERGY FOR ALL ("A cooking solution (improved biomass, gas, electric, etc.) is reliable when it offers a household the predictable ability to cleanly cook essential foods on a daily basis and to continue to do so into the foreseeable future. Reliability is a holistic concept that encompasses not only the verifiability of emissions reduction, but also accounts for end users' needs (e.g. usability of design, long-term durability, affordability, and strength of supply chain). Compromising any

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of those factors can mean that even if a cooking solution is perceived as beneficial, it may not be well suited and will therefore ultimately not meet its targeted goal of cleaner air.”).

[251] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization’s proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 1 (“In February 2020, delegates at the seventh session of the United Nations International Maritime Organization’s (IMO) Pollution Prevention and Response Sub-Committee (PPR 7) agreed on draft amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) that would ban the carriage and use of heavy fuel oil (HFO) as fuel in Arctic waters beginning on July 1, 2024 (IMO Secretariat, 2020). If it were comprehensive, such a ban would dramatically reduce the potential for HFO spills and, in the likely cases where ships that stop using HFO switch to distillates, reduce the amount of black carbon (BC) they emit (Comer, Olmer, Mao, Roy, & Rutherford, 2017a). However, the text of the ban as currently proposed includes exemptions and waivers that would allow HFO to be carried and used in the Arctic until 2029. As proposed, the ban would enter into force for some ships on July 1, 2024, and implementation would be delayed for others. Ships with certain fuel tank protections, where the fuel tank is separated from the outer hull of the ship by at least 76 centimeters (cm), would be exempt until July 1, 2029. Additionally, countries with a coastline that borders IMO’s definition of Arctic waters can waive the HFO ban’s requirements until July 1, 2029 for ships that fly their flag when those ships are in waters subject to their sovereignty or jurisdiction.”). *See also* Farand C. (3 September 2020) *Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade*, Climate Home News (“Under draft plans being negotiated at the International Maritime Organisation (IMO) – the UN body responsible for international shipping – restrictions on heavy fuel oil (HFO), a dirty fuel which propels most of marine transport, would come into effect in July 2024. But a host of exemptions and waivers would allow most ships using and carrying HFO to continue to pollute Arctic waters until 2029.”).

[252] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, Proc. Nat’l. Acad. Sci. 104(12): 4814–4819, 4816 (“In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 GtCO$_2$-eq yr 1 in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO$_2$.”). *See also* Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, Geophys. Res. Lett. 50(5): 1–9, 4, 5 (“Furthermore, we place the warming from ODSs in the broader context of the total anthropogenic warming (which includes well mixed GHGs and ozone, and excludes the cooling effects of aerosols, see the previous section). The warming from all anthropogenic forcings (labeled “AntW” in Figure 2) is found to be 1.26°C in the ensemble mean. ODSs, therefore, have contributed nearly one third (30%) of the total anthropogenic warming over the 1955 to 2005 period.”; “This second key result of our study, the high efficacy of ODSs, stands in contrast to the result obtained from highly idealized equilibrium forcing experiments (Richardson et al., 2019), which have reported an efficacy for CFC11 and CFC12 close to unity. Analyzing the realistic transient evolution of historical forcings over the 1955–2005 period, our model shows that ODSs are almost 20% more effective at warming global temperatures than carbon dioxide.”).

[253] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, Nature 596(7872): 384–388, 384 (“Overall, at the end of the century, worldAvd warms by an additional 2.5 K (2.4–2.7 K) above the RCP 6.0 baseline in worldProj. Of this warming, 1.7 K comes from the previously explored19 additional radiative forcing due to the higher CFC concentrations in worldProj. Newly quantified here is the additional warming of global-mean air temperature of 0.85 K (0.65–1.0 K)—half as much again—that arises from the higher atmospheric CO$_2$ concentrations due to the damaging effect of UV radiation on terrestrial carbon stores.”). *See also* United Nations Environment Programme, Ozone Secretariat (16 September 2022) *World Ozone Day 2022: Global cooperation protecting life on Earth* (“This action has protected millions of people from skin cancer and cataracts over the years since. It allowed vital ecosystems to survive and thrive. It safeguarded life on Earth. And it slowed climate change: if ozone-depleting chemicals had not been banned, we would be looking at a global temperature rise of an additional 2.5°C by the end of this century. This would have been a catastrophe.”); World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 26 (“New studies support previous Assessments in that the decline in ODS emissions due to compliance with the Montreal Protocol avoids global warming of approximately 0.5–1 °C by mid-century compared to an extreme scenario with an uncontrolled increase in ODSs of 3–3.5% per year.”); *and*

Andersen S. O., Gonzalez M., & Sherman N. J. (18 October 2022) *Setting the stage for climate action under the Montreal Protocol*, Eos 103.

[254] Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) *The role of HFCs in mitigating 21st century climate change*, Atmos. Chem. Phys. 13(12): 6083–6089, 6083 ("Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 ºC warming by the end of the century. This combined mitigation on SLCPs would cut the cumulative warming since 2005 by 50% at 2050 and by 60% at 2100 from the CO$_2$-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 ºC warming threshold during this century."). For an updated assessment of HFC mitigation from policy adopted in the lead-up to the Kigali Amendment and locked-in with the entry into force of the Kigali Amendment, *see* Velders G. J. M., Daniel J. S., Montzka S. A., Vimont I., Rigby M., Krummel P. B., Muhle J., O'Doherty S., Prinn R. G., Weiss R. F., & Young D. (2022) *Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies*, Atmos. Chem. Phys. 22(9): 6087–6101, 6099 ("Projected mixing ratios, radiative forcing, and globally averaged temperature changes are calculated from the projected HFC emissions. The 2050 radiative forcing is 0.13–0.18 Wm^{-2} in the current policies K-I scenario and drops to 0.08–0.09 Wm^{-2} when the additional Kigali Amendment controls are considered (in KA-2022). In the current policies K-I scenario, the HFCs are projected to contribute 0.14–0.31 °C to the global surface warming in 2100, compared to 0.28–0.44 °C without policies. Following the Kigali Amendment, the surface warming of HFCs is reduced to about 0.05 °C in 2050 and 0.04 °C in 2100 (KA-2022. In a hypothetical scenario with a full phaseout of HFCs production and consumption in 2023, the contribution is reduced to about 0.01 °C in 2100."). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 3 ("Compliance with the 2016 Kigali Amendment to the Montreal Protocol, which requires phase down of production and consumption of some hydrofluorocarbons (HFCs), is estimated to avoid 0.3–0.5 °C of warming by 2100. This estimate does not include contributions from HFC-23 emissions.").

[255] Montzka S. A., Velders G. J. M., Krummel P. B., Mühle J., Orkin,V. L., Park S., Shah N., & Walter-Terrinoni H. (2018) *Chapter 2: Hydrofluorocarbons (HFCs), in* Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 2.40–2.41 ("With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu *et al.*, 2013 and Velders *et al.*, 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels."). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 21 ("Following the controls of the Kigali Amendment, HFC emissions (excluding HFC-23) in 2050 are projected to be 0.9–1.0 Gt CO$_2$-eq. yr^{-1} in the updated 2022 Kigali Amendment scenario, compared to 4.0–5.3 Gt CO$_2$eq yr^{-1} in the 2018 scenario without control measures (Figure ES-4). The corresponding radiative forcing in 2050 due to HFCs is 0.09–0.10 W m^{-2} with adherence to the Kigali Amendment, compared to 0.22–0.25 W m^{-2} without control measures. Annual average surface warming from HFCs is expected to be 0.04 °C in 2100 under the updated 2022 Kigali Amendment scenario, compared to 0.3–0.5 °C without control measures."); and Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs), in* Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 143 ("In the new scenario following current trends, national policies, and the provisions of the Kigali Amendment, the HFCs are projected to contribute 0.04°C to the global average surface warming in 2100, compared to 0.3– 0.5°C in the baseline scenarios of the previous Assessment (Montzka, Velders et al., 2018; Velders et al., 2022). The updated Kigali Amendment scenario leads to a temperature rise that is slightly

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lower than that of the previous Assessment. For comparison, all greenhouse gases (GHGs) are projected to contribute 1.4–4.4°C to surface warming by the end of the 21st century, following the IPCC scenarios (best estimate for 2081–2100; IPCC, 2021). In hypothetical scenarios with a cease in global production or emissions of HFCs in 2023, the contribution to surface warming is reduced to no more than 0.01°C in 2100.”).

[256] Purohit P., Borgford-Parnell N., Klimont Z., & Höglund-Isaksson L. (2022) *Achieving Paris climate goals calls for increasing ambition of the Kigali Amendment*, NAT. CLIM. CHANGE 12: 339–342, 339 (“Hydrofluorocarbon emissions have increased rapidly and are managed by the Kigali Amendment to the Montreal Protocol. Yet the current ambition is not consistent with the 1.5 °C Paris Agreement goal. Here, we draw on the Montreal Protocol start-and-strengthen approach to show that accelerated phase-down under the Kigali Amendment could result in additional reductions of 72% in 2050, increasing chances of staying below 1.5 °C throughout this century.”).

[257] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2018) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project Report No. 58, World Meteorological Organization, ES-22, 2.40–2.41 (“The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3-0.5 ºC to less than 0.1 ºC (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 ºC for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 ºC) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC.”; “With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu et al., 2013 and Velders et al., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.”).

[258] World Meteorological Organization (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 3 (“Compliance with the 2016 Kigali Amendment to the Montreal Protocol, which requires phase down of production and consumption of some hydrofluorocarbons (HFCs), is estimated to avoid 0.3–0.5 °C of warming by 2100. This estimate does not include contributions from HFC-23 emissions.”). *See also* Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs), in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, 143 (“Under the business-as-usual scenario, if the current fractional rate of HFC-23 destruction continues into the future, radiative forcing due to HFC-23 is expected to reach 0.015 $W\ m^{-2}$ in 2050. Under the scenario in which there is widespread destruction of HFC-23 by-product, the contribution of HFC-23 to overall HFC radiative forcing will be small (Section 7.2.2.1).”).

[259] Dreyfus G., Borgford-Parnell N., Christensen J., Fahey D. W., Motherway B., Peters T., Picolotti R., Shah N., & Xu Y. (2020) ASSESSMENT OF CLIMATE AND DEVELOPMENT BENEFITS OF EFFICIENT AND CLIMATE-FRIENDLY COOLING, Molina M. & Zaelke D., Steering Committee Co-Chairs, xii (“Transitioning to high efficiency cooling equipment can more than double the climate benefits of the HFC phasedown in the near-term by reducing emissions of carbon dioxide (CO_2) and black carbon from the electricity and diesel used to run air conditioners and other cooling equipment. This also will provide significant economic, health, and development co-benefits. … Robust policies to promote the use of best technologies currently available for efficient and climate-friendly cooling have the potential to reduce climate emissions from the stationary air conditioning and refrigeration sectors by 130–260 $GtCO_2e$ by 2050, and 210–460 $GtCO_2e$ by 2060. A quarter of this mitigation is from phasing down HFCs and switching to alternatives with low global warming potential (GWP), while three-quarters is from improving energy efficiency of cooling equipment and reducing electricity demand, which helps achieve a more rapid transition to carbon free electricity worldwide. The mobile air conditioning sector, where energy consumption is expected to nearly triple by 2050, offers significantly more mitigation potential.”). *See also* Purohit P., Höglund-Isaksson L., Dulac J., Shah N., Wei M., Rafaj P., & Schöpp W. (2020) *Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons*, ATMOS. CHEM. PHYS. 20(19): 11305–11327, 11305 (“The combined effect of HFC

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phase-down, energy efficiency improvement of the stationary cooling technologies, and future changes in the electricity generation fuel mix would prevent between 411 and 631 PgCO$_2$ equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2 °C.").

[260] *Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer*, 15 October 2016, C.N.872.2016.TREATIES-XXVII.2.f.

[261] American Innovation and Manufacturing Act, Pub. L. No. 116-260, § 103 (2020) (codified at 42 U.S.C. § 7675). *See also* United States Environmental Protection Agency (*last updated* 25 July 2022) *Proposed Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act*.

[262] *See* *HFCBans.com* (*last visited* 14 June 2023) (States with finalized HFC prohibitions include: California, Colorado, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, Washington, Vermont, and Virginia. States with proposed bans include: Connecticut, Hawaii, New Mexico, Oregon, Pennsylvania, and Texas.).

[263] 168 Cong. Rec. D1,006 (daily ed. Sept. 21, 2022) ("By 69 yeas to 27 nays (Vote No. EX. 343), two-thirds of the Senators present having voted in the affirmative, Senate agreed to the resolution of Advise and Consent to Ratification, as amended, to Treaty Document 117–1, the amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the ''Montreal Protocol''), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the ''Kigali Amendment''), with 1 declaration...."). *See also* White House (21 September 2022) *Statement by President Joe Biden on Senate Ratification of the Kigali Amendment to the Montreal Protocol*; *and* White House (16 November 2021) *A Message to the Senate on the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer*, Briefing Room ("TO THE SENATE OF THE UNITED STATES: With a view to receiving the advice and consent of the Senate to ratification, I transmit herewith the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the "Montreal Protocol"), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the "Kigali Amendment"). The report of the Department of State is also enclosed for the information of the Senate. The principal features of the Kigali Amendment provide for a gradual phasedown in the production and consumption of hydrofluorocarbons (HFCs), which are alternatives to ozone-depleting substances being phased out under the Montreal Protocol, as well as related provisions concerning reporting, licensing, control of trade with non-Parties, and control of certain byproduct emissions."); *discussed in* Mason J. (16 November 2021) *White House sends Kigali amendment on climate-warming gases to Senate*, Reuters.

[264] Portmann R. W., Daniel J. S., & Ravishankara A. R. (2012) *Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases*, Philos. Trans. R Soc. Lond. B Biol. Sci. 367(1593): 1256–1264, 1262 ("By 2008, anthropogenic N$_2$O was the most significant ozone-destroying compound being emitted. Owing to the phase-out of anthropogenic halocarbon emissions, it is likely to become even more dominant in the near future."). *See also* Porter I. (2019) *Mitigation of Nitrous Oxide Emissions*, Presentation at 31st Meeting of the Parties to the Montreal Protocol ("By 2050, lack of controls on N$_2$O will undo 25% of the benefit gained by the Montreal Protocol to reducing ODS from the ozone layer.").

[265] Forster P., *et. al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* Climate Change 2021: The Physical Science Basis (*see* Table 7.15 on the emission metrics for a select species of gases, including methane and nitrous oxide (N$_2$O).).

[266] Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-term marginal abatement cost curves of non-CO$_2$ greenhouse gases*, Environ. Sci. Policy 99: 136–149, 145 (Table 2).

[267] Environmental Protection Agency (2012) Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990–2030, 41 ("Between 1990 and 2005, N$_2$O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 MtCO$_2$e to 126 MtCO$_2$e (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of

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global N_2Oemissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.”).

[268] Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 29 (“Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.”).

[269] Balafoutis A., Beck B., Fountas S., Vangeyte J., van der Wal T., Soto I., Gómez-Barbero M., Barnes A., & Eory V. (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 9(8): 1339, 1–28, 9 (“Tekin (2010) estimated that VRNA can increase wheat production between 1% and 10% offering savings in nitrogen fertilisation between 4% and 37%.”).

[270] Butler A. H., Daniel J. S., Portmann R. W., Ravishankara A. R., Young P. J., Fahey D. W., & Rosenlof K. H. (2016) *Diverse policy implications for future ozone and surface UV in a changing climate*, ENV. RES. LETT. 11(6): 064017, 1–7, 4 (“A key point is that if the world were to achieve reductions of CO_2 and CH_4 concentrations to RCP 2.6 levels, N_2O mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion.”).

[271] *SOP, Save Our Planet* (*last visited* 13 June 2023).

[272] Peterson C., El Mashad H. M., Zhao Y., Pan Y., & Mitloehner F. M. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, SUSTAINABILITY 12(4): 1–17, 14–15 (“These studies seem to indicate that the applied HIGH dose of SOP Lagoon might decrease the number of methanogens that produce methane during the storage of manure as well as hydrolytic microorganisms and their excreted enzymes that biodegrade organic nitrogen into ammonium.”). *See also* Maris S. C., Capra F., Ardenti F., Chiodini M. E., Boselli R., Taskin E., Puglisi E., Bertora C., Poggianella L., Amaducci S., Tabaglio V., & Fiorini A. (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11(3): 407, 1–19, 1 (“[W]e concluded that under our experimental conditions SCM [SOP® COCUS MAIZE+] may be used for reducing N [nitrogen] input (-30%) and N_2O emissions (-23%), while contemporarily maintaining maize yield. Hence, SCM can be considered an available tool to improve agriculture’s alignment to the United Nation Sustainable Development Goals (UN SDGs) and to comply with Europe’s Farm to Fork strategy for reducing N-fertilizer inputs.”).

[273] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, Figure 5.1.

[274] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254, 262 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2).”; “Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

[275] Sand M., Berntsen T. K., Seland Ø., & Kristjánsson J. E. (2013) *Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes*, J. GEOPHYS. RES. 118(14): 7788–7798, 7788 (“The climate model includes a snow model to simulate the climate effect of BC deposited on snow. We find that BC emitted within the Arctic has an almost five times larger Arctic surface temperature response (per unit of emitted mass) compared to emissions at midlatitudes. Especially during winter, BC emitted in North-Eurasia is transported into the high Arctic

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at low altitudes. A large fraction of the surface temperature response from BC is due to increased absorption when BC is deposited on snow and sea ice with associated feedbacks."). *See also* Stohl A., Klimont Z., Eckhardt S., Kupiainen K., Shevchenko V. P., Kopeikin V. M., & Novigatsky A. N. (2013) *Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions*, Atmos. Chem. Phys. 13(17): 8833–8855, 8848 (Fig. 9. Time series of measured EBC and carbon monoxide as well as modeled BC split into different source categories for the Zeppelin station for the period 12 February until 4 March 2010.).

[276] Qian Y., Yasunari T. J., Doherty S. J., Flanner M. G., Lau W. K. M., Ming J., Wang H., Wang M., Warren S. G., & Zhang R. (2014) *Light-absorbing Particles in Snow and Ice: Measurement and Modeling of Climatic and Hydrological impact*, Adv. Atmos. Sci. 32: 64–91, 64 ("Light absorbing particles (LAP, e.g., black carbon, brown carbon, and dust) influence water and energy budgets of the atmosphere and snowpack in multiple ways. In addition to their effects associated with atmospheric heating by absorption of solar radiation and interactions with clouds, LAP in snow on land and ice can reduce the surface reflectance (a.k.a., surface darkening), which is likely to accelerate the snow aging process and further reduces snow albedo and increases the speed of snowpack melt. LAP in snow and ice (LAPSI) has been identified as one of major forcings affecting climate change, e.g. in the fourth and fifth assessment reports of IPCC. However, the uncertainty level in quantifying this effect remains very high. In this review paper, we document various technical methods of measuring LAPSI and review the progress made in measuring the LAPSI in Arctic, Tibetan Plateau and other mid-latitude regions. We also report the progress in modeling the mass concentrations, albedo reduction, radiative forcing, and climatic and hydrological impact of LAPSI at global and regional scales. Finally we identify some research needs for reducing the uncertainties in the impact of LAPSI on global and regional climate and the hydrological cycle."). *See also* Arctic Monitoring and Assessment Programme (2017) Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area, 72 ("Highly reflective surfaces, such as snow and ice in the Arctic increase light absorption by BC particles in the atmosphere. BC also absorbs light after deposition onto (and then into) snow and ice, where it accelerates the melt process (Pedersen et al., 2015). BC has made an important contribution to the observed rise in Arctic surface temperature through the 20th century (although carbon dioxide is still the major factor driving the rise in Arctic temperature) (Quinn et al., 2008; Koch et al., 2011; AMAP, 2015a). It may be technically possible to reduce global anthropogenic BC emissions by up to 75% by 2030 (Shindell et al., 2012; AMAP, 2015a; Stohl et al., 2015). As well as helping to slow warming, BC emission reductions would also have significant health benefits (Anenberg et al., 2012; Shindell et al., 2012)."); International Energy Agency (2016) World Energy Outlook Special Report: Energy and Air Pollution, 115 ("Two areas of clear cross-benefit (for air quality and climate change) are actions to reduce emissions of black carbon, a major component of PM, and of methane (Box 3.4). Black carbon – emitted due to incomplete combustion, particularly from household biomass stoves and diesel vehicles – affects the climate in multiple ways. It absorbs incoming sunlight, leading to warming in the atmosphere, settles on the ground accelerating the melting of Arctic and alpine ice and, along with other pollutants that form aerosols, it affects the formation of clouds, so having a knock-on influence on increased warming."); *and* World Bank & International Cryosphere Climate Initiative (2013) On Thin Ice: How Cutting Pollution Can Slow Warming and Save Lives, 2 ("Climate benefits for cryosphere regions from black carbon reductions carry less uncertainty than they would in other parts of the globe and are sometimes very large. This is because emissions from sources that emit black carbon—even with other pollutants—almost always lead to warming over reflective ice and snow.").

[277] International Maritime Organization (10–17 June 2021) *Marine Environment Protection Committee (MEPC 76)* ("The MEPC adopted amendments to MARPOL Annex I (addition of a new regulation 43A) to introduce a prohibition on the use and carriage for use as fuel of heavy fuel oil (HFO) by ships in Arctic waters on and after 1 July 2024. The prohibition will cover the use and carriage for use as fuel of oils having a density at 15°C higher than 900 kg/m^3 or a kinematic viscosity at 50°C higher than 180 mm^2/s. Ships engaged in securing the safety of ships, or in search and rescue operations, and ships dedicated to oil spill preparedness and response would be exempted. Ships which meet certain construction standards with regard to oil fuel tank protection would need to comply on and after 1 July 2029. A Party to MARPOL with a coastline bordering Arctic waters may temporarily waive the requirements for ships flying its flag while operating in waters subject to that Party's sovereignty or jurisdiction, up to 1 July 2029.").

[278] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 2–3 ("HFO has already been banned in the Antarctic since 2011, without any exemptions or waivers. In the Antarctic, defined by the IMO's MARPOL Convention as a neat circle below 60°S latitude, ships are not only forbidden from using HFO and carrying HFO in their fuel tanks, they cannot even carry HFO as cargo or ballast. There is little

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commercial shipping activity in the Antarctic region, and this made the decision less contentious. The Arctic, meanwhile, has substantial amounts of commercial shipping activity, including fishing and the transport of oil, gas, and minerals from the region. The carriage and use of HFO is especially common for oil tankers, general cargo ships, and bulk carriers in the region, as we will show later in this analysis. The Arctic HFO ban, as currently proposed, would start to apply on July 1, 2024 and would forbid using or carrying HFO as fuel, but would allow HFO cargoes to be transported. In addition to the cargo exemption, the text of the HFO ban allows for exemptions and waivers, as follows."). *See also* Farand C. (3 September 2020) *Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade*, CLIMATE HOME NEWS ("Burning and carrying HFO has been banned in Antarctic waters since 2011, but plans for similar restrictions in the resource-rich Arctic have met with resistance. Russia, which could benefit from the opening of more shipping routes in the region as Arctic sea ice melts, is one of the most vocal opponents.").

[279] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 10–11, 19 ("As shown in Figure 8, had the proposed HFO ban been in place in 2019, it would have banned just 30% of HFO carried as fuel and 16% of the HFO used by ships in the Arctic. Total BC emissions in the Arctic would have fallen by only 5% because the majority of HFO use would have been allowed by virtue of exemptions or waivers. Of the 700 HFO-fueled ships in the Arctic in 2019, 151, or 22% of the fleet, would have been exempt. Of these, 18 would have been eligible for a waiver had they not already been exempt. The flag state with the most exempt ships was Panama, with 31 ships, followed by Marshall Islands with 27, Liberia with 15, Russia with 11, and the Netherlands with 11. Other flag states had fewer than 10 ships exempt. An additional 366 ships, or 52% of the HFO-fueled fleet, would have been eligible for a waiver, including 325 ships flagged to Russia, 20 to Canada, 10 to Norway, 10 to Denmark, and one to the United States. Together, exemptions and waivers would have allowed 74% of the HFO-fueled fleet, by number of ships, to continue to use HFO in the Arctic.").

[280] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 20 ("Moving down Figures 15, 16, and 17, the top bars show the HFO ban without exemptions or waivers, in which case 100% of HFO carriage and use would be banned and BC emissions would decrease by 30%.6 The second bars show that disallowing exemptions and limiting waivers only to IW results in banning 75% of HFO carriage and 82% of HFO use, which would cut BC emissions by 24%. The third bar in the figures shows the impact of allowing waivers in both IW and TS. In this case, 70% of HFO carriage and 75% of HFO use would be banned, and this would cut BC emissions by 22%. Figure 20 shows the location and amount of HFO used that would have been allowed in 2019 under this alternative. Comparing this with Figure 19 shows that HFO remains available for use near shore; this could allow for domestic transportation while banning HFO in the offshore areas. This alternative may strike a balance between allowing HFO to be carried and used for domestic shipping and community resupply while banning a significant amount of HFO carriage and use. However, an HFO spill close to shore would result in larger direct impacts to Arctic coastlines and coastal communities. The most protective alternative is a ban without exemptions and waivers.").

[281] Arctic Council (2019) EXPERT GROUP ON BLACK CARBON AND METHANE SUMMARY OF PROGRESS AND RECOMMENDATIONS 2019, 13 ("At their 2017 meeting the Ministers of the Arctic Council member states adopted an expert group report that recommended a collective, aspirational goal to further reduce black carbon emissions by 25-33 percent relative to 2013 levels by 2025. ").

[282] Organisation for Economic Co-operation and Development (April 2021) THE ECONOMIC BENEFITS OF AIR QUALITY IMPROVEMENTS IN ARCTIC COUNCIL COUNTRIES, 13 ("Additional policies to extensively adopt the best available techniques would allow Arctic Council countries to reduce their emissions more substantially an dhalve their black carbon emissions by 2025, exceeding their collective target.

[283] Organisation for Economic Co-operation and Development (April 2021) THE ECONOMIC BENEFITS OF AIR QUALITY IMPROVEMENTS IN ARCTIC COUNCIL COUNTRIES, 46 ("According to the projections for 2050, with existing policies (the CKLE scenario), 8% of the population living in Arctic Council countries would be exposed to concentration levels of $PM_{2.5}$ above the WHO guidelines. However, in the MTFR-AC scenario, only 1% would be exposed to these concentrations. This decrease I equivalent to a change from 18 million people in the MTFR-AC scenario.").

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[284] International Maritime Organization (1 December 2021) *IMO moves ahead on GHG emissions, Black Carbon and marine litter* ("The International Maritime Organization (IMO) in view of the urgency for all sectors to accelerate their efforts to reduce GHG emissions - as emphasized in the recent IPCC reports and the Glasgow Climate Pact - recognized the need to strengthen the ambition of the Initial IMO GHG Strategy during its revision process. IMO's Marine Environment Protection Committee (MEPC), meeting virtually for its 77th session, 22-26 November 2021, agreed to initiate the revision of its GHG strategy. The MEPC also adopted a resolution on voluntary use of cleaner fuels in the Arctic, to reduce black carbon emissions. In other work, the MEPC adopted a strategy to address marine plastic litter from ships; adopted revised guidelines for exhaust gas cleaning systems (EGCS) and agreed the scope of work on discharge water of EGCS; and considered matters related to the Ballast Water Management Convention."). *See also* Humpert M. (6 December 2021) *IMO adopts new measures to reduce black carbon in Arctic shipping*, ARCTICTODAY.

[285] Guzman J. (1 December 2020) *Every major US bank has now come out against Arctic drilling*, THE HILL ("Goldman Sachs, Morgan Stanley, Chase, Wells Fargo and CitiBank announced commitments not to finance oil and gas projects in the Arctic National Wildlife Refuge (ANWR) earlier this year.").

[286] Marsh A. & Dlouhy J. A. (19 November 2020) *Arctic Oil Fight Comes to Insurers as Trump Plans Lease Sale*, BLOOMBERG GREEN.

[287] Desch S. J., Smith N., Groppi C., Vargas P., Jackson R., Kalyaan A., Nguyen P., Probst L., Rubin M. E., Singleton H., Spacek A., Truitt A., Zaw P. P., & Hartnett H. E. (2017) *Arctic ice management*, EARTH'S FUTURE 5: 107–27, 107 ("Here we investigate a means for enhancing Arctic sea ice production by using wind power during the Arctic winter to pump water to the surface, where it will freeze more rapidly. We show that where appropriate devices are employed, it is possible to increase ice thickness above natural levels, by about 1 m over the course of the winter. We examine the effects this has in the Arctic climate, concluding that deployment over 10% of the Arctic, especially where ice survival is marginal, could more than reverse current trends of ice loss in the Arctic, using existing industrial capacity. We propose that winter ice thickening by wind-powered pumps be considered and assessed as part of a multipronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system."). *See also* Field L., Ivanova D., Bhattacharyya S., Mlaker V., Sholtz A., Decca R., Manzara A., Johnson D., Christodoulou E., Walter P., & Katuri K. (2018) *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, EARTH'S FUTURE 6(6): 882–901 (discussing testing hollow silica beads to enhance albedo of Arctic sea ice); *and* Bodansky D. & Hunt H. (2020) *Arctic Climate Interventions*, INT. J. MAR. COAST. LAW 35(3): 596–617, 605–606 ("Arctic ice management focuses on saving Arctic ice directly, either by increasing the rate of freezing or by decreasing the rate of melting. One proposed technique to increase freezing would be to spray seawater directly on top of the ice during the Arctic winter, when despite global warming it is still generally very cold.[41] Ice is an insulator and slows the freezing of the water beneath it. Pumping water from under sea ice and spraying it on top, where it would be directly exposed to frigid air, would thus increase the rate of freezing and result in thicker ice… A second option focuses on decreasing the rate of melting of Arctic ice by spraying reflective beads on top of the ice in order to increase its albedo.[43]").

[288] Lovejoy T. E. & Nobre C. (2018) *Amazon's Tipping Point*, SCI. ADV. 4(2): eaat2340, 1 ("We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 20–25% deforestation."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 28 ("Ultimately, current research cannot eliminate the possibility that changes across the boreal zone due to a warming climate could act as a net positive climate feedback, thanks to the potential for permafrost thaw and wildfires to liberate the soil carbon that makes up the majority of stored carbon across this ecosystem. Consequently, boreal forest dieback and shifts represent one of the more potentially immediate and significant climate system tipping elements (Table 7).").

[289] Griscom B. W., *et al.* (2017) *Natural climate solutions*, PROC. NAT'L. ACAD. SCI. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when

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constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."). *See also* Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the Unites States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, Perspective, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 ("Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. … The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty."); *and* World Wildlife Fund (2020) *Living Planet Report 2020 – Bending the curve of biodiversity loss*, Almond R. E. A., Grooten M., & Petersen T. (eds.), 6 ("The global Living Planet Index continues to decline. It shows an average 68% decrease in population sizes of mammals, birds, amphibians, reptiles and fish between 1970 and 2016. … It matters because biodiversity is fundamental to human life on Earth, and the evidence is unequivocal – it is being destroyed by us at a rate unprecedented in history. Since the industrial revolution, human activities have increasingly destroyed and degraded forests, grasslands, wetlands and other important ecosystems, threatening human well-being. Seventy-five per cent of the Earth's ice-free land surface has already been significantly altered, most of the oceans are polluted, and more than 85% of the area of wetlands has been lost.").

[290] Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VT. J. ENVT'L. LAW 23: 94–123, 94 ("Burning trees for energy delivers a one-two punch against climate change mitigation efforts. Harvesting woody biomass reduces the sequestration potential of forest carbon sinks, while the combustion of woody biomass releases large quantities of carbon into the air.[1] Forest regrowth may not offset these emissions for many decades[2]—well beyond the time the world has left to slow warming to avoid catastrophic impacts from climate change."). *See also* Raven P., *et al.* (11 February 2021) *Letter Regarding Use of Forests for Bioenergy*, WOODWELL CLIMATE RESEARCH CENTER ("Trees are more valuable alive than dead both for climate and for biodiversity. To meet future net zero emission goals, your governments should work to preserve and restore forests and not to burn them.").

[291] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575: 592–595, 593 ("Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 30% forest-cover loss. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales."). *See also* Taylor L. (5 September 2022) *The Amazon rainforest has already reached a crucial tipping point,* NEW SCIENTIST ("Marlene Quintanilla at the Amazon Geo-Referenced Socio-Environmental Information Network (RAISG) and her colleagues, working in partnership with various groups, including the Coordinator of Indigenous Organizations of the Amazon River Basin, used forest coverage data to map how much of the Amazon was lost between 1985 and 2020 and also looked at forest density, rainfall patterns and carbon storage. …The report finds that 33 per cent of the Amazon remains pristine and 41 per cent of areas have low degradation and could restore themselves. But 26 per cent of areas have been found to have gone too far to restore

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themselves: 20 per cent is lost entirely and 6 per cent is highly degraded and would need human support to be restored.”).

[292] Lovejoy T. E. & Nobre C. (2018) *Amazon’s Tipping Point*, Sci. Adv. 4(2): eaat2340, 1 (“We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 20–25% deforestation.”). *See also* Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 3-263 (“Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass being reduced by about 40%, which can lead to a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4°C (*medium confidence*), although pronounced biomass losses may occur at 1.5°C– 2°C of global warming.”).

[293] Douville H., *et al*. (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1149 (“Both deforestation and drying are projected to increase by 2100, resulting in a worst-case scenario of up to a 50% loss in forest cover by 2050 (Soares-Filho et al., 2006; Boisier et al., 2015; Steege et 50 al., 2015; Gomes et al., 2019).”).

[294] Wang-Erlandsson L., *et al.* (2022) *A planetary boundary for green water*, Nat. Rev. Earth Environ. 3: 380–392, 380 (“Green water — terrestrial precipitation, evaporation and soil moisture — is fundamental to Earth system dynamics and is now extensively perturbed by human pressures at continental to planetary scales. However, green water lacks explicit consideration in the existing planetary boundaries framework that demarcates a global safe operating space for humanity. In this Perspective, we propose a green water planetary boundary and estimate its current status. The green water planetary boundary can be represented by the percentage of ice-free land area on which root-zone soil moisture deviates from Holocene variability for any month of the year. Provisional estimates of departures from Holocene-like conditions, alongside evidence of widespread deterioration in Earth system functioning, indicate that the green water planetary boundary is already transgressed. Moving forward, research needs to address and account for the role of root-zone soil moisture for Earth system resilience in view of ecohydrological, hydroclimatic and sociohydrological interactions.”); *discussed in* Stockhom Resilience Center (26 April 2022) *Freshwater boundary exceeds safe limits* (“Now researchers have explored the water boundary in more detail. The authors argue that previous assessments did not sufficiently capture the role of green water and particularly soil moisture for ensuring the resilience of the biosphere, for securing land carbon sinks, and for regulating atmospheric circulation. “The Amazon rainforest depends on soil moisture for its survival. But there is evidence that parts of the Amazon are drying out. The forest is losing soil moisture as a result of climate change and deforestation,” says Arne Tobian, second author and PhD candidate at the Stockholm Resilience Centre and Potsdam Institute for Climate Impact Research. “These changes are potentially pushing the Amazon closer to a tipping point where large parts could switch from rainforest to savannah-like states,” he adds.”).

[295] Boulton C. A., Lenton T. M., & Boers N. (2022) *Pronounced loss of Amazon rainforest resilience since the early 2000s*, Nat. Clim. Chang. 12(3): 271–78, 277 (“Other factors, including rising atmospheric temperatures in response to anthropogenic greenhouse gas emissions, may additionally have negative effects on Amazon resilience (and are contributing to the warming of northern tropical Atlantic SSTs; Fig. 6a). Furthermore, the rapid change in climate is triggering ecological changes but ecosystems are having difficulties in keeping pace. In particular, the replacement of drought-sensitive tree species by drought-resistant ones is happening slower than changes in (hydro)meteorological conditions50, potentially reducing forest resilience further. In summary, we have revealed empirical evidence that the Amazon rainforest has been losing resilience since the early 2000s, risking dieback with profound implications for biodiversity, carbon storage and climate change at a global scale. We further provided empirical evidence suggesting that overall drier conditions, culminating in three severe drought events, combined with pronounced increases in human land-use activity in the Amazon, probably played a crucial role in the observed resilience loss. The amplified loss of Amazon resilience in areas closer to human land use suggests that reducing deforestation will not just protect the parts of the forest that are directly threatened but also benefit Amazon rainforest resilience over much larger spatial scales.”).

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[296] Lenton T. M., Held H., Kriegler E., Hall J. W., Lucht W., Rahmstorf S., & Schellnhuber H. J. (2008) *Tipping elements in the Earth's climate system*, Proc. Nat'l. Acad. Sci. 105(6): 1786–1793, 1790 ("A large fraction of precipitation in the Amazon basin is recycled, and, therefore, simulations of Amazon deforestation typically generate 20–30% reductions in precipitation (78), lengthening of the dry season, and increases in summer temperatures (79) that would make it difficult for the forest to reestablish, and suggest the system may exhibit bistability."). *See also* Staal A., Fetzer I., Wang-Erlandsson L., Bosmans J. H. C., Dekker S. C., van Nes E. H., Rockström J., & Tuinenburg O. A. (2020) *Hysteresis of tropical forests in the 21st century*, Nat. Commun. 11(4978): 1–8, 5 ("Whether the Amazon in particular is an important global 'tipping element' in the Earth system is a question of great scientific and societal interest[36,37]. Despite our incomplete understanding of Amazon tipping, it is generally considered to be true that the forest's role in the hydrological cycle is so large that deforestation and/or climate change may trigger a tipping point [2,36–38]. More recently, the possibility of fire-induced tipping has also been suggested [5,6]. Although fire occurs at a local scale, a considerable portion of the Amazon would be susceptible to this kind of tipping; by accounting for the feed-backs at both local and regional scales, it becomes more likely that the Amazon is a tipping element. Although under the current climate a majority of the Amazon forest still appears resilient to disturbance (also see ref. 39), we show that this resilience may deteriorate as a result of redistributions of rainfall due to global climate change.").

[297] Gatti L. V., *et al.* (2021) *Amazonia as a carbon source linked to deforestation and climate change*, Nature 595(7867): 388–393, 388 ("Southeastern Amazonia, in particular, acts as a net carbon source (total carbon flux minus fire emissions) to the atmosphere. Over the past 40 years, eastern Amazonia has been subjected to more deforestation, warming and moisture stress than the western part, especially during the dry season… the intensification of the dry season and an increase in deforestation seem to promote ecosystem stress, increase in fire occurrence, and higher carbon emissions in the eastern Amazon. This is in line with recent studies that indicate an increase in tree mortality and a reduction in photosynthesis as a result of climatic changes across Amazonia."). *See also* Brienen R. J. W., *et al.* (2015) *Long-term decline of the Amazon carbon sink*, Nature 519(7543): 344–348, 344 ("While this analysis confirms that Amazon forests have acted as a long-term net biomass sink, we find a long-term decreasing trend of carbon accumulation. Rates of net increase in above-ground biomass declined by one-third during the past decade compared to the 1990s. This is a consequence of growth rate increases levelling off recently, while biomass mortality persistently increased throughout, leading to a shortening of carbon residence times.").

[298] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 5.6, 5-740 ("To estimate an upper limit on the impact of Amazon forest dieback on atmospheric CO_2, we consider the *very unlikely* limiting case of negligible direct-CO_2 effects (Section 5.4.1). Emergent constraint approaches (Section 5.4.6) may be used to estimate an overall loss of tropical land carbon due to climate change alone, of around 50 PgC per °C of tropical warming (Cox et al., 2013; Wenzel et al., 2014). This implies an upper limit to the release of tropical land carbon of <200 PgC over the 21st century (assuming tropical warming of <4°C and no CO_2-fertilization), which translates to $dCO_2/dt<0.5$ ppm yr^{-1}. Boreal forest dieback is not expected to change the atmospheric CO_2 concentration substantially because forest loss at the south is partly compensated by: (i) temperate forest invasion into previously boreal areas; and (ii) boreal forest gain at the north (Friend et al., 2014; Kicklighter et al., 2014; Schaphoff et al., 2016) (*medium confidence*). An upper estimate of this magnitude, based on statistical modelling of climate change alone, is of 27 Pg vegetation carbon loss in the southern boreal forest, which is roughly balanced by gains in the northern zone (Koven, 2013).").*See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 20 ("Strong evidence points toward an increasing frequency and severity of wildfires throughout the arctic and boreal north (Flannigan et al., 2009; Hanes et al., 2019; Kasischke & Turetsky, 2006; McCarty et al., 2020). Field observations have demonstrated that wildfire can act as a major driver of regional permafrost thaw, with fire contributing toward the expansion of thermokarst (areas where thaw leads to ground subsidence) area in western Canada (Gibson et al., 2018), Alaska (Y. Chen et al., 2021), and Siberia (Yanagiya & Furuya, 2020)."; Table 4).

[299] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) Irrecoverable Carbon: the places we must protect to avert climate catastrophe, Conservation International, 7 ("'Irrecoverable carbon' refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change... There are high concentrations of

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irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves, Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, Nat. Clim. Change 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth's ecosystems*, Nat. Sustain. 5: 37–46.

[300] Rockström J., Beringer T., Hole D., Griscom B., Mascia M. B., Folke C., & Creutzig F. (2021) *We Need Biosphere Stewardship That Protects Carbon Sinks and Builds Resilience*, Proc. Nat'l. Acad. Sci. 118(38): 1–8, 2 ("Using the reduced complexity climate model MAGICC6 ("Model for the Assessment of Greenhouse Gas Induced Climate Change Version 6"), we examined changes in global mean temperature up till now and in the future under the RCP2.6 emission scenario—the only emission pathway that aligns with the Paris agreement—but assumed that ecosystems on land had stopped absorbing CO_2 from 1900 onwards. In such a world, global temperatures would have risen much faster (Fig. 1C, red line). In fact, we would have already crossed the 1.5 °C threshold, demonstrating that terrestrial ecosystems have reduced warming by at least 0.4 °C since 1900.").

[301] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, Sci. Adv. 7(3): 1–8, 1 ("The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040."). *See also* Hubau W., *et al.* (2020) *Asynchronous carbon sink saturation in African and Amazonian tropical forests*, Nature 579: 80–87, 85 ("In summary, our results indicate that although intact tropical forests remain major stores of carbon and are key centres of biodiversity11, their ability to sequester additional carbon in trees is waning. In the 1990s intact tropical forests removed 17% of anthropogenic CO_2 emissions. This declined to an estimated 6% in the 2010s, because the pan-tropical weighted average per unit area sink strength declined by 33%, forest area decreased by 19% and anthropogenic CO_2 emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation46 and degradation47, and the future carbon balance will also depend on secondary forest dynamics48 and forest restoration plans49, our analyses show that they are also affected by atmospheric chemistry and climatic changes. Given that the intact tropical forest carbon sink is set to end sooner than even the most pessimistic climate driven vegetation models predict4,5, our analyses suggest that climate change impacts in the tropics may become more severe than predicted. Furthermore, the carbon balance of intact tropical forests will only stabilize once CO_2 concentrations and the climate stabilizes."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 20 ("Based on model projections, under the intermediate scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and oceans are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, land and oceans begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is very unlikely that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions32 (SSP2-4.5, SSP3-7.0, SSP5-8.5). … Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).").

[302] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, Sci. Adv. 7(3): 1–8, 3 ("This…calls into question the future viability of the land sink, along with Intended Nationally Determined Contributions (INDCs) within the Paris Climate Accord, as these rely heavily on land uptake of carbon to meet pledges. In contrast to Representative

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Concentration Pathway 8.5 (RCP8.5), warming associated with scenario RCP2.6 could allow for near-current levels of biosphere productivity, preserving the majority land carbon uptake (~10 to 30% loss).”). *See also* Rockström J., Beringer T., Hole D., Griscom B., Mascia M. B., Folke C., & Creutzig F. (2021) *We Need Biosphere Stewardship That Protects Carbon Sinks and Builds Resilience*, Proc. Nat’l. Acad. Sci. 118(38): 1–8, 1–2 (“All major global climate models whose simulations give us hope of meeting the target of the Paris Climate Agreement—to keep warming well below 2 °C—take the continued provision of this gigantic biosphere endowment for granted, merely concluding, as in the recent IPCC report, that the efficiency of nature’s carbon sink may reduce slightly for high emission pathways. This means that the ability of intact nature to continue to sequester carbon is already factored into the climate models and thus in the estimate of the remaining carbon budget to hold to the Paris climate target. Yet this fundamental assumption relies on terrestrial and marine ecosystems remaining sufficiently intact and resilient to human pressures, even as climate change progresses (3). It is therefore concerning that the IPCC now concludes that Earth’s temperature is slightly more sensitive to rising CO_2 concentrations than previously thought (4)—meaning our remaining carbon budget to achieve the Paris target may have effectively shrunk. If we were able to more accurately simulate feedbacks in the global carbon cycle, such as tipping points in forest ecosystems (5) and abrupt permafrost thaw (6), the estimated remaining budget could disappear altogether.”).

[303] Girardin C. A. J., Jenkins S., Seddon N., Allen M., Lewis S. L., Wheeler C. E., Griscom B. W., & Malhi Y. (2021) *Nature-based solutions can help cool the planet — if we act now*, Comment, Nature 593: 191–194, 192 (“A subset of nature-based solutions can be used specifically to limit warming. These ‘natural climate solutions’ aim to reduce atmospheric greenhouse-gas concentrations in three ways. One is to avoid emissions by protecting ecosystems and thus reducing carbon release; this includes efforts to limit deforestation. Another is to restore ecosystems, such as wetlands, so that they sequester carbon. The third is to improve land management — for timber, crops and grazing — to reduce emissions of carbon, methane and nitrous oxide, as well as to sequester carbon (see ‘Three steps to natural cooling’).”).

[304] Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, Front. For. Glob. Change 2(27): 1–10, 1 (“The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.”).

[305] United Nations Environment Programme & GRID-Arendal (2017) Smoke on Water: Countering Global Threats from Peatlands Loss and Degradation, A Rapid Response Assessment, Crump J. (ed.), 9 (“Current greenhouse gas emissions from drained or burning peatlands are estimated to be up to five percent of all emissions caused by human activity – in the range of two billion tonnes of CO_2 per year. If the world has any hope of keeping the global average temperature increase under two degrees Celsius then urgent action must be taken to keep the carbon locked in peatlands where it is – wet, and in the ground to prevent an increase in emissions. Furthermore, already drained peatlands must be rewetted to halt their ongoing significant emissions. However, this is not as simple as it seems. Knowing the location of peatlands continues to be a challenge.”). *See also* Humpenöder F., Karstens K., Lotze-Campen H., Leifeld J., Menichetti L., Barthelmes A., & Popp A. (2020) *Peatland Protection and Restoration are Key for Climate Change Mitigation*, Environ. Res. Lett. 15(10): 1–12, 10 (“However, in line with other studies (Leifeld et al 2019), our results indicate that it is possible to reconcile land use and GHG emissions in mitigation pathways through a peatland protection and restoration policy (RCP2.6 + PeatRestor). Our results suggest that the land system would turn into a global net carbon sink by 2100, as projected by current mitigation pathways, if about 60% of present-day degraded peatlands, mainly in the tropical and boreal climate zone, would be rewetted in the coming decades, next to the protection of intact peatlands. Therefore, peatland protection and restoration are key for climate change mitigation. At the same time, our results indicate that the implementation costs of peatland protection and restoration measures are low, and that there are almost no impacts on regional food security.”).

[306] Intergovernmental Panel on Climate Change (2019) *Summary for Policymakers*, *in* The Ocean and Cryosphere in a Changing Climate, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.*

(eds.), SPM-30 ("Restoration of vegetated coastal ecosystems, such as mangroves, tidal marshes and seagrass meadows (coastal 'blue carbon' ecosystems), could provide climate change mitigation through increased carbon uptake and storage of around 0.5% of current global emissions annually (*medium confidence*). Improved protection and management can reduce carbon emissions from these ecosystems.").

[307] Booth M. S. (2018) *Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy*, ENVIRON. RES. LETT. 13(3): 1–10, 8 ("For bioenergy to offer genuine climate mitigation, it is essential to move beyond the assumption of instantaneous carbon neutrality. The [net emissions impact (NEI)] approach provides a simple means to estimate net bioenergy emissions over time, albeit one that tends to underestimate actual impacts. The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels."). *See also* Sterman J. D., Siegel L., & Rooney-Varga J. N. (2018) *Does Replacing Coal with Wood Lower CO_2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy*, ENVIRON. RES. LETT. 13(015007): 1–10, 6 ("Scenario 2 shows the realistic case with the combustion efficiency and supply chain emissions estimated for wood pellets (supplementary table S5), again assuming 25% of the biomass is harvested by thinning. Because production and combustion of wood generate more CO_2 than coal, the first impact of bioenergy use is an increase in atmospheric CO_2. Regrowth gradually transfers C from the atmosphere to biomass and soil C stocks, leading to a carbon debt payback time of 52 years; after 100 years CO_2 remains 62% above the zero C case."); *and* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VT. J. ENVTL. LAW 23: 94–123.

[308] UN Climate Change Conference (2 November 2021) *Glasgow Leaders' Declaration on Forests and Land Use* ("We therefore commit to working collectively to halt and reverse forest loss and land degradation by 2030 while delivering sustainable development and promoting an inclusive rural transformation.").

[309] UN Climate Change Conference (2 November 2021) *The Global Forest Finance Pledge: Financing the protection, restoration, and sustainable management of forests* ("Here in Glasgow at COP26, we announce our intention to collectively provide US$12 billion for forest-related climate finance between 2021-2025. This will incentivise results and support action in Official Development Assistance (ODA) eligible forest countries where increased ambition and concrete steps are shown towards ending deforestation by no later than 2030."); *and* UN Climate Change Conference (3 November 2021) *COP26 World Leaders Summit – Presidency Summary* ("Over 120 countries covering more than 90% of the world's forests endorsed the Glasgow Leaders' Declaration on Forests & Land Use committing to work collectively to halt and reverse forest loss and land degradation by 2030, backed by the biggest ever commitment of public funds for forest conservation and a global roadmap to make 75% of forest commodity supply chains sustainable."). *See also* Einhorn C. & Buckley C. (1 November 2021, *updated* 10 November 2021) *Global Leaders Pledge to End Deforestation by 2030*, THE NEW YORK TIMES; *and* Rannard G. & Gillett F. (2 November 2021) *COP26: World leaders promise to end deforestation by 2030*, BBC NEWS.

[310] The White House (2021) PLAN TO CONSERVE GLOBAL FORESTS: CRITICAL CARBON SINKS; *discussed in* United States Department of State (3 November 2021) *Plan to Conserve Global Forests: Critical Carbon Sinks*, Fact Sheet ("At COP26 during the World Leaders Summit Forest Day session on November 2, 2021, the United States announced the **Plan to Conserve Global Forests: Critical Carbon Sinks**. This decade-long, whole-of-government Plan sets forth the U.S. approach to conserving critical global terrestrial carbon sinks, deploying a range of diplomatic, policy, and financing tools. The first-of-its-kind plan for the U.S. government seeks to catalyze the global effort to conserve and restore the forests and other ecosystems that serve as critical carbon sinks. Subject to Congressional appropriations, by 2030, the United States intends to dedicate up to $9 billion of our international climate funding to support the objectives of the Plan…. The Plan supports collective goals the United States has previously endorsed, including efforts to end natural forest loss by 2030; to significantly increase the rate of global restoration of degraded landscapes and forestlands; and to slow, halt, and reverse forest cover and carbon loss. The Plan outlines the initial approaches the United States intends to deploy to achieve four key objectives: Incentivize forest and ecosystem conservation and forest landscape restoration; Catalyze private sector investment, finance, and action to conserve critical carbon sinks; Build long-term capacity and support the data and monitoring systems that enhance accountability; Increase ambition for climate and conservation action.").

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[311] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, Philos. Trans. R. Soc. A 379(2210): 1–17, 1, 11 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."; "Another consideration for active methane-removal systems is the volume of air needed to be processed to remove teragrams of methane. If air handling is to be undertaken at large scales, it would make economic sense to convert other greenhouse gases simultaneously, particularly the catalytic reduction of N_2O to N_2. Although our current paper emphasizes methane removal, co-removal of other gases would reduce unit costs."). *See also* Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E."). For more history on this proposal, *see* Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) *Methane removal and atmospheric restoration*, Nat. Sustain. 2: 436–438, 436 ("In contrast to negative emissions scenarios for CO_2 that typically assume hundreds of billions of tonnes removed over decades and do not restore the atmosphere to preindustrial levels, methane concentrations could be restored to ~750 ppb by removing ~3.2 of the 5.3 Gt of CH_4 currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH_4 could be oxidized to CO_2, a thermodynamically favourable reaction…. In total, the reaction would yield 8.2 additional Gt of atmospheric CO_2, equivalent to a few months of current industrial CO_2 emissions, but it would eliminate approximately one sixth of total radiative forcing. As a result, methane removal or conversion would strongly complement current CO_2 and CH_4 emissions-reduction activities. The reduction in short-term warming, attributable to methane's high radiative forcing and relatively short lifetime, would also provide more time to adapt to warming from long-lived greenhouse gases such as CO_2 and N_2O."). Klaus Lackner critiqued the Jackson *et al.* article in a published response, arguing that implementing zeolite mechanisms to facilitate CH_4 removal is not practical. Lackner noted CH_4 removal faces the challenge of extreme dilution in the atmosphere, so "the amount of air that would need to be moved [to facilitate CH_4 removal] would simply be too great" to be economically feasible. However, Lackner did note passive methods of CH_4 removal through the use of zeolites may still be a viable solution. Lackner further argues that N_2O may be a more worthy target for removal due to its long lifetime in the atmosphere: *see* Lackner K. S. (2020) *Practical Constraints on Atmospheric Methane Removal*, Nat. Sustain. 3: 357. Jackson *et al.* published a response to Lackner, acknowledging his stature in the greenhouse gas removal field and his concerns about the feasibility and energy requirements of their proposed mechanism, offering additional explanation about alternative options for use of the captured methane instead of just converting it to CO_2 as suggested in the original study: *see* Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., Field C. B., & Abernethy S. (2020) *Reply to: Practical constraints on atmospheric methane removal*, Nat. Sustain. 3: 358–359. Another study looking at removing non-CO_2 GHGs investigated the potential of using solar chimney power plants (SCPPs) with select photocatalysts (depending on what GHGs desired to be captured). While the SCPP serves as a source of renewable energy that could remove methane and nitrous oxide among other atmospheric pollutants, scaling up the prototype would require a massive amount of land area (roughly 23 times the size of the entire Beijing municipality) and a chimney stretching 1000–1500 m into the air, which limits how practical the existing technology may be: *see* de Richter R., Tingzhen M., Davies P., Wei L., & Caillol S. (2017) *Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis*, Prog. Energy Combust. Sci. 60: 68–96.

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[312] Nisbet-Jones P. B. R., Fernandez J. M., Fisher R. E., France J. L., Lowry D., Waltham D. A., Woolley Maisch C. A., & Nisbet E. G. (2021) *Is the destruction or removal of atmospheric methane a worthwhile option?*, PHILOS. TRANS. R. SOC. A 380(2215): 1–12, 5 ("Methane is relatively difficult to oxidize compared to other hydrocarbons. The major destruction options include (i) thermal-catalytic oxidation, which is typically with metal catalysts; (ii) photocatalytic oxidation; (iii) biological uptake by aerobic methanotrophic bacteria or their bio-engineered methane-oxidising enzymes and (iv) removal by uptake on zeolites or porous polymers, with the added benefit of not emitting CO2 waste."). *See also* Ming T., Li W., Yuan Q., Davies P., de Richter R., Peng C., Deng Q., Yuan Y., Caillol S., & Zhou N. (2022) *Perspectives on removal of atmospheric methane*, ADV. APPL. ENER. 5(100086): 1–9, 1 ("This article reviews proposed methods for atmospheric methane removal at a climatically significant scale. These methods include enhancement of natural hydroxyl and chlorine sinks, photocatalysis in solar updraft towers, zeolite catalyst in direct air capture devices, and methanotrophic bacteria.").

[313] Advanced Research Projects Agency-Energy (8 April 2021) *Reducing Emissions of Methane Every Day of the Year*, ARPA-E Programs ("**Program Description**: REMEDY (Reducing Emissions of Methane Every Day of the Year) is a three-year, $35 million research program to reduce methane emissions from three sources in the oil, gas, and coal value chains: 1) Exhaust from 50,000 natural gas-fired lean-burn engines. These engines are used to drive compressors, generate electricity, and increasingly repower ships. 2) The estimated 300,000 flares required for safe operation of oil and gas facilities. 3) Coal mine ventilation air methane (VAM) exhausted from 250 operating underground mines. These sources are responsible for at least 10% of U.S. anthropogenic methane emissions. Reducing emissions of methane, which has a high greenhouse gas warming potential, will ameliorate climate change.").

[314] Advanced Research Projects Agency-Energy (30 September 2020) *Prevention and Abatement of Methane Emissions* ("We're open to all options – but specifically are looking for solutions that: Prevent methane emissions from anthropogenic activities. In other words, solutions which intervene before anthropogenic emissions escape to the atmosphere. Abate methane emissions at their source. Sources include vents, leaks, and exhaust stacks. Remove methane from the air. As mentioned above, methane only lasts about 9 years in the atmosphere. Nature is very good at getting rid of methane using reactions in the atmosphere and methanotrophs in the soil. Maybe we can learn from Nature, and help her out."). *See also* Lewnard J. (16 November 2020) *REMEDY – Reducing Emissions of Methane Every Day of the Year*, ARPA-E Presentation, 7 ("Example Potential Approaches, Not Intended to Limit or Direct… "Geo-engineering": Accelerate tropospheric reactions; Accelerate soil/methanotroph reactions").

[315] Advanced Research Projects Agency-Energy (2 December 2021) *U.S. Department of Energy Awards $35 Million for Technologies to Reduce Methane Emissions*, Press Release ("MAHLE Powertrain (Plymouth, MI) will develop a catalytic system to oxidize methane in the exhaust gas of lean-burn natural gas fired engines. (Selection amount: $3,257,089).... Johnson Matthey, Inc. (Wayne, PA) is developing new technology, which uses a noble metal catalyst to combust the dilute methane in coal mine ventilation systems. (Selection amount: $4,346,015) Massachusetts Institute of Technology (Cambridge, MA) is developing a low-cost copper-based catalyst for reducing methane emissions. (Selection amount: $2,020,903)…."). *See also* Advanced Research Projects Agency-Energy (2 December 2021) *REMEDY—Reducing Emissions of Methane Every Day of the Year: Project Descriptions*, Press Release.

[316] *See* CHIPS and Science Act, Pub. L. No. 117-167 § 10771 (2022); United States Senate (2022) *CHIPS and Science Act of 2022: Section-by-Section Summary*; *and* White House (9 August 2022) *FACT SHEET: CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China*, Briefing Room; *discussed in* Meyer R. (10 August 2022) *Congress Just Passed a Big Climate Bill. No, Not That One.*, THE ATLANTIC ("The bill could direct about $12 billion in new research, development, and demonstration funding to the Department of Energy, according to RMI's estimate. That includes doubling the budget for ARPA-E, the department's advanced-energy-projects skunk works."); *and* Ovide S. (10 August 2022) *Taxpayers for U.S. Chips*, THE NEW YORK TIMES.

[317] Alicat Scientific, *Frost Methane mitigates methane gas emissions from Arctic Circle permafrost* (*last visited* 13 June 2023) ("Frost Methane and collaborators from University of Alaska Fairbanks tested their methane-capture technology for the first time on August 13, 2021. The team deployed their equipment at a lake in the Arctic Circle, about 67.25 degrees north. Laughlin Barker, Frost Methane's Senior Embedded Systems Engineer, described the lake as, 'basically a Jacuzzi, there's so much natural gas.'").

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[318] In the U.S., the Consolidated Appropriations Act of 2022 and Investment and Innovation and Jobs Act of 2021 allocated $49 million of funding per year to the Department of Energy for CDR technology and a $3.5 billion investment in four direct air capture hubs, which is expected to remove a million tonnes of CO_2 a year. Additionally, the CHIPS and Science Act of 2022 included several provisions relating to carbon dioxide removal, including $1 billion in funding for carbon removal research and development, establishing a Basic Energy Science Program to research carbon conversion and sequestration in geologic formations, and creating "at least two" carbon storage research centers. *See* Consolidated Appropriations Act, Pub. L. No. 117-103, 136 Stat. 222-227 (2022); Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, § 40308 (2021) (codified at 42 U.S.C. § 16371); *and* CHIPS and Science Act, Pub. L. No. 117-167, §§ 10102, 10771 (2022).

[319] A Swiss company, Climeworks, deployed the world's largest direct air capture and storage plant for carbon dioxide, where they work with the Icelandic start-up Carbfix to store carbon by injecting the carbon into subsurface ground, where it reacts with rock formations to turn into rocks within two years. *See* Climeworks, *Carbon dioxide removal: our service to fight global warming* (*last visited* 14 June 2023) ("At Climeworks, we offer carbon dioxide removal for individuals and businesses who want to fight climate change. With our service, you can take action on behalf of the planet by permanently removing your unavoidable CO_2 emissions. To achieve this, we combine our direct air capture technology with permanent underground storage (direct air capture & storage = DAC+S). Direct air capture, as the term implies, is a technology that captures carbon dioxide directly from the air — such as our Orca facility in Hellisheidi, Iceland. Permanent underground storage is what happens after we hand the air-captured CO_2 over to our storage partner — Carbfix. They transport the CO_2 deep underground, where it reacts with basalt rock through a natural process, transforms into stone, and remains for over 10,000 years. This makes our carbon dioxide removal service both effective and permanent."); *and* Carbfix, *How it works* (*last visited* 14 June 2023) ("Trees and vegetation are not the only form of carbon drawdown from the atmosphere. Vast quantities of carbon are naturally stored in rocks. Carbfix imitates and accelerates these natural processes, where carbon dioxide is dissolved in water and interacts with reactive rock formations, such as basalts, to form stable minerals providing a permanent and safe carbon sink. The Carbfix process captures and permanently removes CO_2. The technology provides a complete carbon capture and injection solution, where CO_2 dissolved in water – a sparkling water of sorts – is injected into the subsurface where it reacts with favorable rock formations to form solid carbonate minerals via natural processes in about 2 years. For the Carbfix technology to work, one needs to meet three requirements: favorable rocks, water, and a source of carbon dioxide."); *discussed in* Rawnsley J. (11 August 2022) *Racing against the clock to decarbonise the planet*, Financial Times. For a discussion on carbon dioxide storage through a mineral carbonation process, *see* Snæbjörnsdóttir S. Ó., Sigfússon B., Marieni C., Goldberg D., Gislason S. R., & Oelkers E. H. (2020) *Carbon dioxide storage through mineral carbonation*, Nat. Rev. Earth Environ. 1: 90–102; Galeczka I. M., Stefánsson A., Kleine B. I., Gunnarsson-Robin J., Snæbjörnsdóttir S. Ó., Sigfússon B., Gunnarsdóttir S. H., Weisenberger T. B., & Oelkers E. H. (2022) *A pre-injection assessment of CO_2 and H_2S mineralization reactions at the Nesjavellir (Iceland) geothermal storage site*, Int. J. Greenh. Gas Control 115(103610): 1–18; *and* Ratouis T., Snæbjörnsdóttir S. Ó., Voigt M. J., Sigfússon B., Aradóttir E. A., & Hjörleifsdóttir V. (2022) *A transport model of long-term CO_2 and H_2S injection into basaltic rocks at Hellisheidi, SW-Iceland*, Int. J. Greenh. Gas Control 114(103586): 1–20. In July 2022, Carbfix was awarded 16 billion Icelandic Króna (US $116 million) by the European Union's Innovation Fund to build the Coda Terminal Plant, which could store up to 3 million tonnes of CO_2 annually by 2031. *See also* Carbfix (11 July 2022) *Carbfix's Coda Terminal awarded large EU grant* ("Carbfix has been selected for grant award from the European Innovation Fund to build the Coda Terminal, a large-scale CO_2 transport and storage hub at Straumsvík, Iceland. The hub will be the first of its kind in the world. Operations are set to commence in mid-2026 and full capacity will be achieved in 2031, when up to 3 million tons of CO_2 will be annually stored by permanently mineralizing it underground."); *and* European Commission (12 July 2022) *Innovation Fund: EU invests €1.8 billion in clean tech projects**, Press Release ("Today, the EU is investing over €1.8 billion in 17 large-scale innovative clean-tech projects with a third round of awards under the Innovation Fund. Grants will be disbursed from the Innovation Fund to help bring breakthrough technologies to the market in energy-intensive industries, hydrogen, renewable energy, carbon capture and storage infrastructure, and manufacturing of key components for energy storage and renewables…. A project in Iceland will build a highly scalable onshore carbon mineral storage terminal with an estimated overall storage capacity of 880 million tonnes of CO_2."); *discussed in* (21 July 2022) *Carbfix gets the biggest EU grant any Icelandic company has been awarded*, Iceland Monitor.

[320] International Energy Agency (2022) *Direct Air Capture* ("Eighteen DAC plants are currently operational in Europe, the United States and Canada. All of these plants are small scale, and the large majority of them capture CO2 for utilisation – for drinks carbonation, for instance – with only two plants storing the captured CO2 in geological

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formations for removal. Only a few commercial agreements are in place to sell or store the captured CO2, while the remaining plants are operated for testing and demonstration purposes. The first large-scale DAC plant of up to 1 Mt CO_2/year is in advanced development and is expected to be operating in the United States by the mid-2020s. An improved investment environment led to announcements of several new DAC projects in 2021, including the Storegga Dreamcatcher Project (United Kingdom; aimed at carbon removal) and the HIF Haru Oni eFuels Pilot Plant (Chile; producing synthetic fuels from electrolysis-based hydrogen and air-captured CO_2). Synthetic fuels (up to 3 million litres) are also set to be produced by the Norsk e-Fuel AS consortium in Norway by 2024, including (but not using exclusively) CO_2 captured from DAC. In June 2022 1PointFive and Carbon Engineering announced plans to deploy 70 large-scale DAC facilities by 2035 (each with a capture capacity of up to 1 million tonnes per year) under current policy and voluntary and compliance market conditions, while Climeworks announced the construction of their largest plant to date, Mammoth (capture capacity up to 36 000 t CO_2/year), which should become operational by 2024."). *See also* Cross J. N., Sweeney C., Jewett E. B., Feely R. A., McElhany P., Carter B., Stein T., Kitch G. D., & Gledhill D. K. (2023) Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio, National Oceanic and Atmospheric Administration Special Report.

[321] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2023) *Global warming overshoots increase risks of climate tipping cascades in a network model*, Nat. Clim. Chang. 13: 75–82, 78–79 ("We define a high climate-risk zone as the region where the likelihood for no tipping event is smaller than 66% or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d–f). For convergence temperatures of 1.5 °C and above, our results indicate that the high climate-risk zone spans the entire state space for final convergence temperatures of 1.5–2.0 °C. Only if final convergence temperatures are limited to or, better, below today's levels of global warming, while peak temperatures are below 3.0 °C, the tipping risks remain below 33% (Fig. 3d)…In the worst case of a convergence temperature of 2.0 °C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0 °C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail notable sea-level rise, biosphere degradation or considerable North Atlantic temperature drops.").

[322] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping point*s, Science 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…."); Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, Proc. Nat'l. Acad. Sci. 115(33): 8252–8259, 8254 ("This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. The challenge that

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humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System’s stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*).”; “The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

[323] Sun X., Wang P., Ferris T., Lin H., Dreyfus G., Gu B., Zaelke D., & Wang Y. (2022) *Fast Action on Short-lived Climate Pollutants and Nature-based Solutions to Help Countries Meet Carbon Neutrality Goals*, Adv. Clim. Chang. Res. 13: 564–577, 569 (“While more than 130 countries have committed to reaching net-zero emissions, only some of these jurisdictions include non-CO_2 pollutants in their pledges (Hale et al., 2021). As demonstrated by the summary of scientific studies above, countries need to include fast acting strategies on SLCPs and NbS in their climate policies to secure the most avoided warming on the way to meeting their carbon neutrality goals.”).

[324] United Nations (9 August 2021) *Guterres: The IPCC Report is a code red for humanity*, UN Regional Information Centre for Western Europe (“UN Secretary-General António Guterres says a report published today by the Intergovernmental Panel on Climate Change (IPCC) is a “code red for humanity.” “The alarm bells are deafening, and the evidence is irrefutable: greenhouse gas emissions from fossil fuel burning and deforestation are choking our planet and putting billions of people at immediate risk,” the Secretary-General says in a statement.”).

[325] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4 (“Human activities are estimated to have caused approximately 1.0 ºC of global warming above pre-industrial levels, with a *likely* range of 0.8 ºC to 1.2 ºC. Global warming is *likely* to reach 1.5 ºC between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).”). In addition to cutting CO_2 emissions and emissions of the super climate pollutants, the IPCC 1.5 ºC Report also calculates the need for significant CO_2 removal. *Id.*, at 17 (“C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.”).

[326] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat’l. Acad. Sci. 114(39): 10315–10323, 10319 (“Box 2. Risk Categorization of Climate Change to Society. … Warming of such magnitudes also has catastrophic human health effects. Many recent studies (**50**, **51**) have focused on the direct influence of extreme events such as heat waves on public health by evaluating exposure to heat stress and hyperthermia. It has been estimated that the likelihood of extreme events (defined as 3-sigma events), including heat waves, has increased 10-fold in the recent decades(**52**). Human beings are extremely sensitive to heat stress. For example, the 2013 European heat wave led to about 70,000 premature mortalities (**53**). The major finding of a recent study (**51**) is that, currently, about 13.6% of land area with a population of 30.6% is exposed to deadly heat. … According to this study, a 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of

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the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3°C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (**54**). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5°C). The current rate of loss of species is ∼1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (**56**). Global warming of 6°C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (**57**). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (**58**), motivated us to categorize warming beyond 5°C as unknown??, implying the possibility of existential threats.").

[327] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254, 8256 ("This risk is represented in **Figs. 1** and 2 by a planetary threshold (horizontal broken line in **Fig. 1** on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (***Biogeophysical Feedbacks***) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (**15**, **16**). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (**12**, **17**), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (***Tipping Cascades***). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. **18**). This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. … Hothouse Earth is likely to be uncontrollable and dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability (**12**, **39**, **49**, **50**) (especially for the most climate vulnerable), and ultimately, the habitability of the planet for humans.").

[328] United Nations Environment Programme (2023) *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*, 1–38, 22 ("In the interests of academic freedom, it is suggested that no formal governance framework for SRM indoor research is required at this time. However, it would be advantageous to develop a set of norms or voluntary code of conduct that would promote reporting, transparency, inclusiveness and data-sharing. To govern small-scale outdoor SRM experiments or operational deployment of SRM systems, several existing frameworks could be relevant (Annex 5)… There is general agreement among this group of experts that governance of large-scale SAI deployment is valuable given the inherent risks associated with changing stratospheric conditions caused by large-scale interventions over long time periods (i.e. multiple decades). A broader framework for the governance of the stratosphere would address the changes that occur in the stratosphere from SAI experiments or deployment, and by other activities such as rocket launches, but might not address other concerns that are specific to SRM.").

[329] Hunter D. B., Salzman J. E., & Zaelke D. (2021) *Glasgow Climate Summit: COP26*, UCLA School of Law, Public Law Research Paper No. 22-02, 3 ("More generally, COP26 may also reflect an evolution (and a vindication) of the Paris Agreement's more flexible policy approach—an evolution which supported significantly higher climate ambition than was expected and certainly more than would have occurred if COP26 had been hosted in 2020, as originally intended. Four shifts in focus reflect this new architecture; first, the near-unanimous recognition of the impending climate emergency and the need to limit warming to 1.5 degrees Celsius; second, the recognition "that 2030 is the new 2050," as French President Emmanuel Macron said, and that major emission cuts have to be made in this decade (note also that the U.S.-China Joint Glasgow Declaration marked the first time that the United States and China acknowledged the urgency of climate action in this "critical decade" of the 2020s); third, the recognition that cutting non-CO2 emissions (particularly methane) is essential for slowing warming in the next couple of decades and that cuts to CO2 alone cannot address the near-term emergency; and fourth, the addition of sector-specific approaches in recognition that it is often more efficient and effective to address individual sectors of the economy in reaching climate solutions."). *See also* Zaelke D. & Dreyfus G. (29 December 2021) *The good, the bad and the ugly of climate*

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change in 2021 — but it's not too late to act, THE HILL; Zaelke D., Picolotti R., & Dreyfus G. (14 November 2021) *Glasgow climate summit: A glass half full*, THE HILL; Bledsoe P., Zaelke D., & Dreyfus G. (8 November 2021) *How to Limit Temperature Increases in the Very Near Term*, THE NEW YORK TIMES; *and* Zaelke D. (21 September 2021) *A new UN climate architecture is emerging focused on need for speed*, THE HILL.