Primer on Short-Lived Climate Pollutants

Slowing the rate of global warming over the near term by cutting short-lived climate pollutants to complement carbon dioxide reductions for the long term

Institute for Governance & Sustainable Development

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The Institute for Governance & Sustainable Development's mission is to promote just and sustainable societies and to protect the environment by advancing the understanding, development, and implementation of effective, accountable and democratic systems of governance for sustainable development.

Beginning in 2005, the Institute embarked on a "fast-action" climate mitigation campaign to promote strategies that will result in significant reductions of emissions, temperature, and impacts in the near term, focusing primarily on strategies to reduce non-CO_2 climate pollutants, to complement cuts in CO_2, which is responsible for more than half of all warming. It is essential to reduce both non-CO_2 pollutants and CO_2. Neither alone is sufficient to limit the increase in global temperature to a safe level.

IGSD's fast-action strategies include reducing emissions of short-lived climate pollutants—black carbon, methane, tropospheric ozone, and hydrofluorocarbons. They also include measures to capture, reuse, and / or store CO_2 after it is emitted, including biosequestration and strategies to turn biomass into more stable forms of carbon for long-term storage.

Durwood Zaelke, President*

IGSD

Institute for Governance & Sustainable Development

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Executive Summary

Carbon dioxide (CO_2) emissions are responsible for 55-60% of anthropogenic radiative forcing.[1] Fast and aggressive CO_2 mitigation is therefore essential to combat the resulting climate change. But this is not enough. CO_2 mitigation must be combined with fast and aggressive reductions of the pollutants causing the other 40-45% of warming.[2] These pollutants include black carbon, tropospheric ozone, methane, and hydrofluorocarbons (HFCs). Because these pollutants have atmospheric lifetimes of only days to a decade and a half, they are referred to as short-lived climate pollutants (SLCPs). Reducing SLCPs is critical for slowing the rate of climate change over the next several decades and for protecting the people and regions most vulnerable to near-term climate impacts.

Although we have known about SLCPs for more than thirty-five years,[3] the following scientific developments have catapulted them to the front lines in the battle against climate change.

- *First* is the recognition that we have already added enough greenhouse gases to warm the planet by 2.4°C or more during this century.[4] Much of this warming has been offset by cooling aerosols, primarily sulfates, which are being reduced under current air pollution policies. These reductions are important, but will contribute to near-term warming. Without fast-action mitigation to cut SLCPs, warming may cross the 1.5° to 2°C threshold by mid-century. Reducing SLCPs is the most effective strategy for constraining warming in the near term, since most of their warming effect disappears within weeks to a decade and a half after reductions.

- *Second* is the recognition that in addition to being climate forcers, three of the four SLCPs are also air pollutants that damage public health and ecosystems. Reducing them will prevent millions of premature deaths every year, protect tens of millions of tonnes of crops, and contribute to sustainable development.
- *Third* is the recognition that the benefits for health, crops, and sustainable development will accrue primarily in the nations or regions that take action to mitigate these pollutants, due to the stronger impacts black carbon and tropospheric ozone have near their emissions sources.
- *Fourth* is the recognition that there are practical and proven ways to reduce all four of these pollutants and that existing laws and institutions are often available to support the reductions.

Reducing three of the SLCPs—black carbon, tropospheric ozone, and methane—has the potential to avoid ~0.5°C global average warming by 2050[5] and 0.84°C in the Arctic by 2070.[6] This would cut the current rate of global warming by half, the rate of warming in the Arctic by two thirds, and the rate of warming over the elevated regions of the Himalayas and Tibet by at least half.[7]

Reducing SLCPs will in turn:

- Help stabilize regional climate systems and reduce heat waves, fires, droughts, floods and hurricanes in mid-latitudes, and slow shifts in monsoons, expansion of desertification, and increases in cyclones in the tropics.
- Slow the melting of glaciers and Arctic sea ice and the rate of sea-level rise.[8]
- Slow the pace of other climate impacts and provide critical time to adapt to unavoidable impacts.

The primary direct local benefits for developing countries from reducing SLCPs include:

- Saving millions of lives a year and significantly reducing other illnesses.
- Improving food security.
- Expanding access to sustainable energy for the billions forced to depend on traditional cooking and heating fuels.

Preventing growth in the other SLCP, HFCs, can increase the warming prevented by 2050 to ~0.6°C and can prevent an additional ~0.4°C warming by 2100. Reductions in all of these SLCPs can be achieved quickly, and in most cases by using existing technologies and existing laws and institutions.

Using existing technologies and institutions to reduce these non-CO_2 climate pollutants may offer the best near-term protection for the countries that are most vulnerable to climate change impacts, including island nations, countries with low-lying coastal areas, and agriculture-dependent countries in Asia and Africa already suffering droughts, floods, and shifting rainfall. Slowing the rate of climate change and reducing near-term impacts is a critical complement to adaptation strategies and to sustainable development, with the potential to provide global benefits for climate, crops, and health valued at $5.9 trillion annually, starting in 2030.

Each of these four SLCPs are being addressed in the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC). The CCAC is comprised of developing and developed countries, along with UNEP, UNDP, the European Commission, and the World Bank, as well as non-governmental organizations.[9] The G8 countries joined the Coalition and their leaders requested the World Bank to conduct a study of how best to integrate SLCP reductions in its programs.

In addition to being included in the CCAC, HFCs are addressed in the Rio + 20 declaration, *The Future We Want*, where leaders supported phasing down HFC production and use.[10] Such a phase down can be achieved through the Montreal Protocol, while simultaneously improving the energy efficiency of refrigerators, air conditioners, and other equipment and products that use these chemicals, thus reducing CO_2 emissions as well. The Federated States of Micronesia has made a formal proposal to amend the Montreal Protocol to do this, as have the North American Parties (Mexico, Canada, and the U.S.).[11] As of 2013 more than 100 Parties have expressed support.[12] Action at national and regional levels, such as the European Union's regulatory efforts, also can help reduce HFCs, as can voluntary efforts.

Although reducing SLCPs is essential for reducing near-term climate impacts, it is not sufficient. Aggressive reductions in CO_2 emissions also are essential for limiting temperature rise. However, in contrast to the short lifetime of SLCPs, only about half of CO_2 emissions are removed from the atmosphere in the first hundred years with a significant fraction lasting for several millennia.[13] Reducing CO_2 emissions now, in line with 450 parts per million (ppm) scenarios, can avoid approximately 0.15°C of additional warming compared to the warming expected from a business-as-usual (BAU) scenario within 30 years, growing to 0.5°C within 50 years.[14] However, such cuts to CO_2 alone, would still see temperatures rise above 2°C by the middle of this century (*see* Fig. 5).

Importantly, SLCP and CO_2 reductions are complementary, and if large-scale reductions of both are undertaken immediately there is a high probability of keeping the increase in global temperature to less than 1.5°C above the pre-industrial temperature for the next 30 years and below the 2°C guardrail for the next 60 to 90 years (s*ee* Fig. 4 & 5).

Introduction to Short-lived Climate Pollutants

CO_2 emissions account for 55-60% of current anthropogenic radiative forcing. Fast and aggressive CO_2 cuts are essential to combat the resulting climate change. But this is not enough. CO_2 cuts must be combined with fast and aggressive cuts to SLCPs, which are causing the other 40-45% of forcing.

Black Carbon

Black carbon is a potent climate-forcing aerosol that remains in the atmosphere for only a few days or weeks.[15] It is a component of soot and is a product of the incomplete combustion of fossil fuels, biofuels, and biomass.[16] Black carbon contributes to climate change in several ways: it warms the atmosphere directly by absorbing solar radiation and emitting it as heat, it contributes to melting by darkening the surfaces of ice and snow when it is deposited on them, and it can also affect the microphysical properties of clouds in a manner than can perturb precipitation patterns. Recent estimates of black carbon's radiative forcing confirm that it is the second leading cause of global warming.[17] The total climate forcing of black carbon is 1.1 W m^{-2}, second only to CO_2 (1.7 W m^{-2}).[18]

Black carbon also harms human health; it is a primary component of fine particle air pollution (PM2.5), and can cause or contribute to a number of adverse health effects, including asthma and other respiratory problems, low birth weights, heart attacks, and lung cancer.[19]

The main sources of black carbon are open burning of biomass, diesel engines, and the residential burning of solid fuels such as coal, wood, dung, and agricultural residues.[20] In 2000, global emissions of black carbon were estimated at approximately 7.5 million tons, with a large uncertainty range.[21]

Black carbon is co-emitted with other pollutants, some of which are light in color and cause cooling by scattering solar radiation back into the atmosphere.[22] The type and quantity of pollutants differs by source, and a high ratio of warming to cooling pollutants indicates the most promising sources to target for producing fast cooling.[23] A recent assessment of black carbon confirmed that emissions from diesel engines and some industrial and residential coal sources have the highest ratio of black carbon to lighter co-emitted pollutants compared to other black carbon sources.[24]

Another recent study of co-emitted pollutants known collectively as "brown carbon" indicates that even black carbon sources that have a high proportion of lighter co-emitted pollutants, such as the open burning of biomass, may still cause net warming.[25] This is because the warming from brown carbon appears to be offsetting some or all of the lighter particles' cooling effect. This, in turn, would mean that the lighter pollutants are not offsetting as much warming from black carbon as assumed in many models.

Over areas of snow and ice, such as the Arctic, even sources with a large proportion of pollutants that normally cause cooling still produce significant warming.[26] This is because deposition of both darker and lighter particles, including dust, reduces the reflectivity (albedo) of snow and ice, allowing more solar radiation to be absorbed, which causes local warming and increases surface melting.[27] Regardless of the climate effect, all particle pollutants harm human health.[28]

Thanks to modern pollution controls and fuel switching, black carbon emissions in North America and Europe were significantly curbed in the early 1900s. However, mobile sources, particularly diesel vehicles, continue to be a major source category for these regions.[29] Black carbon sources in developing countries are significantly different from those in North America and Europe. In developing countries, a much larger proportion of black carbon emissions comes from residential heating and cooking, and industry.[30] According to UNEP, global emissions of black carbon are expected to remain relatively stable through 2030, with continuing reductions in North America and Europe largely offset by continued growth in other parts of the world.[31]

Methane

Methane is a powerful greenhouse gas with a 100-year global warming potential 21 times that of CO_2 and an atmospheric lifetime of approximately 12 years.[32] About 60% of global methane emissions are due to human activities.[33] The main sources of anthropogenic methane emissions are oil and gas systems; agriculture, including enteric fermentation, manure management, and rice cultivations; landfills; wastewater treatment; and emissions from coal mines. Methane is the primary component of natural gas, with some emitted to the atmosphere during its production, processing, storage, transmission, and distribution.[34]

The radiative forcing of methane in 2005 was 0.48 W/m^2, which is about 30% of CO_2 radiative forcing.[35] According to a recent UNEP and WMO assessment, anthropogenic methane emissions are expected to grow 25% over 2005 levels by 2030, driven by increased production from coal mining and oil and gas production, and growth in agricultural and municipal waste emissions.[36]

Tropospheric Ozone

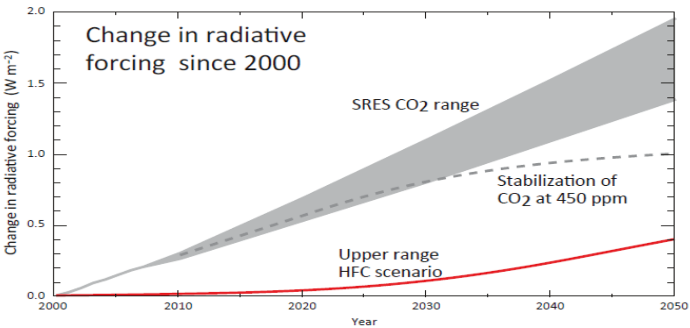
Ozone is a reactive gas which, when in the stratosphere, absorbs dangerous ultraviolet radiation; however, lower atmosphere (tropospheric) ozone is a major air and climate pollutant which causes warming and is harmful to human health and crop production.[37] Breathing ozone is particularly dangerous to children, older adults and people with lung diseases, and can cause bronchitis, emphysema, asthma, and may permanently scar lung tissue.[38] Its impacts on plant include not only lower crop yields but also a reduced ability to absorb CO_2.[39]

Tropospheric ozone is not emitted directly but instead forms from reactions between precursor gases, both human-produced and natural. These precursor gases include carbon monoxide, oxides of nitrogen (NOx), and volatile organic compounds (VOCs), which include methane. Globally increased methane emissions are responsible for approximately two thirds of the rise in tropospheric ozone.[40] Reducing emissions of methane will lead to significant reductions in tropospheric ozone and its damaging effects.[41]

Hydrofluorocarbons (HFCs)

HFCs are factory-made chemicals used primarily in refrigeration and insulating foams. They have a warming effect hundreds to thousands of times more powerful than CO_2. The average lifetime of the mix of HFCs, weighted by usage, is 15 years.[42] HFCs are the fastest growing greenhouse gases in many countries, including the U.S., where emissions grew nearly 9% between 2009 and 2010 compared to 3.6% for CO_2.[43] Globally, HFC emissions are growing 10 to 15% per year and are expected to double by 2020. Without fast action to limit their growth, by 2050 the annual climate forcing of HFCs could equal nearly 20% of the forcing from CO_2 emissions in a BAU scenario, and up to 40% of the forcing from CO_2 emissions under a scenario where CO_2 concentrations have been limited to 450 parts ppm (*see* Fig. 1).[44] This is about the same as the forcing from present annual CO_2 emissions from the transportation sector.

Figure 1: HFCs Projected to be up to 20-40% of RF of CO_2 in 2050



Projected radiative forcing of climate by HFCs and CO_2 since 2000, when the influence of HFCs was essentially zero. The HFC climate forcing for an upper range scenario is compared with the CO_2 forcing for the range of scenarios from IPCC-SRES and the 450 ppm CO_2 stabilization scenario. Clearly, the contribution of HFCs to radiative forcing could be very significant in the future; by 2050, it could be as much as a quarter of that due to CO_2 increases since 2000, if the upper range HFC scenario is compared to the median of the SRES scenario. Alternatively, the contribution of HFCs to radiative forcing could be one fifth the radiative forcing due to CO_2 increases since 2000, if the upper range HFC scenario is compared to the upper range of the SRES scenario. The contribution of HFCs to radiative forcing could also be as much as 40% of the radiative forcing by CO_2 under the 450 ppm scenario.[45]

Both CO_2 Mitigation and SLCP Mitigation are Critical for Climate Safety

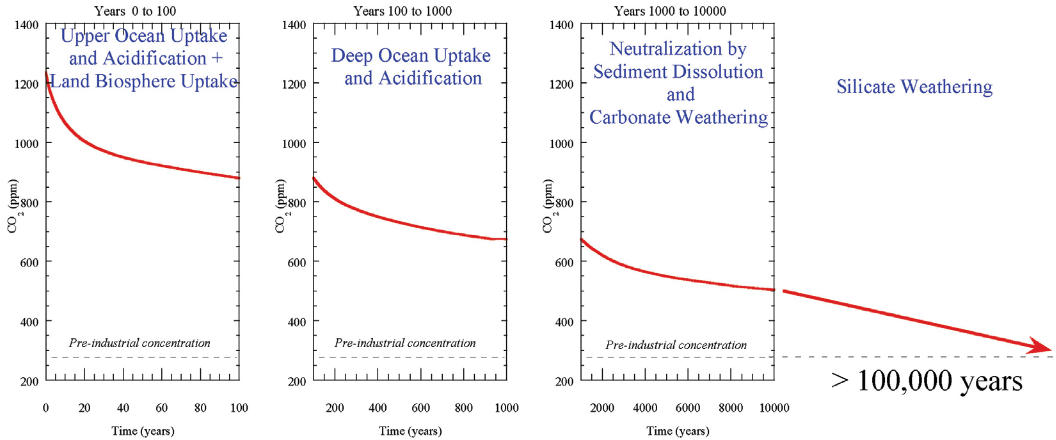
Importance of Immediate CO_2 Mitigation

CO_2 is the single most significant climate forcer, accounting for 55-60% of present climate forcing. Substantial and immediate reductions in CO_2 emissions are necessary to limit global temperature rise, although CO_2 reductions are less effective for limiting warming over the next 30 years.[46] Even after reductions in emissions take place, resultant reductions in warming will be gradual, taking almost half a century.[47] For example, keeping CO_2 emissions to below 450 ppm by 2100 is predicted to prevent approximately 0.15°C of BAU warming in the first 30 years, with prevented warming increasing to 0.5°C 50 years after significant reductions begin (*see* Fig. 5).[48] Cuts to CO_2 alone, while providing significant avoided temperatures compared to BAU warming, would still see temperatures rise above 2°C by the middle of this century (*see* Fig. 5).

CO_2 emissions will continue to cause warming over the long term because of their long lifetime in the atmosphere. While approximately 50% of CO_2 is removed from the atmosphere within a century, a substantial portion (20-40%) of CO_2 emissions remains in the atmosphere for millennia (*see* Fig. 2).[49] CO_2's long atmospheric lifetime combined with the thermal inertia of the ocean, which causes trapped heat to be released over many centuries, means that if CO_2 emissions were to cease, more than 80% of the expected decrease in global mean temperatures would not be realized for up to a thousand years.[50]

The long legacy of warming due to anthropogenic CO_2 will cause a number of long-term impacts, such as sea level rise, that are irreversible on human timescales, even if emissions were to cease tomorrow.[51] Committed sea-level rise from thermal expansion alone could be as high as one meter if atmospheric CO_2 concentrations are allowed to exceed 600 ppm (*see* Fig. 4).[52] (Atmospheric CO_2 concentrations reached 394 ppm in 2012 and could reach as high as 1,100 ppm by the end of this century under BAU scenarios.[53])

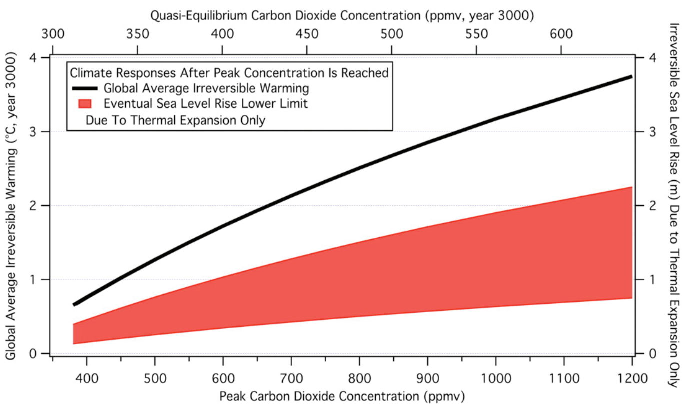
Figure 2: Time Scales for Removal of CO_2 from the Atmosphere



Model simulation of atmospheric CO_2 concentration for >100,000 years following a large CO_2 release from combustion of fossil fuels. Different fractions of the released gas recover on different timescales.[54]

Significantly reducing CO_2 emissions will require a massive decarbonization of the global economy and energy systems. It requires a portfolio of actions including conservation and efficiency improvements to reduce the carbon intensity of energy use, along with the replacement of fossil fuels with renewables, carbon capture, reuse, and storage, and numerous other steps.[55] However, building a new, cleaner energy infrastructure to reduce CO_2 emissions will require considerable energy from the present infrastructure. The very effort to put in place a sustainable energy system will likely require increased emissions over the short term. Therefore, the prevention of climate impacts from such an effort would likely be delayed for several decades.[56]

Figure 3: Irreversible Sea-Level Rise and Warming from CO_2



The black line shows irreversible global average surface warming based upon peak atmospheric CO_2 concentrations. The red band shows lower limit range of corresponding sea-level rise from thermal expansion only, due to peak atmospheric CO_2 concentrations.[57]

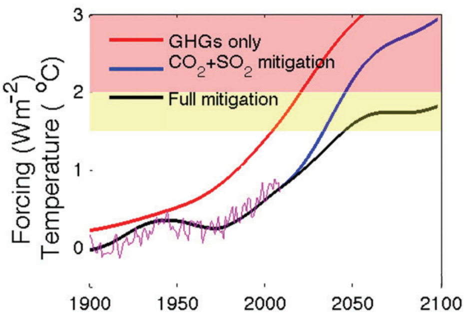
Importance of Immediate SLCP Mitigation

Cutting SLCPs is a critical climate strategy for reducing the near-term rate of global warming, particularly in regions most vulnerable to climate change, as well as for offsetting the near-term warming that will result from reductions of cooling aerosols such as sulfates, which are important to reduce to protect public health and ecosystems despite the warming this will cause.

SLCPs account for approximately 40-45% of present climate forcing.[58] In contrast to CO_2, the short atmospheric lifetimes of SLCPs means that reducing them will produce as much as 90% of predicted prevented warming within a decade, with the final 10% delayed for hundreds of years due to ocean thermal inertia. Reducing three of the non-CO_2 SLCPs—black carbon, tropospheric ozone, and methane—has the potential to avoid 0.5°C global warming by 2050[59] and 0.7°C in the Arctic by 2040,[60] which can cut the rate of global warming by half, the rate of Arctic warming by two thirds, and can reduce warming in the high altitude Himalayan-Tibetan Plateau by at least half.[61] (During the past half century, the rate of global warming has been about 0.13°C per decade.[62] The rate of warming in the Arctic is currently at least twice the global average, and the rate in the Himalayas and Tibet is about three times the global average.[63]) Adding HFC reductions to these black carbon, tropospheric ozone and methane reductions can increase the reduction in the rate of global warming from 50% to about 60%.[64]

While the measured warming from climate pollutants is presently about 0.8°C above preindustrial levels, the total warming that is committed but yet not fully realized from historic emissions through 2005 is estimated to be 2.4 to 4.3°C.[65] Up to 1.15°C of this committed warming is currently being 'masked' by emissions of cooling aerosols, primarily sulfates, from fossil fuel and biomass combustion which are now being rapidly reduced to protect human health and ecosystems. [66] Un-masking this committed warming could push global temperatures over the 2°C guardrail by mid-century (*see* Fig. 4, blue line).[67] Reducing HFCs, black carbon, tropospheric ozone, and methane is essential for limiting this warming (*see* Fig. 4, black line).

Figure 4: Warming Avoided Through Combined SLCP and CO_2 Mitigation

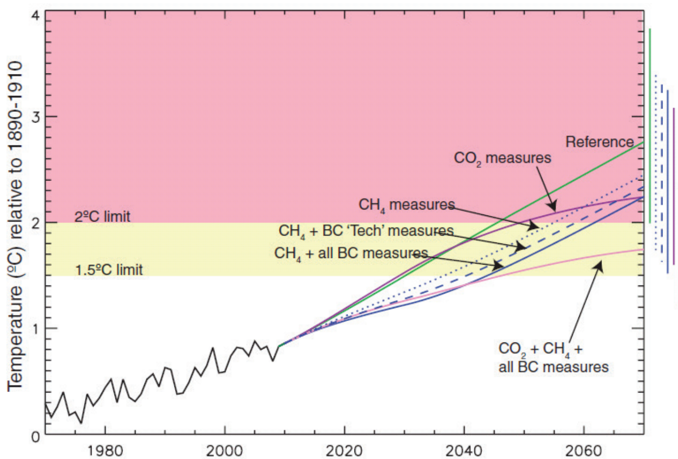


The red line depicts strong mitigation of CO_2 (peaking in 2015 and remaining at 2015 levels until 2100, reaching a concentration peak of 430 ppm by 2050), but no mitigation of non-CO_2 greenhouse gases, and does not account for forcing from aerosols or land use change; the blue line is the same as the red line except it includes warming and cooling aerosol forcing and the mitigation of cooling sulfate aerosols; the black line is the same as the blue line except it includes mitigation of all SLCPs including HFCs; the pink and yellow backgrounds show zones beyond 2°C and 1.5°C.[68]

Benefits of Combined CO_2 and SLCP Mitigation

CO_2 and SLCPs can be thought of as two separate control knobs for temperature increase that operate independently and on different timescales.[69] Both must be turned down simultaneously and immediately as part of a comprehensive climate strategy to prevent possible near-term, abrupt climate change and long-term climate destabilization. The combination of CO_2 mitigation and SLCP mitigation provides the greatest chance of keeping global temperatures below 1.5°C for the next 30 to 40 years and provides the best chance to keep global temperatures below the 2°C guardrail through 2100.[70]

Figure 5: Temperature Rise Predictions Under Various Mitigation Scenarios



Observed temperatures through 2009 and projected temperatures thereafter under various scenarios, all relative to the 1890–1910 mean. Results for future scenarios are the central values from analytic equations estimating the response to forcings calculated from composition-climate modeling and literature assessments. The rightmost bars give 2070 ranges, including uncertainty in radiative forcing and climate sensitivity.

A portion of the uncertainty is systematic, so that overlapping ranges do not mean there is no significant difference.)[71] (Note: HFC mitigation is not included in this graph, although it is included in Fig. 4, above.)

Benefits for Climate Vulnerable Regions

Global warming is expressed as a global average increase in surface temperature, but warming is experienced unevenly across different regions, with some of the world's most vulnerable regions warming much faster than the global average rate.[72] For example, Africa is warming about one and a half times faster than the average, and the Arctic and the Himalayan-Tibetan plateau are warming two to three times of the average global rate.[73] Therefore, it is particularly important that SLCP reductions may be able to rapidly reduce the rate of regional warming in places such as the Arctic, the high elevation regions of the Himalayas and Tibet,[74] and other regions with vulnerable climates, including those where enhanced warming may trigger amplifying feedbacks and/or the passage of potential climate tipping points–the points at which a chain of events escalate such that it is impossible to return to former condition.

Warming in the Arctic and Himalayan-Tibetan plateau in particular could lead to dangerous climate feedbacks that cause warming to accelerate past tipping points. One example of such a feedback is the melting of Arctic snow and sea-ice, which reached a record low in September 2012.[75] As the reflective ice and snow is replaced with darker heat-absorbing land and ocean, warming can amplify,[76] which in turn further reduces ice and snow cover, creating the dangerous feedback loop.[77]

Black carbon is estimated to be responsible for 50% of the increase in Arctic warming, or almost 1°C of the total 1.9°C increase between 1890 and 2007.[78] Approximately 50% of the warming on the Himalayan-Tibetan plateau has also been attributed to black carbon.[79] Cutting black carbon, tropospheric ozone and methane can cut the rate of warming in the Arctic by two thirds and the rate of warming over the elevated regions of the Himalayan-Tibetan plateau by at least half.[80] Reducing these pollutants is essential, though not sufficient for saving the Arctic and other vulnerable places in the short term.[81]

Benefits for Human Health and Food Security

In addition to climate benefits, reducing SLCPs provides strong benefits for public health and food security. Cutting these local air pollutants can save up to 4.7 million lives each year, increase global crop yields by up to 135 million metric tons and repair the ability of plants to sequester carbon, a function now being impaired by tropospheric ozone.[82] According to one study, the deaths avoided from technically possible reductions in black carbon and methane would represent "*1-8% of cardiopulmonary and lung cancer deaths among those age 30 years and older, and 1-7% of all deaths for all ages.*"[83] Improvements in crop production are estimated to be up to 4% of total annual global production of the four major staple grains: maize, rice, soybeans, and wheat.[84]

Due to the heightened effects of black carbon and tropospheric ozone near emissions sources, these benefits, including much of the climate mitigation benefits, are enjoyed largely by the regions making the cuts. For example, eliminating emissions of black carbon from traditional solid biomass stoves with improved cook stoves would have a major impact in reducing black carbon direct climate effects over South Asia (by about 60%).[85]

Mitigation Measures for Short-lived Climate Pollutants

Black Carbon and Methane Mitigation

Recent studies have identified fourteen mitigation measures targeting emissions of black carbon and methane that can provide immediate benefits.[86] These measures are capable of reducing global methane emissions by ~38% and emissions of black carbon by ~77%, realizing "nearly 90% of the maximum reduction in net GWP," from these sources.[87]

Methane Control Measures

- Control fugitive emissions from oil and gas production
- Control emissions from coal mining
- Control fugitive emissions from long distance gas transmission
- Capture gas from municipal waste and landfills
- Capture gas from wastewater treatment facilities
- Capture gas from livestock manure
- Intermittent aeration of constantly flooded rice paddies

Black Carbon Control Measures

- Install particulate filters on diesel vehicles
- Replace traditions cooking stoves with clean burning biomass stoves
- Modernize brick kilns
- Modernize coke ovens
- Ban open burning of biomass
- Eliminate high emitting on and off-road diesel vehicles
- Provide global access to modern cooking and heating

Reducing diesel black carbon emissions along with other key sources, including brick kilns and residential solid fuel burning, can quickly reduce warming because of the low levels of co-emitted cooling aerosols from these sources.[88] In addition, replacing the millions of kerosene-fueled simple wick lamps used in many developing countries, with low cost and low-emission lamps, could provide significant black carbon mitigation.[89]

Most of the control measures for reducing black carbon, and for reducing tropospheric ozone by reducing one of its precursors, methane, can be implemented today with existing technologies, and often with existing laws and institutions, including through enhancement and enforcement of existing air quality regulations.[90]

Half of the identified black carbon and methane measures can be implemented with a net cost savings averaged globally.[91] Recent analysis indicates that approximately 64% of predicted reductions in methane from the identified measures can be achieved for less than $250 per metric ton, well below the estimated ~$1000 per metric ton value gained from climate mitigation, improved health outcomes, and crop production.[92] For black carbon, improved efficiencies from modernizing brick kilns and replacing traditional wood burning stoves can lead to a net cost savings, and together account for approximately half of possible black carbon reductions.[93] Recent research indicates that a large portion of the remaining black carbon mitigation measures will likely cost substantially less than the value of the health, climate, and crop benefits achieved (*see* Table 1).[94] All of these mitigation measures are ultimately cost effective when the $5.9 trillion annual benefits that start in 2030 are taken into account, and can be achieved by linearly phasing in the identified fourteen targeted control measures from 2010 through 2030 (*see* Table 1).[95]

Table 1: Valuation of Global Benefits from Full Implementation of 14 SLCP Measures [96]

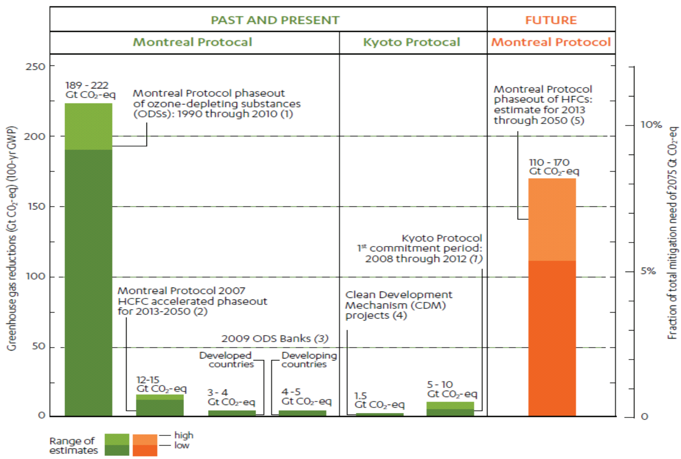
	Methane Measures	Black Carbon Measures	Total
Climate Benefit[97]	*$331 (449 – 213)*	*$225 (343 – 13)*	*$556 (792 – 226)*
Crop Benefit[98]	*$4.2 (5.4 – 3)*	*$4 (7.2 – 0.8)*	*$8.2 (12.6 – 3.8)*
Health Benefit[99]	*$148 (247 – 49)*	*$5142 (9853 – 1564)*	*$5290 (10100 – 1613)*
Total	*$483.2 (701.4 – 265)*	*$5371 (10203.2 – 1577.8)*	*$5854.2 (10904.6 – 1845.2)*

HFC Mitigation

The mitigation approach for reducing HFCs is different from that for black carbon and methane. Because they are manmade, HFCs can be most effectively controlled through a phase down of their production and consumption, which could take place under the Montreal Protocol. The successful phase-out of CFCs and the ongoing phase-out of HCFCs have made the Montreal Protocol the world's most effective climate treaty.[100] Between 1990 and 2010 the Montreal Protocol reduced CO_2-eq emissions nearly twenty times more than the initial commitment period of the Kyoto Protocol (*see* Fig. 6).[101]

There have been two proposals put forth to phase down high-GWP HFCs under the Montreal Protocol, one by the Federated States of Micronesia and the other by the North American countries, the U.S., Canada, and Mexico.[102] The proposals are similar, and each would reduce 85-90% of HFC production and use, providing climate mitigation equivalent to 100 billion tonnes of CO_2 emissions by 2050 (range of 87-146 billion tonnes) (*see* Fig. 7), at very low cost. The HFC amendments would substantially eliminate the global warming caused by one of the six Kyoto Protocol greenhouse gases by avoiding the production and use of high-GWP HFCs, providing up to 7% of the total CO_2-eq mitigation needed to have a 75% chance of staying below the 2˚C guardrail.[103]

Figure 6: Climate Protection of the Montreal Protocol and the Kyoto Protocol



UNEP, Climate Protection of the Montreal Protocol and the Kyoto Protocol (2012)[104]

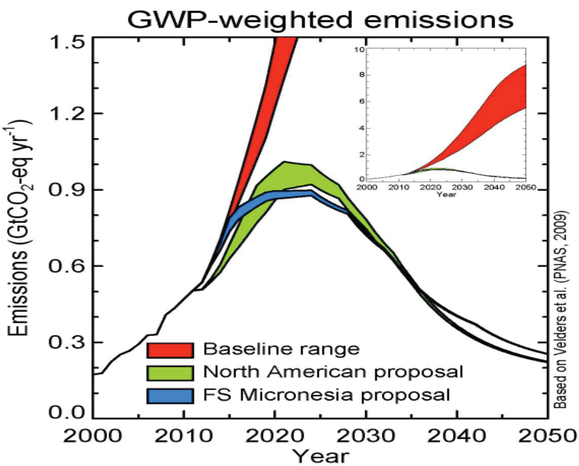
HFCs are now the fastest growing GHG pollutant in the U.S. and in many other countries. This is due in part to their being used as replacements for HCFCs, which are now being phased out, and in part to the growing global demand for air conditioning and refrigeration.[105] This demand is increasing as the world warms and as the population grows and gets richer. If left unchecked, by 2050 warming from annual emissions of HFCs could be equivalent to 20% of warming from annual CO_2 emissions under a BAU scenario, and up to 45% of the warming from annual CO_2 emissions under a 450 ppm CO_2 stabilization scenario.[106]

Many national governments have taken action to reduce HFCs. Such action includes: creating national databases of equipment containing HFCs in Hungary, Slovenia, and Estonia; mandatory refrigerant leakage checks for mobile equipment in Germany, Sweden, and the Netherlands; and producer responsibility schemes requiring producers and suppliers of HFCs to take back recovered bulk HFCs for further recycling, reclamation and destruction in Sweden and Germany.[107] California is reducing HFC use in mobile air conditioning systems through its Low Emission Vehicle (LEV III) regulation by requiring that all passenger cars, light duty trucks, and medium-duty passenger vehicles use refrigerants with a global warming potential less than or equal to 150, as of model year 2017.[108] The U.S. allows manufacturers of cars and light-trucks to generate credits towards their compliance with CO_2 emission standards and fuel economy CAFE standards by employing HFC alternative refrigerants in mobile air conditioning systems for model year 2012-2016 vehicles.[109] According to the new rules for model years 2017-2025, U.S. CAFE standards continue to provide HFC alternative credits and include credits for improvements in mobile air conditioner efficiency.[110] The EC is currently strengthening its f-gas regulations.

Private companies are also taking voluntary action to limit HFCs. The Consumer Good Forum, a global network of over 650 retailers, manufactures, service providers, and other stakeholders from over seventy countries has pledged to begin phasing out HFCs in new equipment beginning in 2015.[111]

Because the global weighted average lifetime of HFCs now in use is 15 years, HFCs are included in the CCAC.[112] In the Rio +20 declaration, *The Future We Want*, more than one hundred heads of State recognized the climate damage from HFCs and called for the gradual phase down of their production and consumption.[113] In addition, 108 countries have joined the *Bangkok Declaration* calling for the use of low-GWP alternatives to CFCs and HCFCs.[114]

Figure 7: Projected HFC Emission Reductions from FSM and NA Proposals



The North American proposal and the Micronesian proposal are similar; both decrease the cumulative (2013-2050) direct GWP-weighted emissions of HFCs to 22-24 $GtCO_2$-eq from 110-170 $GtCO_2$-eq, for a total of ~87 to 146 $GtCO_2$-eq in mitigation. This is equivalent to a reduction from projected annual emissions of 5.5 to 8.8 $GtCO_2$-eq/yr in 2050 to less than ~0.3 $GtCO_2$-eq/yr.[115]

Climate and Clean Air Coalition to Reduce SLCPs

The CCAC was launched in February 2012, and now has 27 State partners, as well as the European Commission, World Bank, United Nations Environment Programme, United Nations Development Programme, and United Nations Industrial Development Organization. The State partners are: Australia, Bangladesh, Canada, Chile, Colombia, Côte d´Ivoire, Denmark, Dominican Republic, Ethiopia, Finland, France, Germany, Ghana, Israel, Italy, Japan, Jordan, the Republic of Korea, the Republic of Maldives, Mexico, the Netherlands, Nigeria, Norway, Sweden, Switzerland, the U.K., and the U.S. The CCAC also has 18 NGO partners: Bellona Foundation, Center for Clean Air Policy, Center for Human Rights and Environment, Clean Air Initiative for Asian Cities, Clean Air Institute, Clean Air Task Force, ClimateWorks Foundation, Earthjustice, Environmental Defense Fund, Global Alliance for Clean Cookstoves, Institute for Advanced Sustainability Studies, Institute for Governance and Sustainable Development, International Centre for Integrated Mountain Development, International Council on Clean Transportation, International Cryosphere Climate Initiative, International Institute for Sustainable Development, International Union of Air Pollution Prevention and Environmental Protection Associations, Molina Center for Strategic Studies in Energy and the Environment, Stockholm Environment Institute.[116] IGSD was elected to be the initial NGO representative on the Coalition's Steering Committee. UNEP is representing the Intergovernmental Organizations.

In conjunction with the Rio+20 summit in June 2012, the Coalition and the World Bank joined New York City Mayor Michael R. Bloomberg, Chair of the C40 Cities Climate Leadership Group, former U.S. President Bill Clinton, and Rio de Janeiro Mayor

Eduardo Paes to announce the launch of the *Solid Waste Network* to help cities reduce methane emissions through solid waste management.[117]

The CCAC is the first-ever global effort specifically dedicated to reducing emissions of SLCPs as a collective challenge. The CCAC seeks to reduce SLCPs by supporting and coordinating existing programs such as the Clean Cookstove Initiative and the Global Methane Initiative, while "driving development of national action plans and the adoption of policy priorities; building capacity among developing countries; mobilizing public and private action; raising awareness globally; fostering regional and international cooperation, and; improving scientific understanding of the pollutant impacts and mitigation."[118]

Five targeted initiatives have been approved by the CCAC for rapid implementation:[119]

- Reducing black carbon emissions from heavy duty diesel vehicles and engines;
- Mitigating black carbon and other pollutants from brick production;
- Mitigating short-lived climate pollutants from the municipal solid waste sector;
- Promoting HFC alternative technologies and standards; and
- Accelerating methane reductions from oil and natural gas production.

The Coalition is developing additional proposals including one addressing open burning of biomass by Ghana and another on cookstoves from Bangladesh.

The CCAC Secretariat is hosted by UNEP's Paris office, and will manage a dedicated Trust Fund, with an initial contribution of $16.7 million from the U.S., Canada, Sweden, and Norway. [120]

The World Bank indicated that it has $12 billion of its portfolio contributing to the CCAC's goals.[121] It further indicated that it wants to significantly expand its funding for SLCP mitigation, going from 12% of its portfolio in 2012 to 15% by 2015 and 20% by 2020.[122] Also, the G8 leaders commissioned the World Bank to prepare a report on ways to integrate reductions of SLCPs into their activities and to assess funding options for methane reductions.[123]

Other Regional and Global SLCP Mitigation Initiatives

In addition to the CCAC there are a number of other global and regional initiatives that target SLCPs. For example, the Executive Body of the Convention on Long-Range Transboundary Air Pollution (CLRTAP) recently approved an amendment to the Gothenburg Protocol adopting new PM requirements and including specific language on black carbon, making it the first international treaty to act on the link between air pollution and climate change.[124] The Global Alliance for Clean Cookstoves and the Global Methane Initiative are both specifically targeting some of the largest global sources of black carbon and methane emissions.[125] UNEP's Atmospheric Brown Cloud program is also addressing black carbon and tropospheric ozone, with a focus on Asia and plans to expand to Latin America and Africa.[126] Finally, the International Maritime Organization (IMO) is currently considering whether to control black carbon emissions from ships.[127] The Arctic Environment Ministers recently called for "urgent action" to reduce SLCPs to protect the Arctic and reduce the risk of feedback mechanisms that accelerate warming and lead to irreversible impacts, and encouraged the Arctic Council to consider a new "instrument or other arrangements to enhance efforts to reduce emissions of black carbon from the Arctic States" for decision at the 2015 Arctic Ministerial meeting.[128]

Conclusion

Reducing SLCPs will reduce near-term climate impacts, slow dangerous feedbacks, allow more time to adapt, and reduce the risk of passing tipping points that could lead to irreversible climate damage. In addition to providing near-term climate benefits, cutting SLCPs would also provide major benefits for human health and food security and would contribute to sustainable development goals. Cutting SLCPs to achieve near-term climate benefits is an important complement to reducing CO_2 emissions, but SLCP reductions are not a substitute for the immediate action urgently needed to reduce CO_2. Reducing both CO_2 and SLCPs provides the best chance of limiting global temperature rise to below 2°C through 2100. As highlighted by Nobel Laureate Mario Molina and co-authors, regulatory measures in dedicated venues are often the preferred way to reduce SLCPs.[129]

Endnotes

[1] Forster P. *et al.* (2007), Changes in Atmospheric Constituents and in Radiative Forcing, *in* IPCC, Climate Change 2007: The Physical Science Basis, at Figure 2.21.

[2] *Id.*

[3] The science of SLCPs dates back to the 1970s. *See* e.g., Ramanathan V. (1975) *Greenhouse effect due to chlorofluorocarbons: climatic implications,* Sci. 190:50*; see also* Wang *et al*. (1976) *Greenhouse effects due to man-made perturbations of trace gases*, Sci. 194:685. A major WMO-UNEP-NASA-NOAA report in 1985 concluded that non-CO_2 greenhouse gases in the atmosphere are adding to the greenhouse effect by an amount comparable to the effect of CO_2.(Ramanathan *et al.* (1985) *Trace gas trends and their potential role in climate change*, J. Geophys Res. 90:5547.) This finding has been confirmed and strengthened in the following decades by hundreds of studies culminating in IPCC reports (IPCC (1990) Overview Chapter, in IPCC (1990) First Assessment Report; IPCC (1995) IPCC (1995) Second Assessment Report: Climate Change 1995; IPCC (2001) Third Assessment Report: Climate Change 2001; *and* IPCC (2007) Climate Change 2007: Synthesis Report.) In short, researchers have had at least 25 years to carefully develop the science of SLCPs and assess the findings. Bond *et al.* is the most recent assessment in this field. Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. of Geophys. Res. – Atmos., DOI:10.1002/jgrd.50171.

[4] Ramanathan V. & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues*, Proc. Nat'l Acad. Sci. USA 107:8055, 8056 ("CO_2 (1.65 Wm^{-2}) and

the non-CO_2 GHGs (1.35 Wm^{-2}) have added 3 (range: 2.6–3.5) Wm^{-2} of radiant energy since preindustrial times….. The 3 Wm^{-2} energy should have led to a warming of 2.4 °C (14). The observed warming trend (as of 2005) is only about 0.75 °C (15), or 30% of the expected warming. Observations of trends in ocean heat capacity (16) as well as coupled ocean–atmosphere models suggest that about 20% (0.5 °C warming) is still stored in the oceans (17). The rest of the 50% involves aerosols or particles added by air pollution.”).

[5] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, SCI. 335:183, 183. (“We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050.”); *see also* Bond, *et al.*, and accompanying press release. Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. OF GEOPHYS. RES. –ATMOS., DOI:10.1002/jgrd.50171; *and* American Geophysical Union (2013) *Black carbon is much larger cause of climate change than previously assessed*, press release.

[6] *See* United Nations Environment Programme & World Meteorological Organization (herein after UNEP/WMO) (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, at Table 5.2.

[7] During the past half century, the rate of global warming has been about 0.13°C per decade. IPCC (2007) TECHNICAL SUMMARY, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, 36. The rate of warming in the Arctic is currently at least twice the global average and in the Himalayas and Tibet three times the average. Arctic Monitoring and Assessment Programme (2011) SNOW, WATER, ICE AND PERMAFROST IN THE ARCTIC, EXECUTIVE SUMMARY AND KEY MESSAGE, 4. Average global surface temperatures have increased by 0.8°C, over the 1880–1920 average, and under business-as-usual it could increase by an additional 2°C by 2070. Hansen J. *et al.* (2010) *Global surface temperature change*, REV. GEOPHYS. 48:4004; IPCC (2007) TECHNICAL SUMMARY, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, 36; *and* UNEP/WMO (2011) INTEGRATED ASSESSMENT

of Black Carbon and Tropospheric Ozone.

[8] For analysis of these impacts *see* Schneider, S. H. *et al.* (2007) Assessing key vulnerabilities and the risk from climate change, *in* Climate Change 2007: Impacts, Adaptation and Vulnerability 779-810; *and* IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change.

[9] Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants, http://www.unep.org/ccac/.

[10] United Nations (2012) Resolution adopted by the General Assembly: The future we want, A/res/66/288.

[11] Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (11 May 2012); *see also* Proposed Amendment to the Montreal Protocol (submitted by the United States, Canada, and Mexico), (9 May 2012).

[12] UNEP (2010) Declaration on the global transition away from hydrochlorofluorocarbons (HCFCs) and clholrofluorocarbons (CFCs); *see also* UNEP (2011) Report of the combined ninth meeting of the Conference of the Parties to the Vienna Convention on the Protection of the Ozone Layer and the Twenty-Third Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer; *and* UNEP (2012) Report of the Twenty-Fourth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer: Advance Copy.

[13] Solomon S. *et al.* (2007) Climate Change 2007: Physical Science Basis ("While more than half of the CO_2 emitted is currently removed from the atmosphere within a century … about 20% … remains … for many millennia."); *see also* Archer D *et al.* (2009) *Atmospheric lifetime of fossil fuel carbon dioxide*, Annu. Rev Earth Planet. Sci. 37:117-34 ("Equilibration with the ocean will absorb most of it [CO_2] on a timescale of 2 o 20 centuries. Even if this equilibration were allowed to run to completion, a substantial fraction of the CO_2, 20-40%, would remain in the atmosphere awaiting slower chemical reactions with $CaCO_3$ and igneous rocks."); Matthews H. D. & Caldeira K.

(2008) *Stabilizing climate requires near-zero emissions*, J. Geopysical Res. 35(4) ("[W]hile approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia."); *and* Hansen J. *et al*. (2007) *Climate change and trace gases*, Phil. Trans. R. Soc. 365:1925-1954 ("About one-quarter of fossil fuel CO_2 emissions will stay in the air "forever", i.e. more than 500 years…. Resulting climate changes would be … irreversible.").

[14] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 241 ("For example, mitigation of 0.15°C due to CO_2 measures takes place only around 2050 (Figure 6.1) under the CO_2 measures scenario; 30 years after emissions begin to decline rapidly. The influence of the CO_2 reductions grows rapidly, however, so that they mitigate roughly 0.5°C by 2070. Hence a delay of 20 years in implementation of those CO_2 reductions would mean that only ~0.15°C of warming mitigation relative to the reference scenario would be achieved within the 2070 timeframe examined here. Thus delayed CO_2 measures plus all the near-term measures examined here would lead to warming of about 2.1°C in 2070 rather than the 1.75°C shown in Figure 6.1. Conversely, a delay in reducing emissions of short-lived species would have a large impact on near-term warming rates, but little effect on 2070 temperatures (see Figure 5.12).")

[15] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon; *see also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone.

[16] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon; *see also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone.

[17] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. of Geophys. Res. –Atmos., doi:10.1002/jgrd.50171 ("We estimate that black carbon, with a total climate forcing of +1.1 W m^{-2}, is the second most important human emission in terms of its climate-forcing in the present-day atmosphere; only carbon dioxide is estimated to have a greater forcing."). This study confirms earlier

estimates by Jacobson (2001) and Ramanathan and Carmichael (2008), which also concluded that black carbon is the second largest contributor to global warming after CO_2. *See* Jacobson M. Z. (2001) *Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols,* NAT. 409:695–69; *and* Ramanathan V. & Carmichael G. (2008) *Global and regional climate changes due to black carbon*, NAT. GEOSCI. 1:221; *see also* U.S. Envtl. Prot. Agency (2012) REPORT TO CONGRESS ON BLACK CARBON, 4, 18 ("The sum of the direct and snow/ice albedo effects of BC on the global scale is likely comparable to or larger than the forcing effect from methane, but less than the effect of carbon dioxide; however, there is more uncertainty in the forcing estimates for BC….")

[18] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. OF GEOPHYS. RES. –ATMOS., doi:10.1002/jgrd.50171 ("The best estimate of industrial-era climate forcing of black carbon through all forcing mechanisms, including clouds and cryosphere forcing, is +1.1 W m^{-2} with 90% uncertainty bounds of +0.17 to +2.1 W m^{-2}. ").

[19] Janssen N. AH *et al.* (2012) *Health effects of black carbon,* World Health Organization; *see also* Smith K. R. *et al.* (2009) *Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants*, THE LANCET 274(9707):2091-2103.

[20] U.S. Envtl. Prot. Agency (2012) REPORT TO CONGRESS ON BLACK CARBON.

[21] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. OF GEOPHYS. RES. –ATMOS., doi:10.1002/jgrd.50171 ("With this method, a bottom-up estimate of total global emissions in the year 2000 is about 7500 Gg BC yr-1, with an uncertainty range of 2000 to 29000 Gg yr-1."); *see also* U.S. Envtl. Prot. Agency (2012) REPORT TO CONGRESS ON BLACK CARBON.

[22] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. OF GEOPHYS. RES. –ATMOS.; *see also* U.S. Envtl. Prot. Agency

(2012) Report to Congress on Black Carbon.

[23] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. of Geophys. Res. –Atmos.; *see also* U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon

[24] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. of Geophys. Res. –Atmos. ("Major sources of BC, ranked in order of increasing POA:BC [primary organic aerosol:black carbon] ratio, are diesel vehicles, residential burning of coal, small industrial kilns and boilers, burning of wood and other biomass for cooking and heating, and all open burning of biomass. A few of these sources also emit significant quantities of SO_2.")

[25] Chung C. E., Ramanathan V., & Decremera D. (2012) *Observationally constrained estimates of carbonaceous aerosol radiative forcing*, Proc. Natl. Acad. Sci. USA, 109(29):11624-1162 ("10.4.1.12 Forcing by light-absorbing organic carbon, known as brown carbon, has not been explicitly considered here, although some of the models listed in Table 10.2 assume a small amount of absorption. Carbonaceous aerosols (CA) emitted by fossil and biomass fuels consist of black carbon (BC), a strong absorber of solar radiation, and organic matter (OM). OM scatters as well as absorbs solar radiation. The absorbing component of OM, which is ignored in most climate models, is referred to as brown carbon (BrC)…. Organic aerosol was known to cool the planet significantly. The OM forcing estimated by the [IPCC AR4] models was negative, about −0.1 to −0.4 Wm^{-2}. By integrating and analyzing aerosol observations, we have shown here that organic aerosol, because of the warming effects of brown carbon, neither cools nor warms the planet. We attribute the negative bias in the modeling studies primarily to the neglect of the 20% absorption caused by BrC, particularly over biomass-burning regions in Asia, Africa, and South America."); *see also* Feng Y., Ramanathan V. & Kotamarthi V. R. (2013) *Brown carbon: a significant atmospheric absorber of solar radiation,* Atmos. Chem. & Phys. Disc. 13:2795-2833.

[26] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the*

climate system: a scientific assessment, Accepted for publication in the J. of Geophys. Res. –Atmos., DOI:10.1002/jgrd.50171 ("Light-absorbing particles in snow can significantly reduce snow albedo. Because of the high albedo of snow, even aerosol with relatively high single-scatter albedo (*e.g.,* aerosol with a high OA:BC ratio) causes positive radiative forcing.")

[27] *Id.*

[28] *Id.* ("Evidence supporting the link between particles and adverse respiratory and cardiovascular health continues to mount. High human exposures to particulate matter in urban settings are linked to sources that emit black carbon and to intense exposures in indoor air. Thus, reducing particulate matter is desirable to improve human welfare, regardless of whether those reductions reduce climate warming.") (internal citations omitted).

[29] U.S. Envtl. Prot. Agency (2012) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010.

[30] U.S. Envtl. Prot. Agency (2012) Report to Congress on Black Carbon.

[31] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone.

[32] IPCC (2007) Climate Change 2007: The Physical Science Basis, 129, 132.

[33] US EPA (2010) Methane and Nitrous Oxide Emissions from Natural Sources, ES-2 ("Natural sources of CH_4 are estimated to produce 37 percent of the total CH_4 flux into the atmosphere every year.").

[34] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone.

[35] Solomon S. *et al.* (2007), Technical Summary *in* Climate Change 2007: The Physical Science Basis, at Figure TS.5.

[36] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone. ("Without implementation of measures beyond current and planned regulations, methane (CH_4) emissions are expected to increase in the future. Increased coal mining and oil and gas production, coupled with growth in agricultural activities

and municipal waste generation, are likely to lead to more than 25 per cent higher global athropogenic CH_4 emissions by 2030 relative to 2005. The projected increase in fossil fuel production is the main driving force behind this growth.").

[37] *Id.*

[38] *Id.*; *see also* U.S. Envtl. Prot. Agency (2003) Ozone: good up high bad nearby.

[39] UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers; *see also* Reilly J. *et al.* (2007) *Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone*, Energy Policy 35(11):5370-5283.

[40] Reducing other ozone precursors can have varying effects on the climate, for example cutting non-methane VOCs can provide some additional cooling but reducing NOx is predicted to produce warming due to its importance for removing methane from the atmosphere. UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 57 ("Two-thirds of the O_3 radiative forcing to date may be attributed to the increase in atmospheric CH_4 over the last century, and hence CH_4 emissions are responsible for a large part of the increase.").

[41] *Id.*

[42] UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer.

[43] U.S. Envtl. Prot. Agency (2012) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010.

[44] UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer.

[45] *Id.*

[46] Archer D. *et al.* (2005) *Fate of fossil fuel CO_2 in geologic time*, J. of Geophys. Res. 110:C09S05 ("[W]hile approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia."); *see also* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric

Ozone, 241 ("For example, mitigation of 0.15°C due to CO_2 measures takes place only around 2050 (Figure 6.1) under the CO_2 measures scenario; 30 years after emissions begin to decline rapidly.").

[47] Myhrvold N. P. & Caldeira K. (2012) *Greenhouse gases, climate change and the transition from coal to low-carbon electricity*, Environ. Res. Let. 7:014019, 4-5 ("Conservation is thus equivalent to phasing out 1 TWe of coal power over 40 yr without any replacement technology. Even in this case, GHGs (particularly CO_2) emitted by coal during the phaseout linger in the atmosphere for many years; in addition, ocean thermal inertia causes temperature changes to lag radiative forcing changes. Consequently, conservation takes 20 yr to achieve a 25% reduction in HGE [high-GHG-emission scenario] warming and 40 yr to achieve a 50% reduction…. Natural gas plants emit about half the GHGs emitted by coal plants of the same capacity, yet a transition to natural gas would require a century or longer to attain even a 25% reduction in HGE warming…. Carbon capture and storage (CCS) also slows HGE warming only very gradually. Although CCS systems are estimated to have raw GHG emissions of 17%–27% that of unmodified coal plants, replacement of a fleet of conventional coal plants by coal-fired CCS plants reduces HGE warming by 25% only after 26–110 yr.").

[48] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 241 ("For example, mitigation of 0.15°C due to CO_2 measures takes place only around 2050 (Figure 6.1) under the CO_2 measures scenario; 30 years after emissions begin to decline rapidly. The influence of the CO_2 reductions grows rapidly, however, so that they mitigate roughly 0.5°C by 2070. Hence a delay of 20 years in implementation of those CO_2 reductions would mean that only ~0.15°C of warming mitigation relative to the reference scenario would be achieved within the 2070 timeframe examined here. Thus delayed CO_2 measures plus all the near-term measures examined here would lead to warming of about 2.1°C in 2070 rather than the 1.75°C shown in Figure 6.1. Conversely, a delay in reducing emissions of short-lived species would have a large impact on near-term warming

rates, but little effect on 2070 temperatures (see Figure 5.12).")

[49] Solomon S. *et al.* (2007) CLIMATE CHANGE 2007: PHYSICAL SCIENCE BASIS ("While more than half of the CO_2 emitted is currently removed from the atmosphere within a century … about 20% … remains … for many millennia."); *see also* Archer D *et al.* (2009) *Atmospheric lifetime of fossil fuel carbon dioxide*, ANNU. REV EARTH PLANET. SCI. 37:117-34 ("Equilibration with the ocean will absorb most of it [CO_2] on a timescale of 2 o 20 centuries. Even if this equilibration were allowed to run to completion, a substantial fraction of the CO_2, 20-40%, would remain in the atmosphere awaiting slower chemical reactions with $CaCO_3$ and igneous rocks."); Matthews H. D. & Caldeira K. (2008) *Stabilizing climate requires near-zero emissions*, J. GEOPHYSICAL RES. 35(4) ("[W]hile approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia."); *and* Hansen J. *et al*. (2007) *Climate change and trace gases*, PHIL. TRANS. R. SOC. 365:1925-1954 ("About one-quarter of fossil fuel CO_2 emissions will stay in the air "forever", i.e. more than 500 years…. Resulting climate changes would be … irreversible.").

[50] UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 6 ("In the case of an SLCF this means that, when its concentration and hence its radiative forcing is reduced by emission controls, the global mean temperature will achieve most of its decrease towards a new equilibrium value in about a decade. About 10 per cent of the full decrease will not be realized for hundreds of years, since the redistribution of heat stored in the deep ocean while the SLCF was active, and hence its upwards transport, will continue for hundreds of years …. In the case of CO_2, more than 80 per cent of the expected decrease in global mean temperature after emission reductions will not be realized for hundreds of years. This is because the drawing down of atmospheric CO_2 into the deep ocean, and hence the decrease in its radiative forcing, is roughly offset by the upward transport of heat to the surface, since both phenomena are achieved by the same physics of deep-ocean mixing….") *citing* Solomon S. *et al.* (2009) *Irreversible climate change due to carbon dioxide emissions,*

PROC. NATL. ACAD. SCI. USA 106:1704, 1704 ("[C]limate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years."); *and* Matthews D & Weaver J. (2010) *Committed climate warming*, NAT. GEOSCI. 3:142.

[51] Solomon S. *et al.* (2009) *Irreversible climate change due to carbon dioxide emissions,* PROC. NATL. ACAD. SCI. USA 106(6):1704-1709 ("Anthropogenic carbon dioxide will cause irrevocable sea level rise…. An assessed range of models suggests that the eventual contribution to sea level rise from thermal expansion of the ocean is expected to be 0.2–0.6 m per degree of global warming (5). Fig. 4 uses this range together with a best estimate for climate sensitivity of 3 °C (5) to estimate lower limits to eventual sea level rise due to thermal expansion alone. Fig. 4 shows that even with zero emissions after reaching a peak concentration, irreversible global average sea level rise of at least 0.4–1.0 m is expected if 21st century CO_2 concentrations exceed 600 ppmv and as much as 1.9 m for a peak CO_2 concentration exceeding 1,000 ppmv.").

[52] *Id.*

[53] National Oceanic & Atmospheric Administration, TRENDS IN ATMOSPHERIC CARBON DIOXIDE; *see also* Solomon S. *et al.* (2007) CLIMATE CHANGE 2007: PHYSICAL SCIENCE BASIS.

[54] Solomon S. *et al.* (2011) *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia,* National Research Council.

[55] B. Metz *et al.* (2007) CLIMATE CHANGE: MITIGATION OF CLIMATE CHANGE, 19-22.

[56] Myhrvold N. P. & Caldeira K. (2012) *Greenhouse gases, climate change and the transition from coal to low-carbon electricity*, ENVIRON. RES. LET. 7:014019, 1 ("The use of current infrastructure to build this new low-emission system necessitates additional emissions of greenhouse gases, and the coal-based infrastructure will continue

to emit substantial amounts of greenhouse gases as it is phased out. Furthermore, ocean thermal inertia delays the climate benefits of emissions reductions.... We show that rapid deployment of low-emission energy systems can do little to diminish the climate impacts in the first half of this century.”).

[57] Solomon S. *et al.* (2009) *Irreversible climate change due to carbon dioxide emissions*, Proc. Natl. Acad. Sci. USA 106(6):1704-1709.

[58] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 6, 159 (“In the case of an SLCF this means that, when its concentration and hence its radiative forcing is reduced by emission controls, the global mean temperature will achieve most of its decrease towards a new equilibrium value in about a decade. About 10 per cent of the full decrease will not be realized for hundreds of years, since the redistribution of heat stored in the deep ocean while the SLCF was active, and hence its upwards transport, will continue for hundreds of years…. Over the longer term, from 2070 onwards, there is still a reduction in warming in the early measures case, but the value becomes quite small. This reinforces the conclusions drawn from previous analyses that reducing emissions of O_3 precursors and BC can have substantial benefits in the near term, but that long-term climate change is much more dependent on emissions of long-lived GHGs such as CO_2.”).

[59] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183, 183. (“We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050.”).

[60] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 246 (“The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7°C (range 0.2 to 1.3°C) at 2040. This is a large portion of the 1.1°C (range 0.7 to 1.7°C) warming projected under the reference scenario for the Arctic…”).

[61] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term*

climate change and improving human health and food security, SCI. 335:183, 183, 185 ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050. *** 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…"); *see also* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 3 ("If the measures were to be implemented by 2030, they could halve the potential increase in global temperature projected for 2050 compared to the Assessment's reference scenario based on current policies and energy and fuel projections. *** This could reduce warming in the Arctic in the next 30 years by about two-thirds compared to the projections of the Assessment's reference scenario").

[62] IPCC (2007) TECHNICAL SUMMARY, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, 36 ("The rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years.")

[63] Arctic Monitoring and Assessment Programme (2011) SNOW, WATER, ICE AND PERMAFROST IN THE ARCTIC, EXECUTIVE SUMMARY AND KEY MESSAGE, 4 ("The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world."); *see also* Qiu J. (2008) *China: The third pole*, NAT. 454:393, 393, ("The proximate cause of the changes now being felt on the [Tibetan] plateau is a rise in temperature of up to 0.3°C a decade that has been going on for fifty years — approximately three times the global warming rate.").

[64] Institute for Advanced Sustainability Studies (2012) SHORT LIVED CLIMATE FORCERS: PATHWAYS TO ACTION – WORKSHOP SUMMARY ("… inclusion of HFCs mitigation would further reduce the warming by another 20% (about 0.1°C), thus increasing the total reduction of warming between now and 2050 to about 0.6°C" (citing Ramanathan V. & Xu Y. (2010)); *see also* Ramanathan V & Xu Y. (2010)

The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues, PROC. NAT'L ACAD. SCI. USA 107:8055, 8055 ("These actions [to reduce emissions of SLCPs including HFCs, methane, black carbon, and ground-level ozone], even if we are restricted to available technologies … can reduce the probability of exceeding the 2°C barrier before 2050 to less than 10% and before 2100 to less than 50% [when CO_2 concentrations are stabilized below 441 ppm during this century]").

[65] Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead*, PROC. NAT'L ACAD. SCI. USA 105:14245; *see also* Schellnhuber H. J. (2008) *Global warming: stop worrying, start panicking?* PROC. NAT'L ACAD. SCI. USA 105:14239.

[66] Ramanathan V & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues*, PROC. NAT'L ACAD. SCI. USA 107:8055.

[67] *Id.*

[68] *Id.*

[69] National Research Council of the National Academies (2011) CLIMATE STABILIZATION TARGETS: EMISSIONS, CONCENTRATIONS, AND IMPACTS OVER DECADES TO MILLENNIA, 3; *see also* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE; *and* United Nations Environment Program (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS.

[70] Ramanathan V & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues*, PROC. NAT'L ACAD. SCI. USA 107:8055, 8055, ("These actions [to reduce emissions of SLCPs including HFCs, methane, black carbon, and ground-level ozone], even if we are restricted to available technologies … can reduce the probability of exceeding the 2°C barrier before 2050 to less than 10% and before 2100 to less than 50% [when CO_2 concentrations are stabilized below 441 ppm during this century]"*); see also* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE: SUMMARY FOR DECISIONS

Makers, 12 ("[T]he combination of CO_2, CH_4, and BC measures holds the temperature increase below 2°C until around 2070… [and] adoption of the Assessment's near-term measures (CH_4 + BC) along with the CO_2 reductions would provide a substantial chance of keeping the Earth's temperature increase below 1.5˚C for the next 30 years."); UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 240 ("Hence adoption of the near-term measures analyzed in this Assessment would increase the chances for society to keep the Earth's temperature increase below 1.5°C for the next 40 years if these measures were phased in along with CO_2 reductions."); *and* Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183, 184 ("The combination of CH_4 and BC measures along with substantial CO_2 emissions reductions [under a 450 parts per million (ppm) scenario] has a high probability of limiting global mean warming to <2°C during the next 60 years, something that neither set of emissions reductions achieves on its own….")

[71] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183; *and* UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone; based on Ramanathan V. & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues*, Proc. Nat'l Acad. Sci. USA 107: 8055.

[72] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 99 ("While global mean temperatures provide some indication of climate impacts and their simplicity makes them widely used indicators, temperature changes can vary dramatically from place to place…. In the case of the short-lived climate forcing by aerosols and O_3, the forcing itself is also very unevenly distributed, and hence can cause even greater regional contrasts in the temperature response. "); *and* Christensen, J. H. *et al.* (2007) Regional Climate Projections*, in* Climate Change 2007: The Physical Science Basis.

[73] Qiu J. (2008) *China: The third pole*, Nat. 454:393, 393 ("The

proximate cause of the changes now being felt on the [Tibetan] plateau is a rise in temperature of up to 0.3 °C a decade that has been going on for fifty years — approximately three times the global warming rate"); *see also* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message, 4 ("The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world"); *and* Cruz R. V. *et al.* (2007) Asia*, in* Climate Change 2007: Impacts, Adaptation and Vulnerability, 475 ("In all four regions [of Africa] and in all seasons, the median temperature increase [between 1980 and 2099] lies between 3°C and 4°C, roughly 1.5 times the global mean response.").

[74] Wallack, J. S. and Ramanathan, V. (2009) *The other climate changes, why black carbon also matters*, Foreign Affairs 88(5) (2009).

[75] According to passive microwave data analyzed by the National Snow and Ice Data Center and NASA, on 16 September 2012 the Arctic reached a new record minimum of 1.32 million square miles, 18% less than the previous record minimum set in 2007 and nearly 50% less than the 1979 to 2000 average. National Snow & Ice Data Center, *Arctic sea ice extent settles a record seasonal minimum*, (16 September 2012); *and* Derksen C. & Brown R. (2012) *Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections'*, Geophys. Res Lett. (in press).

[76] Flanner M. G. *et al.* (2011) *Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008*, Nat. Geosci. 4:151; *see also* Arctic Monitoring and Assessment Programme (2011) Snow, Water, Ice and Permafrost in the Arctic, Executive Summary and Key Message; and Stroeve J. *et al.* (2007) *Arctic sea ice decline: faster than forecast*, Geophys. Res. Lett. 34:L09501.

[77] Lenton T. M. (2011) *2°C or not 2°C? That is the climate question*, Nat. 473(7).

[78] Jacobson M. (2010) *Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health*, J. Geophys Res. 115:3795.

[79] Menon S. *et al.* (2010) *Black carbon aerosols and the third polar*

ice cap, ATMOS. CHEM. PHYS., 10:4559; *see also* Ramanathan V. *et al.* (2007) *Atmospheric brown clouds: Hemispherical and regional variations in long range transport, absorption, and radiative forcing*, J. OF GEOPHYS. RES., 12:D22S21; *and* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE.

[80] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, SCI. 335:183, 183, 185. ("We identified 14 measures targeting methane and BC emissions that reduce projected global mean warming ~0.5°C by 2050. *** 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…"); *see also* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE: SUMMARY FOR DECISIONS MAKERS, 3 ("If the measures were to be implemented by 2030, they could halve the potential increase in global temperature projected for 2050 compared to the Assessment's reference scenario based on current policies and energy and fuel projections. *** This could reduce warming in the Arctic in the next 30 years by about two-thirds compared to the projections of the Assessment's reference scenario").

[81] Menon S. *et al.* (2010) *Black carbon aerosols and the third polar ice cap*, ATMOS. CHEM. PHYS., 10:4559

[82] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, SCI. 335:183, 183 ("This strategy avoids 0.7 to 4.7 million annual premature deaths from outdoor air pollution and increases annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond."); *see also* UNEP/WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE: SUMMARY FOR DECISIONS MAKERS; *and* UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS.

[83] Anenberg *et al.* (2012) *Global air quality and health co-benefits*

of mitigating near-term climate change through methane and black carbon emission controls, Envtl. Health Perspectives, 120:831, 831, 838 ("We estimate that, for $PM_{2.5}$ [black carbon] and ozone respectively, fully implementing these [14] measures could reduce global population-weighted average surface concentrations by 23-34% and 7-17% and avoid 0.6-4.4 and 0.04-0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia…. Based on our estimates, avoided deaths would represent 1-8% of cardiopulmonary and lung cancer deaths among those age 30 years and older, and 1-7% of all deaths for all ages, assuming constant baseline mortality rates.").

[84] UNEP/WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers, 3 ("Full implementation of the identified measures could avoid … the loss of 52 million tonnes (within a range of 30–140 million tonnes), 1–4 per cent, of the global production of maize, rice, soybean and wheat each year.").

[85] Ramanathan V. & Carmichael G. (2008) *Global and regional climate changes due to black carbon*, Nat. Geosci. 1:221.

[86] The UNEP/WMO and Shindell *et al.* studies analyzed the 1650 individual control measures in the technology and emission databases of the IIASA Greenhouse gas: Air pollution Interactions and Synergies (GAINS) climate model. These were grouped into 400 categories which were then analyzed for their impacts on emissions of methane, carbon monoxide, black carbon, organic carbon, sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon dioxide. The measures were further analyzed to determine the net effect of the changes in global radiative forcing (RF) due to changes in emissions of the studied gases and aerosols, and ranked according to their efficacy at reducing global RF. 130 measures were shown to reduce global RF and the top 16 of those measures were shown to produce almost 90% of the total mitigation potential. Shindell *et al.* combined four measures into two larger categories of measures, reducing to 14 the original 16 measures. *See* Shindell D. *et al.* (2012) *Simultaneously mitigating near-term*

climate change and improving human health and food security, Sci. 335:183; *and* UNEP/WMO (2011)) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decisions Makers.

[87] UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers ("These measures can accomplish about 38 per cent reduction of global methane emissions and around 77 per cent of black carbon emissions, if implemented between now and 2030, relative to a 2030 'reference' emission scenario.")*; see also* Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183.

[88] Bond T. C. *et al.* (2013) *Bounding the role of black carbon in the climate system: a scientific assessment*, Accepted for publication in the J. of Geophys. Res. –Atmos., DOI:10.1002/jgrd.50171 ("For a few of these sources, such as diesel engines and possibly residential biofuels, warming is strong enough that eliminating all emissions from these sources would reduce net climate forcing (*i.e.,* produce cooling).").

[89] Lam N. *et al.* (2012) *Household light makes global heat: high black carbon emissions from kerosene wick lamps*, Environ. Sci. Technol. ("Kerosene-fueled wick lamps used in millions of developing-country households are a significant but overlooked source of black carbon (BC) emissions. We present new laboratory and field measurements showing that 7-9% of kerosene consumed by widely used simple wick lamps is converted to carbonaceous particulate matter that is nearly pure BC…Kerosene lamps have affordable alternatives that pose few clear adoption barriers and would provide immediate benefit to user welfare. The net effect on climate is definitively positive forcing as co-emitted organic carbon is low. No other major BC source has such readily available alternatives, definitive climate forcing effects, and co-benefits. Replacement of kerosene-fueled wick lamps deserves strong consideration for programs that target short-lived climate forcers.").

[90] Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O.,

Ramanathan, V., and Kaniaru, D. (2009) *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions,* Proc. Natl. Acad. Sci. USA ("BC can be reduced by approximately 50% with full application of existing technologies by 2030…. Strategies to reduce BC could borrow existing management and institutions at the international and regional levels, including existing treaty systems regulating shipping and regional air quality."); *see also* UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers ("National efforts to reduce SLCFs can build upon existing institutions, policy and regulatory frameworks related to air quality management, and, where applicable, climate change. *** Regional air pollution agreements, organizations and initiatives may be effective mechanisms to build awareness, promote the implementation of SLCF mitigation measures, share good practices and enhance capacity. *** Global actions can help enable and encourage national and regional initiatives and support the widespread implementation of SLCF measures. A coordinated approach to combating SLCFs can build on existing institutional arrangements, ensure adequate financial support, enhance capacity and provide technical assistance at the national level."); *and* Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183, 188 ("Many other policy alternatives exist to implement the CH_4 [methane] and BC measures, including enhancement of current air quality regulations.").

[91] UNEP (2011) Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers ("About 50 per cent of both methane and black carbon emissions reductions can be achieved through measures that result in net cost savings (as a global average) over their technical lifetime. The savings occur when initial investments are offset by subsequent cost savings from, for example, reduced fuel use or utilization of recovered methane. A further third of the total methane emissions reduction could be addressed at relatively moderate costs.").

[92] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term*

climate change and improving human health and food security, Sci. 335:183 ("using $430 for climate and discounted health and agricultural values, gives a total benefit of ~$1100 per metric ton of CH_4 (~$700 to $5000 per metric ton, using the above analyses). IEA estimates (37) indicate roughly 100 Tg/year of CH_4 emissions can be abated at marginal costs below $1100, with more than 50 Tg/year costing less than 1/10 this valuation (including the value of CH_4 captured for resale). Analysis using more recent cost information in the GAINS model (38, 39) finds that the measures analyzed here could reduce 2030 CH_4 emissions by ~110 Tg at marginal costs below $1500 per metric ton, with 90 Tg below $250. The full set of measures reduce emissions by ~140 Tg, indicating that most would produce benefits greater than—and for approximately two-thirds of reductions far greater than—the abatement costs. Of course, the benefits would not necessarily accrue to those incurring costs.").

[93] *Id.* ("GAINS estimates show that improved efficiencies lead to a net cost savings for the brick kiln and clean-burning stove BC measures. These account for ~50% of the BC measures' impact.").

[94] *Id.* ("The regulatory measures on high-emitting vehicles and banning of agricultural waste burning, which require primarily political rather than economic investment, account for another 25%. Hence, the bulk of the BC measures could probably be implemented with costs substantially less than the benefits given the large valuation of the health impacts.").

[95] *Id.*

[96] Shindell D. *et al.* (2012) *Simultaneously mitigating near-term climate change and improving human health and food security*, Sci. 335:183 ("Global impacts of measures on climate, agriculture, and health and their economic valuation. Valuations are annual values in 2030 and beyond, due to sustained application of the measures, which are nearly equal to the integrated future valuation of a single year's emissions reductions (without discounting). Climate valuations for CH_4 use GWP100 and an SCC [social coast of carbon] of $265 per metric ton.")

[97] *Id.* ("Global impacts of measures on climate, agriculture, and health

and their economic valuation. Valuations are annual values in 2030 and beyond, due to sustained application of the measures, which are nearly equal to the integrated future valuation of a single year's emissions reductions (without discounting). Climate valuations for CH_4 use GWP100 and an SCC [social cost of carbon] of $265 per metric ton…. As noted in the main text, a GWP-based valuation neglects differences in the regional effects of these pollutants on temperatures, precipitation and sunlight available for photosynthesis relative to CO_2. As Figure 2 in the main text shows, regional effects can be quite distinct in the case of the BC measures. Additionally, the SCC includes some CO_2-specific factors such as fertilization of ecosystems which would not be present with forcing from methane or other short-lived species. As damages are often though to scale as a power of temperature change, there may also be somewhat less valuation of near-term changes than of later changes in a warmer future world and the climate valuation would grow more sharply with time for short lived species than for CO_2. Further work is clearly needed to better define appropriate techniques for valuation of non-CO_2 climate impacts.")

[98] *Id.* ("Valuation of crop yield changes uses year 2000 global market prices from the Food and Agriculture Organization (faostat. fao.org)….").

[99] *Id.* ("Valuation of premature mortalities is based on the value of a statistical life (VSL) approach. The relationship between mortality risks and willingness-to-pay (WTP) is used to determine the VSL, which is an expression of the value that people affix to small changes in mortality risks in monetary terms. We employ the United States Environmental Protection Agency's (USEPA) preferred VSL of $9,500,000 for 2030…Valuations in the main text are presented using country-specific VSLs.") (internal citations omitted).

[100] Velders G. J. M. *et al.* (2007) *The importance of the Montreal Protocol in protecting climate*, Proc. Nat'l. Acad. Sci. USA 104:4814.

[101] UNEP (2012) The Montreal Protocol and the Green Economy: Assessing the contributions and co-benefits of a Multilateral Environmental Agreement.

[102] Proposed Amendment to the Montreal Protocol (submitted

by the Federated States of Micronesia), (11 May 2012); *see also* Proposed Amendment to the Montreal Protocol (submitted by the United States, Canada, and Mexico), (9 May 2012).

[103] The cumulative BAU emission from the 6 Kyoto gases from 2000-50 is about 975 GtC-eq (=650 x 1.5, Fig. 1, Scenario 6 (England *et al.*)), which is equivalent to approximately 3575 Gt CO_2-eq. The cumulative Kyoto-gas emission budget for 2000-50 is 1500 GtCO_2-eq. if the probability of exceeding 2˚C is to be limited to approximately 25% (Meinshausen *et al*., pg. 1160). Therefore, the total mitigation needed by 2050 is approximately 2075 GtCO_2-eq. The 87-147 GtCO_2-eq. from the proposed HFC phase down represents 4-7% of the total mitigation needed by 2050, and up to 8% if all HFCs are replaced by low-GWP substitutes. England M. H. *et al*. (2009) *Constraining future greenhouse gas emissions by a cumulative target*, PROC. NAT'L. ACAD. SCI. USA 106:16539; Meinshausen M. *et al.* (2009) *Greenhouse-gas emission targets for limiting global warming to 2°C*, NAT. 458:1158; *and* Velders G. J. M. *et al.* (2009) *The large contribution of projected HFC emissions to future climate forcing*, PROC. NAT'L. ACAD. SCI. USA 106:10949.

[104] UNEP (2012) THE MONTREAL PROTOCOL AND THE GREEN ECONOMY: ASSESSING THE CONTRIBUTIONS AND CO-BENEFITS OF A MULTILATERAL ENVIRONMENTAL AGREEMENT; *citing* the following sources listed as they are cited in the figure *(1)* Velders G. J. M. *et al.* (2007) *The importance of the Montreal Protocol in protecting climate*, PROC. NAT'L. ACAD. SCI. USA 104:4814; *(2)* Velders G. J. M. *et al*. (2007) The Montreal Protocol, Celebrating 20 years of environmental progress, ed. Kaniaru D (Cameron May, London, UK); *(3)* Montreal Protocol Technology and Economic Assessment Panel (2009) TASK FORCE DECISION XX/8 INTERIM REPORT: ENVIRONMENTALLY SOUND MANAGEMENT OF BANKS OF OZONE-DEPLETING SUBSTANCES; *(4)* UNEP Riso (2009) A PRIMER ON CDM PROGRAMME OF ACTIVITIES; *(5)* Velders G. J. M. *et al.* (2007) *The importance of the Montreal Protocol in protecting climate*, PROC. NAT'L. ACAD. SCI. USA 104:4814; *(6)* Velders G. J. M. *et al.* (2009) *The large contribution of projected*

HFC emissions to future climate forcing, Proc. Nat'l. Acad. Sci. USA 106:10949. Note: Estimates are for direct emissions, and do not include CO_2 reductions from energy efficiency improvements.

[105] Montreal Protocol Technology and Economic Assessment Panel (2009) Task Force Decision XX/8 Report: Assessment of Alternatives to HCFCs and HFCs and Update of the TEAP 2005 Supplement Report Data.

[106] Velders G. J. M. *et al.* (2009) *The large contribution of projected HFC emissions to future climate forcing*, Proc. Nat'l. Acad. Sci. USA 106:10949 ("Global HFC emissions significantly exceed previous estimates after 2025 with developing country emissions as much as 800% greater than in developed countries in 2050. Global HFC emissions in 2050 are equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios and contribute a radiative forcing equivalent to that from 6–13 years of CO_2 emissions near 2050. This percentage increases to 28–45% compared with projected CO_2 emissions in a 450-ppm CO_2 stabilization scenario business-as usual scenarios from 2010 to 2050").

[107] Schwarz W. *et al.* (2011) Preparatory Study for a Review of Regulation (EC) No 842/2006 on Certain Fluorinated Greenhouse Gases: Final Report.

[108] California Air Resources Board, Amendments to the Low-Emission Vehicle Program – LEV III

[109] US EPA (2011) EPA and NHTSA Finalize Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks.

[110] US EPA (2012) 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, 40 CFR Parts 85, 86 and 600 ("In addition to the grams-per-mile CO_2-equivalent credits, for the first time the agencies are establishing provisions in the CAFE program that would account for improvements in air conditioner efficiency. Improving A/C efficiency leads to real-world fuel economy benefits, because as explained above, A/C operation represents an additional load on the engine. Thus, more efficient A/C operation imposes less of a load

and allows the vehicle to go farther on a gallon of gas.")

[111] Consumer Goods Forum, *Better Lives Through Better Business* (29 March 2012).

[112] Velders G. J. M. *et al.* (2009) *The large contribution of projected HFC emissions to future climate forcing*, Proc. Nat'l. Acad. Sci. USA 106:10949.

[113] United Nations (2012) Resolution adopted by the General Assembly: The Future We Want, A/res/66/288.

[114] UNEP (2010) Declaration on the Global Transition away from Hydrochlorofluorocarbons (HCFCs) and Cholrofluorocarbons (CFCs). *See also* UNEP (2011) Report of the Combined Ninth Meeting of the Conference of the Parties to the Vienna Convention on the Protection of the Ozone Layer and the Twenty-Third Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer.

[115] Prepared for IGSD by Dr. Guus Velders, based on Velders G. J. M. *et al.* (2009) *The large contribution of projected HFC emissions to future climate forcing*, Proc. Nat'l. Acad. Sci. USA 106:10949. *See also* Velders G. J. M. *et al.* (2007) *The importance of the Montreal Protocol in protecting climate*, Proc. Nat'l. Acad. Sci. USA 104:4814; Proposed Amendment to the Montreal Protocol (submitted by the Federated States of Micronesia), (28 Apr. 2011 at 4-6 and 9)*; and* UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer 10.

[116] Climate and Climate Air Coalition to Reduce Short Lived Climate Pollutants, Partners.

[117] C40 Cities Climate Leadership Group, Video: *C40 Mayors Demonstrate Progress in Greenhouse Gas Reductions and Announce New Actions to Take on Climate Change*, (27 June 2012).

[118] Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants. *See also* US Dept. of State, *The Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants: Fact Sheet*, (16 Feb. 2012).

[119] Press Release, UNEP, *New Climate and Clean Air Coalition*

Expands to 13 Members, (24 April 2012).

[120] *Id.*

[121] Barton-Dock M., *Buying Time as the Climate Click Ticks on, World Bank Blogs*, (19 July 2012).

[122] Rachel Kyte, *Doha: Keeping Hope Alive – Just, World Bank Blogs*, (12 December 2012) ("At the Bank, we want to expand the SLCP-relevant part of our IDA/IBRD portfolio from 12 percent in 2012 to 15 percent by 2015 and 20 percent by 2020, and will work on payment for results for methane reduction. We also plan to increase impact on SLCPs through our GEF, Carbon Finance, Global Gas Flaring, and Montreal Protocol portfolios.").

[123] G8 Camp David Declaration, (19 May, 2012).

[124] *Economic Commission for Europe, Draft decision on amending annex I to the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, (2 May 2012). The published final decisions is forthcoming.

[125] Global Alliance for Clean Cookstoves; Global Methane Initiative.

[126] UNEP (2008) ATMOSPHERIC BROWN CLOUDS: REGIONAL ASSESSMENT REPORT WITH FOCUS ON ASIA, 3 ("1. Five regional ABC hotspots around the world have been identified: i) East Asia; ii) Indo-Gangetic Plain in South Asia; iii) Southeast Asia; iv) Southern Africa; and v) the Amazon Basin. By integrating and assimilating ABC surface observations with new satellite observations and chemistry transport model (CTM), the ABC Science Team produced global maps of ABC hotspots.

[127] International Maritime Organization, Marine Environment Protection Committee (MEPC) *IMO Environment Meeting Completes Packed Agenda* (19 July 2011).

[128] Ministry of the Environment Sweden (2013) CHAIRS CONCLUSIONS FROM THE ARCTIC ENVIRONMENT MINISTERS MEETING: ARCTIC CHANGE – GLOBAL EFFECTS, 2.

[129] *See* Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O., Ramanathan, V., and 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. USA.