Institute for Governance & Sustainable Development

Radiative Heating of an Ice-Free Arctic Ocean
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Plain language summary
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"Additional heating due to complete Arctic sea ice loss would hasten global warming by an estimated 25 years"

Pistone et al. 2019 answer the question of how much more forcing enters the climate system if the Arctic is annually ice-free during the summer. Previous work by the authors showed that the ice lost between 1979 and 2011 was additional forcing equivalent to 25% from CO2 during the same time frame.[1]

Observations have shown that "Arctic sea ice retreat per degree of global warming is 2.1 times larger than the CMIP5 ensemble-mean result", which suggests that the Arctic could become annually ice free within decades.[2] The ice that typically covers the Arctic Ocean reflects back incoming solar radiation, and without the ice, the ocean absorbs that energy, approximately 6 times more than the ice-covered surface.[3]

If Arctic sea ice is completely gone during the sunlit parts of the year, the Arctic Ocean region albedo is decreased by 11.5%, adding 21 W/m^2 of solar heating to the region, relative to the 1979 baseline, which averaged over the globe amounts to 0.71 W/m^2.[4] Of this 0.71 W/m^2, 0.21 W/m^2 occurred between 1979 and 2011.[5]

The authors found that this 0.71 W/m^2 of forcing would be equivalent to the forcing of adding 1 trillion tons of CO_2 to the atmosphere, which is the equivalent to CO_2 concentration going from 400ppm to 456.7 ppm[6] and would be equivalent 25 years of CO_2 emissions at the current rate of 40 billion tons of CO_2 per year.[7] This means that if the Arctic were to be annually ice free, the time for achieving carbon neutrality and adapting to climate change would be drastically shortened.[8]

Clouds can further alter the forcing in the Arctic region, so in addition to the baseline scenario of cloud cover remaining the same as present day,[9] the authors considered two extremes scenarios: one with completely clear skies and a second with overcast skies.[10] Without any clouds present, the forcing in the Arctic Ocean (whenever averaged over the globe) is 2.2 W/m^2, three times more than the baseline, and for overcast skies, the forcing drops by half to 0.37 W/m^2, meaning that even with the negative feedback from clouds, the loss of Arctic sea ice can still contribute 0.34 W/m^2 of forcing.[11]

[1] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 1 ("Satellite observations suggest that the albedo changes associated with the decline of Arctic sea ice during 1979–2011 contributed a global-mean increase in solar heating of 0.21 W/m^2, which is a quarter as large as the direct radiative forcing from rising CO_2 concentrations during the same period (Pistone et al., 2014)."); *see also* Pistone K., *et al.* (2014) *Observational determination of albedo decrease caused by vanishing Arctic sea ice*, PROC. NAT'L. ACAD.

SCI. 111(9):3322–3326, 3322 ("The decline of Arctic sea ice has been documented in over 30 y of satellite passive microwave observations. The resulting darkening of the Arctic and its amplification of global warming was hypothesized almost 50 y ago but has yet to be verified with direct observations. This study uses satellite radiation budget measurements along with satellite microwave sea ice data to document the Arctic-wide decrease in planetary albedo and its amplifying effect on the warming. The analysis reveals a striking relationship between planetary albedo and sea ice cover, quantities inferred from two independent satellite instruments. We find that the Arctic planetary albedo has decreased from 0.52 to 0.48 between 1979 and 2011, corresponding to an additional 6.4 ± 0.9 W/m^2 of solar energy input into the Arctic Ocean region since 1979. Averaged over the globe, this albedo decrease corresponds to a forcing that is 25% as large as that due to the change in CO_2 during this period, considerably larger than expectations from models and other less direct recent estimates. Changes in cloudiness appear to play a negligible role in observed Arctic darkening, thus reducing the possibility of Arctic cloud albedo feedbacks mitigating future Arctic warming.").

[2] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 2 ("The observed Arctic sea ice retreat per degree of global warming is 2.1 times larger than the CMIP5 ensemble-mean result, with no model (blue histogram in Figure 1b) simulating a value as extreme as the observations (red line in Figure 1b). This suggests that there may be substantial systematic biases in the model projections of the level of global warming at which the Arctic becomes annually ice free. Given that this bias exists in the models and that future changes may not follow past observations due to internal climate variability and other factors, we cannot exclude the extreme possibility that the Arctic could become annually ice free during the coming decades. This extreme possibility is the focus of the current study.").

[3] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 1 ("The disappearance of sea ice alters the Earth's energy balance because a low-albedo open ocean surface typically absorbs approximately 6 times more solar radiation than a surface covered with sea ice and snow, which has a substantially higher albedo (e.g., Perovich, 1998).").

[4] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 3 ("Hence, we focus on the baseline estimate scenario in which cloud conditions remain unchanged from the present. We find that the complete disappearance of Arctic sea ice throughout the sunlit part of the year in this scenario would cause the average planetary albedo of the Arctic Ocean (poleward of 60 ºN) to decrease by 11.5% in absolute terms. This would add an additional 21 W/m^2 of annual-mean solar heating over the Arctic Ocean relative to the 1979 baseline state. Averaged over the globe, this implies a global radiative heating of 0.71 W/m^2 (Figure 2).").

[5] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 3 ("Of the 0.71 W/m^2 of globally averaged heating, 0.21 W/m^2 is estimated to have already occurred between 1979 and 2016. Approximately half (0.11 W/m^2) of this realized heating occurred during the CERES observational record (2000–2016), with the other half occurring between 1979 and 1999 as estimated based on the observed relationship between satellite- derived sea ice concentration and albedo (Pistone et al., 2014).").

[6] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 6 ("The estimate of one trillion tons of CO_2 emissions is computed using the following approximate formula: $f = (5.35\ W/m^2)\ \ln[x/R]$ (Myhre et al., 1998). Here f is the radiative forcing relative to an arbitrary reference value R, x is the atmospheric CO_2 concentration, and ln indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO_2 causes a radiative forcing of 3.71 W/m^2. Considering a radiative forcing of 0.71 W/m^2, this translates to an increase in the atmospheric CO_2 concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO_2 is equivalent to 7.77 Gt (Le Quéré et al., 2018), this increase of 56.7 ppm weighs 441 Gt. The mean airborne fraction of CO_2 (i.e., fraction of CO_2 emissions that remain in the atmosphere) is estimated to be 0.44 ± 0.06 (section 6.3.2.4 of Ciais et al., 2013). This implies that the

emissions needed to increase atmospheric CO_2 enough to cause 0.71 W/m^2 of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44).").

[7] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 4 ("This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO_2 into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO_2 have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO_2 per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic sea ice would be equivalent to 25 years of global CO_2 emissions at the current rate.").

[8] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 4 ("This implies that if the Arctic sea ice were to disappear much more rapidly than in current climate model projections, it would drastically shorten the time available to adapt to climate changes and the time for achieving carbon neutrality.").

[9] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 2 ("A source of uncertainty in the present analysis is how cloudiness above the Arctic Ocean may change in the future in response to sea ice retreat. Previous findings suggest that the fractional cloud cover and average cloud optical properties may remain approximately unchanged, which we adopt here as a baseline estimate.").

[10] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 4 ("We examine two perhaps unrealistically extreme future Arctic cloud scenarios: at one extreme, an ice-free Arctic Ocean that is completely cloud free and at the other extreme, an ice-free Arctic Ocean that is completely overcast.").

[11] Pistone K., *et al.* (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYSICAL RESEARCH LETTERS 46, Early Online Version, 1–7, 4 ("We examine two perhaps unrealistically extreme future Arctic cloud scenarios: at one extreme, an ice-free Arctic Ocean that is completely cloud free and at the other extreme, an ice-free Arctic Ocean that is completely overcast. For simplicity, in the latter scenario we use distributions of cloud optical thickness based on present-day observations (see Appendix A). Both of these extreme scenarios are shown in Figure 2. The cloud-free, ice-free Arctic scenario results in a global radiative heating of 2.2 W/m^2 compared with the 1979 baseline state, which is 3 times more than the 0.71 W/m^2 baseline estimate derived above for unchanged clouds. The completely overcast ice-free Arctic scenario results in a global radiative heating of 0.37 W/m^2, which is approximately half as large as the 0.71 W/m^2 baseline estimate (Figure 2b). This suggests that even in the presence of an extreme negative cloud feedback, the global heating due to the complete disappearance of the Arctic sea ice would still be nearly double the already-observed heating due to the current level of ice loss.").