ESD Ideas: Arctic Amplification's Contribution to Breaches of the Paris Agreement

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Abstract.

The Arctic is warming at almost four times the global average rate. Here we reframe this amplified Arctic warming in terms of global climate ambition to show that ~~it causes a breach of~~ without Arctic amplification, the world would breach the Paris Agreement's 1.5°C and 2°C limits 5 and 8 years ~~earlier~~later, respectively. ~~This outsized influence~~ The outsized influence of Arctic warming on global climate targets highlights the need for better modelling and monitoring of Arctic change.

The phenomenon of Arctic amplification is causing the Arctic (North of 66°N) to warm at almost four times the global average rate (Rantanen et al., 2022). ~~This amplified warming~~ However, this statistic is of limited direct relevance to policy-makers, because it is not framed in terms of the central metric of climate policy: global mean temperature change. Here we use the latest generation of climate model outputs to reframe Arctic amplification in terms of the direct contribution of faster temperature rises in the Arctic to global warming. Specifically, we characterise the influence of Arctic amplification on the timing of breaches of the 1.5°C and 2°C warming levels identified in the Paris Agreement, with the aim of providing a more intuitive quantification of the significance of amplified Arctic warming. Arctic amplification is strongest in the winter months and is driven by positive feedbacks involving the vertical structure of the lower atmosphere, changing cloud cover, temperature-dependent increases in thermal radiation to space, and the retreat of sea ice and snow cover (Previdi et al., 2021; Goosse et al., 2018). ~~Observational data indicate that Arctic amplification has caused the region's annual mean temperature to increase by~~ The 2.7°C ~~since the preindustrial period. Arctic warming has therefore~~ Arctic warming since pre-industrial has contributed around 10% of Earth's globally averaged warming to date (Rohde and Hausfather, 2020), despite the region occupying only 4% of the Earth's surface. ~~The Arctic's outsized impact on global temperature rise has been even larger since the turn of the millennium, as amplification has been particularly strong over this period (Chylek et al., 2022; Huang et al., 2017). Here we use the latest generation of climate model outputs to re-frame the Arctic's historical and future contribution to global warming in terms of the year in which the Paris Agreement's temperature targets may be broken. Specifically, we characterise the influence of Arctic amplification on the timing of breaches of the 1.5°C & 2°C warming limits.~~

To characterise future global and Arctic warming, we analyse surface air temperature data from the Coupled Model Intercomparison Project Phase 6 ~~(CMIP6) (Eyring et al., 2016)~~(CMIP6; Eyring et al., 2016). We focus here on future temperature change under the SSP2-4.5 emissions pathway, but also report results for a low (SSP1-2.6) and a high (SSP3-7.0) emissions pathway. The SSP2-4.5 pathway is a plausible intermediate scenario of future greenhouse gas emissions, which would likely meet neither of the Paris temperature goals (Pielke Jr et al., 2022; Hausfather and Peters, 2020). Our analysis compares the year in which global average temperatures breach the two Paris targets in this dataset with the year in which those targets are breached in a modified version of the dataset which excludes the area north of 66°N. Crucially, the latter case is equivalent to an alternative world in which the Arctic warms at the global mean rate. The difference between the two timings therefore represents the time-contribution of Arctic amplification to breaches of the Paris Agreement~~.~~ ~~This methodology does not use models to~~ ’s temperature thresholds. Our definition of Arctic amplification differs from some analyses (e.g. Pithan and Mauritsen, 2014) which use the tropics as the baseline region, rather than the world outside the Arctic.

Our method does not simulate a world without Arctic amplification. Such a world would be radically different to ours since the phenomenon is in large part driven by the Arctic being colder than the rest of the planet (Pithan and Mauritsen, 2014). Neither do we quantify the impacts of Arctic change on temperature rise outside the region, such as via the albedo feedback from loss of snow and ice (Pistone et al., 2014), greenhouse gas emissions from permafrost thaw (MacDougall et al., 2015), and altered atmospheric and oceanic circulation (Liu et al., 2020). Instead, we quantify the rate of local Arctic warming in terms of its ~~contribution to change in global mean surface air temperatures in our present and future world~~direct contribution to global mean temperature change. We also note that our analysis does not imply any change from current estimates in the expected timing of breaching Paris limits, which refer explicitly and only to global mean temperature (UNFCCC. Conference of the Parties (COP), 2015).

The ~~global mean temperature time series exhibits interannual variability, and as such the~~ Paris Agreement is not breached when just one year is warmer than ~~a~~ the target temperature (Smith et al., 2018). Instead ~~the UNFCCC definition of climate change which informs the Paris agreement makes it clear that~~ a multi-decadal ~~climatological~~ average must be used to minimise the effect of internal variability (Rogelj et al., 2017). We therefore define breaches of a temperature threshold as the fractional year when the 20-year running-average temperature crosses that threshold. Many climate models significantly over- or underestimate the warming to date since pre-industrial. To account for this, we scale the modelled temperature anomalies from the pre-industrial baseline to match the observed present-day temperature anomaly. Our results are qualitatively insensitive to the choice of bias correction ~~methodology~~ method (See Methods).

Figure 1 shows ~~observed and projected global mean surface temperature anomalies, and the corresponding anomalies in the counterfactual case where the Arctic warms at the global average rate. We show a multi-model mean and distribution based on the set of first (or only) ensemble runs for each model. Arctic amplification leads to the~~ that under the SSP2-4.5 emissions pathway, the 1.5~~o~~°C temperature threshold ~~being~~ would be breached 4.7 (±0.4) years ~~earlier under the SSP2-4.5 emissions pathway~~later in the absence of Arctic amplification. Across the ensemble of models, the 1.5~~o~~°C threshold is exceeded in the year 2031.8 (±0.9)~~with~~. Whereas, without Arctic amplification, ~~and~~ this scenario breaches the 1.5°C threshold in 2036.6

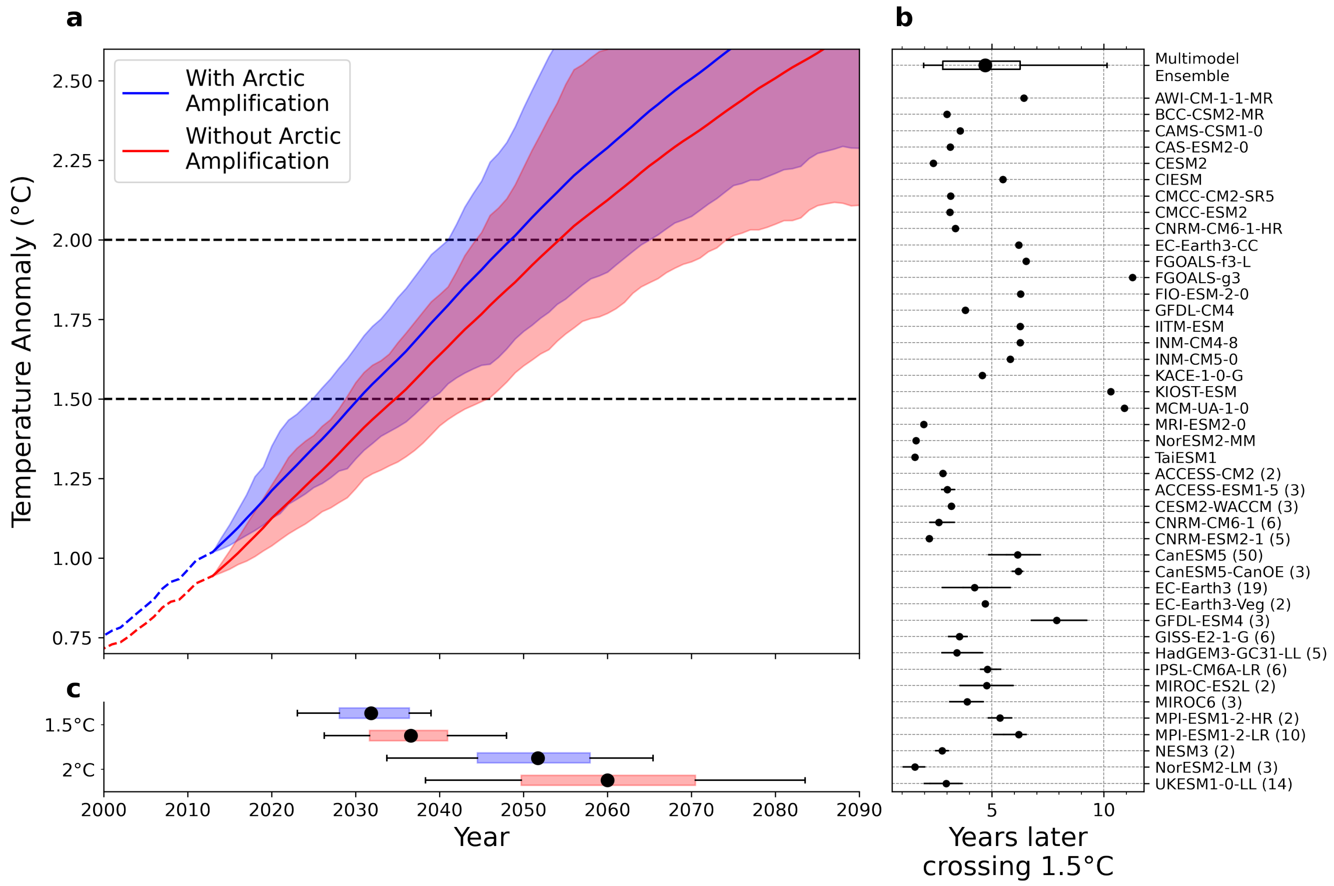

Figure 1. Effect of Arctic amplification on temperature rises above the Paris limits in CMIP6 models. **(a)** Observed ~~(dashed lines)~~ and ~~CMIP6~~ projected global mean temperature anomalies relative to pre-industrial with and without Arctic amplification~~of warming~~. The CMIP6 projections are constructed from the first ~~(or only)~~ ensemble member of each model's SSP2-4.5 scenario, scaled to the observed present-day anomaly. All temperatures anomalies are 20-year, centred, rolling means. ~~Projections are from the SSP2-4.5 emissions pathway and are scaled to diverge from the observed temperature anomaly, which results in a divergence in 2013, half the window-length prior to the present day.~~ Central lines indicate multi-model means, shaded regions represent the spread between the 10% and 90% intervals. **(b)** Number of years ~~earlier in~~ later which each CMIP6 model breaches the 1.5°C temperature threshold ~~as a result of amplified warming in the~~ without Arctic amplification. ~~For models with multiple ensemble members available, error~~ Error bars show the range of this value across ~~the full~~ ensemble members, ~~and~~ dots show the ensemble mean~~value~~, and numbers in brackets following the model names indicate the number of ensemble members~~used~~. For the multi-model ensemble, the box shows the 25th to 75th percentile range, and whiskers show the 5th to 95th percentile range. **(c)** Distributions of crossing years in the multi-model ensemble for the two temperature thresholds, with and without Arctic amplification. The box plots are defined as in (b).~~The mean number of years early with which each temperature threshold is crossed due to Arctic amplification is labelled. Both labelled differences are significant at a 99% confidence level using a one-sided t-test.~~

(±1.1)~~without~~. Measuring from 2023, ~~our world is therefore projected to~~ the world would therefore breach the 1.5°C threshold ~~34.8% earlier as a direct result of amplified warming within the Arcticregion~~53% later without amplified warming in the Arctic. The uncertainty value on the difference in crossing years represents the standard error of the bias-corrected multi-model ensemble. The 2~~°~~°C threshold is passed 8.3 (±1.0) years ~~earlier due to~~ later without Arctic amplification, ~~which brings forward the year when 2°C is exceeded from~~ in 2060.0 (±2.6) ~~to~~ rather than 2051.7 (±1.8), ~~i.e. by 22.4%~~ 29% later. Under a plausible high emissions scenario (SSP3-7.0, not shown) ~~Arctic amplification leads to~~ without Arctic amplification, the 1.5~~°~~°C temperature threshold ~~being~~ would be breached 3.7 (±0.2) years (~~32.2%) earlier~~48%) later, moving the date ~~forward from 2034.5~~ from 2030.8 (±~~0.8) to 2030.8~~ 0.7) to 2034.5 (±~~0.7~~0.8). Under a low emissions pathway (SSP1-2.6), ~~Arctic amplification causes~~ without Arctic amplification the passing of the 1.5~~°C threshold~~ °C threshold is delayed by 6.6 (±1.4) years (~~44.7%)earlier.~~

81%). These results demonstrate the key impact of Arctic warming on the central metric of climate policy~~:~~, the global mean temperature~~. We find that~~ ; amplified Arctic warming reduces the expected time to crossing the 1.5~~°~~°C threshold by ~~32-45%, and has a larger impact on the timing of breaching the~~ 4-7 years relative to a world without such amplification.

Our approach also allows assessment of how uncertainty in Arctic warming over the coming decades contributes to uncertainty in the crossing year for the 1.5~~°C temperature thresholdthan the difference between emissions scenarios. Our findings underscore the importance of accurately representing this relatively small region in Earth system models. This is both because Arctic warming is large, and because CMIP6 models show major differences in projected Arctic temperature change. The Arctic therefore introduces disproportionately large uncertainty into global climate projections. For instance, the CMIP6 inter-model spread in global mean temperature in 2050 is 13% larger than the spread in temperature South of~~ °C threshold. In the multi-model ensemble, the 10th to 90th percentile range in 1.5°C crossing year is 13.9 years. To quantify the impact of near-term Arctic warming on this uncertainty, it is necessary to account for the strong correlation ($r = 0.53$) between Arctic warming and the warming South of 66°~~N~~N across the multi-model ensemble. We therefore calculate a partial correlation coefficient between the rate of Arctic warming and the crossing year across the multi-model ensemble, controlling for warming outside the Arctic. This partial correlation coefficient is equal to -0.39 (significant at 95% confidence). The square of this coefficient, 15%, gives the variance in crossing year for the 1.5°C threshold explained by the near-term Arctic warming rate under the SSP2-4.5 scenario.

~~The Arctic 's role in exceeding the Paris limits also highlights the importance of accurate surface temperature observations in~~ We find that despite occupying only 4% of the global surface area, variability in near-term Arctic warming contributes 15% of the inter-model uncertainty in the ~~region. These have historically been limited by the hostile weather and dynamic sea ice cover, with high latitudes also experiencing poor coverage by satellites. The regional warming to date is therefore relatively poorly constrained, with the observational data used in this paper relying on statistical interpolation to assign temperatures over large portions of the Arctic Ocean without in-situ measurements. As a result, it is important that future research efforts continue to incorporate more new and historical observations from the Arctic into global surface temperature data sets, to better quantify the impact of this rapidly changing regionon global climate mean temperature change~~crossing year. We also assess how the year in which the 1.5°C limit is exceeded varies between low and high scenarios for Arctic amplification influence. To do this we perform a multiple linear regression on the crossing year using two variables: Arctic warming and warming outside of the Arctic (see Methods). Holding the warming outside of the Arctic constant at its multi-model mean of 0.26°C per decade, our regression model predicts that the 10th and 90th percentiles of near-term Arctic warming are represented by crossing years of 2033.2 and 2030.4, respectively, a difference of 2.9 years. We note that this difference in crossing year associated with the lower and upper bounds on projected Arctic warming is larger than the 1.6 year difference between the mean crossing years for the low and high emissions scenarios assessed here (2032.4 and 2030.8, respectively).

While we have focused here only on the direct impact of Arctic warming on global temperature change, the local impacts should not be overlooked. Under 2°C of global warming, Arctic temperatures are expected to rise by 4°C in the annual mean, and 7°C in winter, with profound consequences for local people and ecosystems (Post et al., 2019). Additionally, amplified Arctic warming contributes to the global challenges that motivated the 1.5°C target, such as sea level rise and permafrost thaw. These local and global impacts are a primary motivation for improving the representation of the Arctic in Earth system models and for accurate observational monitoring in the region. Our findings offer additional motivation for such work — that Arctic warming has an outsized influence on both the timing of and uncertainty in projected breaches of the Paris agreement's temperature targets.

Methods

The CMIP6 analysis includes output of all models and ensemble members for which both the historical and SSP scenarios were available on the United Kingdom's CEDA ~~archive. In total, 42 different~~ data archive (43 CMIP6 models and ~~170~~ 172 individual ensemble members~~contribute to our analysis. There is a large variation in warming since pre-industrial across models and their ensemble members. For example, the first ensemble member of UKESM1-0-LL passes 1.5°C of warming in the year 2019.~~). To make reasonable near-term warming projections we ~~therefore~~ adjust model temperatures to match present-day observations. We scale model projections by the ratio of their ~~present day~~ present-day warming anomaly from pre-industrial to that value in observations. 'Present day' here refers to 2013 because taking a 20-year centred rolling mean introduces a 9-year delay. Scaling is carried out independently for global temperatures projections and temperature projections without Arctic amplification. This multiplicative correction has been used in various studies bias correcting global climate models (Watanabe et al., 2012; Graham et al., 2007; Melia et al., 2015). Our results are qualitatively insensitive to the choice of bias-correction method because the observed warming sits close to the median model, such that a roughly equal number of model first ensemble members have their global temperature anomaly adjusted upwards (22 models) as downwards (21 models). With an alternative bias correction method, in which model anomalies from observations are subtracted as a constant offset, we find that the 2°C threshold is passed 5.8 (±0.5) years later without to Arctic amplification, as compared to 8.3 years earlier with our preferred scaling method.

The temperature observations used are the HadCRUT5 data set (Morice et al., 2021), interpolated onto a 0.5° latitude grid. The observational temperature data uses a blend of sea surface temperature over the open ocean, and near-surface air temperature over land and sea ice. This blended global temperature metric is not well-suited for making temperature projections using the CMIP6 ensemble because the fraction of open ocean changes with sea ice coverage, and so is not constant between models and ensemble members or over time (Tokarska et al., 2019). As such we follow the recommendation of Tokarska et al. Tokarska et al. (2019) in using a hybrid temperature metric for our analysis, consisting of blended sea surface temperature and near-surface air temperatures for observations to present day, and of global near-surface air temperature as directly outputted as a model-field for future CMIP6-based projections.

The ~~(non-integer)~~ fractional year in which a temperature threshold is crossed is calculated by linearly interpolating the rolling mean temperature. For the SSP2-4.5 scenario, ~~one model~~ two models (FGOALS-g3 ~~), does~~ and KIOST-ESM) do not cross 2°C by 2100, when the simulation ends. In ~~this case~~these cases, we extrapolate the crossing year based on the 2080-2100 trend. For the low-emissions SSP1-2.6 pathway, we only performed our analysis for the 1.5°C threshold, as a majority of models do not exceed 2°C under that scenario. It should be noted that the mean crossing year of a set of trajectories is not in general equal to the crossing year of the mean trajectory, and for this reason the multi-model mean lines in Figure 1a do not align with the crossing year distributions in Figure 1c. All results quoted in this study refer to the mean crossing year of the individual trajectories.

To estimate the contribution of Arctic warming to uncertainty in the crossing year we calculate an Ordinary Least Squares multiple linear regression for the 1.5 °C threshold crossing year in terms of two variables, (i) the linearised warming North of 66°N over the 30-year period 2013-2044, and (ii) the linearised warming South of 66°N over the same period. This model predicts sensitivities of the crossing year of -6.0 and -49.7 years per °C warming inside and outside the Arctic, respectively. The partial correlation coefficient is also calculated over the same 30-year period 2013-2044.

Code availability. All code required to reproduce our analysis is available at https://github.com/alistairduffey/AA_contrib_to_GMST

Competing interests. The authors declare no competing interests

Author contributions. AD carried out the CMIP6 data analysis. RM conceived the study. AD and RM jointly wrote the manuscript. PI, MT and JS provided critical feedback which shaped the analysis, presentation and manuscript.

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