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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 the Paris Agreement's 1.5°C and 2°C limits 5 and 8 years earlier, respectively. This outsized influence 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 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 ~2.7°C since the preindustrial period. Arctic warming has therefore 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). 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 simulate a world without Arctic amplification. Such a world would be radically different to ours. 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.

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 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 year when the 20-year running-average temperature crosses that threshold. Many climate models significantly over- or under-estimate 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 (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 1.5°C temperature threshold being breached 4.7 (±0.4) years earlier under the SSP2-4.5 emissions pathway. Across the ensemble of models, the 1.5°C threshold is exceeded in the year 2031.8 (±0.9) with Arctic amplification, and 2036.6 (±1.1) without. Measuring from 2023, our world is therefore projected to breach the 1.5°C threshold 34.8% earlier as a direct result of amplified warming within the Arctic region. 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 Arctic amplification, which brings forward the year when 2°C is exceeded from 2060.0 (±2.6) to 2051.7 (±1.8), i.e. by 22.4%. Under a plausible high emissions scenario (SSP3-7.0, not shown) Arctic amplification leads to the 1.5°C temperature threshold being breached 3.7 (±0.2) years (32.2%) earlier, moving the date forward from 2034.5 (±0.8) to 2030.8 (±0.7). Under a low emissions pathway (SSP1-2.6), Arctic amplification causes the passing of the 1.5°C threshold 6.6 (±1.4) years (44.7%) earlier.

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 1.5°C temperature threshold than 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 66°N.

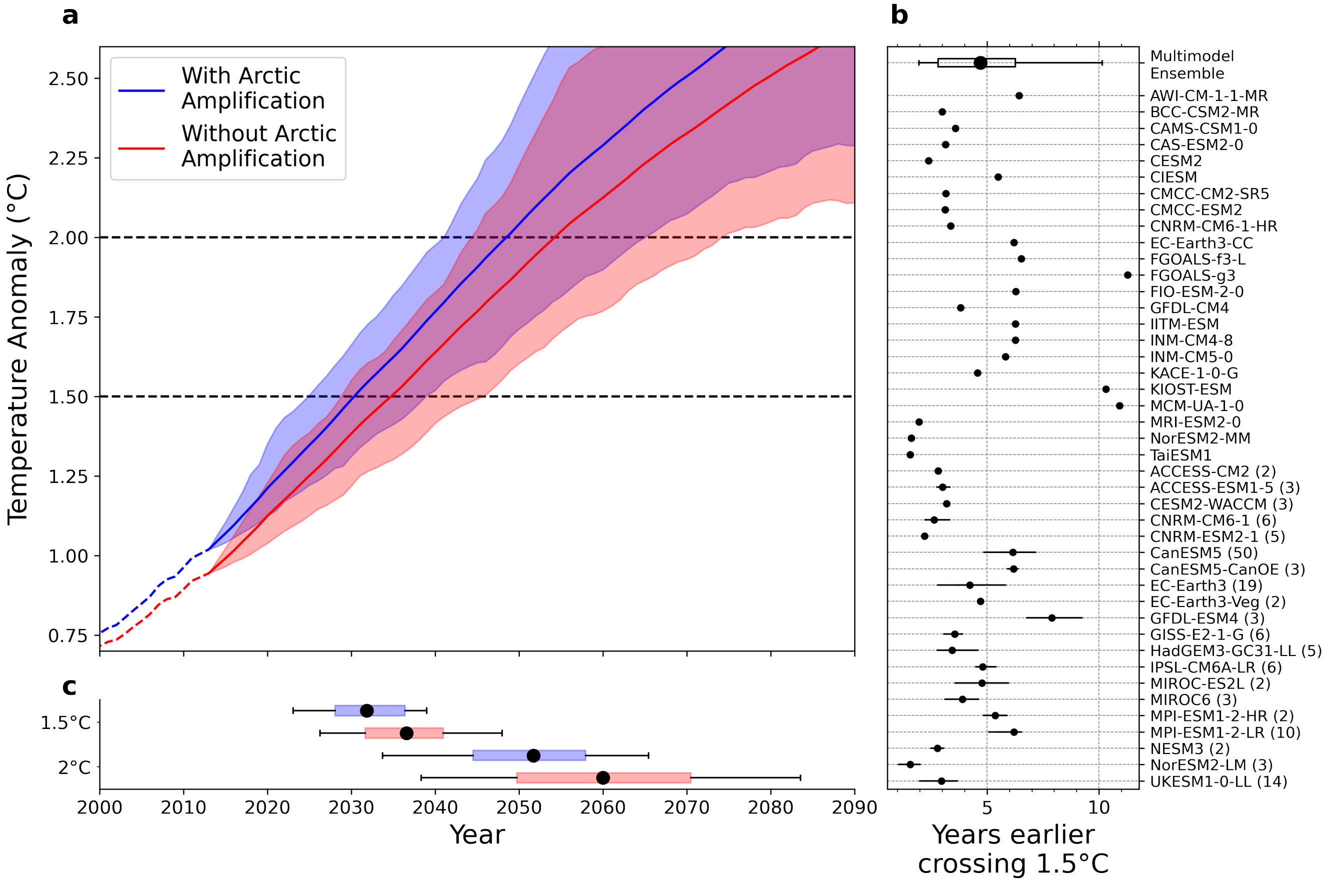

Figure 1. Effect of Arctic amplification on temperature rises above the Paris limits in CMIP6 models. **(a)** Observed (dashed lines) and CMIP6 projected global mean temperature anomalies relative to pre-industrial with and without Arctic amplification of warming. The CMIP6 projections are constructed from the first (or only) ensemble member of each model. 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 which each CMIP6 model breaches the 1.5°C temperature threshold as a result of amplified warming in the Arctic. For models with multiple ensemble members available, error bars show the range of this value across the full ensemble, and dots show the 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.

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The Arctic's role in exceeding the Paris limits also highlights the importance of accurate surface temperature observations 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 region on global climate mean temperature change.

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 CMIP6 models and 170 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 observations. We scale model projections by the ratio of their 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).

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) 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 (FGOALS-g3), does not cross 2°C by 2100, when the simulation ends. In this case, 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.

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

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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