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The Arctic has warmed four times faster than the globe since 1980

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1 Abstract

In recent decades, the warming in the Arctic has been much faster than in the rest of the world, a phenomenon known as Arctic amplification (AA). Numerous studies report that Arctic is warming either twice, more than twice, or even three times as fast as the globe on average. However, the lack of consensus of AA definition precludes its precise quantification. Here we show, by using several observational datasets which cover the Arctic region and adopting a simple definition of AA, that during the last 40 years the Arctic has been warming almost four times faster than the globe as a whole, which is a higher ratio than generally reported in literature. Furthermore, we compared the observed AA ratio to the ratio simulated by state-of-the-art climate models, and show that the models largely underestimate the present AA, a finding that is not very sensitive to the exact definition of AA. The underestimation of AA by climate models most likely results from their inability to realistically simulate feedback mechanisms between sea ice melt and atmospheric temperatures. Our results imply that the

underestimated AA leads to biased projections of climate change both in the Arctic and mid-latitudes.

2 Main

The faster warming rate in the Arctic compared to the globe as a whole is considered nowadays a robust fact. The phenomenon, called Arctic or polar amplification (AA), can be seen in both observations and models (e.g. Holland and Bitz, 2003; Serreze and Francis, 2006; Serreze et al., 2009; Huang et al., 2017).

Arctic amplification is acting to reduce the meridional temperature gradient in mid-latitudes and thus can have implications for mid-latitude weather and climate, in particular via the Polar front jet stream (e.g. Francis and Vavrus, 2012; Cohen et al., 2014; Francis and Vavrus, 2015) and blocking highs (Luo et al., 2018). However it remains debatable whether or not the effects of AA have had discernible influence on recent mid-latitude climate trends (Francis, 2017; Vavrus, 2018; Cohen et al., 2020; Dai and Song, 2020; Blackport and Screen, 2020, 2021) and occurrence of extreme events (Vihma et al., 2020).

While there is no doubt on the enhanced warming in the Arctic with increasing greenhouse gases, there seems to be no clear consensus on the relative importance of the feedback mechanisms leading to AA (Richter-Menge and Druckenmiller, 2020). During the last decade, multiple factors have been proposed to explain AA: reduced surface albedo due to sea-ice loss and snow retreat (Screen and Simmonds, 2010; Taylor et al., 2013; Dai et al., 2019), Planck feedback (Pithan and Mauritsen, 2014), lapse-rate feedback (Stuecker et al., 2018), surface thermal inversion (Bintanja et al., 2011), cloud feedback (Taylor et al., 2013), ocean heat transport (Beer et al., 2020) and meridional atmospheric moisture transport (Graversen and Burtu, 2016; Woods and Caballero, 2016; Kim et al., 2017). Furthermore, the reduced pollution in Europe may have contributed to the Arctic warming during the last decades (Navarro et al., 2016; Krishnan et al., 2020), and possible reductions of Asian aerosols under a strong mitigation policy

may increase the future AA (Merikanto et al., 2021).

Also, there is little consensus on the magnitude of AA. Numerous recent studies on AA report that the Arctic warms either nearly twice (e.g. Yu et al., 2021), about twice (e.g. Walsh, 2014), or more than twice (e.g. Richter-Menge and Druckenmiller, 2020; Jansen et al., 2020) as fast as the global average. The recent Arctic Monitoring and Assessment Programme (AMAP) report states the rate of Arctic warming as being three times as fast as the global warming during the period 1971-2019 (AMAP, 2021).

The difficulty in defining AA is that both the period of interest and the area of Arctic can be defined in multiple ways. The warming can be calculated using linear trends for the last 30-50 or even longer periods of years. Moreover, the area of Arctic can be defined using the area poleward of 60°N, 65°N or 70°N latitude thresholds, or definitions not based on latitude (Davy et al., 2018). Uncertainties arising when calculating AA in observations and models have also been emphasized (Hind et al., 2016; Davy et al., 2018; Smith et al., 2019).

While there have been improvements in climate models to realistically represent the evolution of Arctic climate (Davy and Outten, 2020) and sea ice (Stroeve et al., 2012) under global warming, most models in the latest generation of Coupled Model Intercomparison Project phase 6 (CMIP6) still fail to simulate plausible sensitivity of sea-ice loss to the rise of global temperatures (Notz and Community, 2020). Because the sea ice loss is one of main mechanisms causing AA, natural follow-up question arising is whether climate models are able to reproduce the magnitude of the observed AA.

The primary motivation of this study comes from the lack of consistent definition and thus consensus on the magnitude of AA in the literature. Also, as AA is not constant in time, the estimates referred to in previous studies are potentially outdated. Our objective is to move towards a more consistent definition of AA, quantify its magnitude by utilizing most recent observational datasets covering the Arctic region, and assess the ability of climate models to reproduce AA.

3 Observed and simulated Arctic amplification

We begin by showing the evolution of global mean and Arctic mean temperatures during 1900-2019 (Fig. 1) by considering the four observational datasets: GISTEMP, BEST, CW and ERA5 (see Methods). Compared to the global temperatures (Fig 1, light colors), the temperature variations in the Arctic (Fig 1, dark colors) have been much more amplified. The multi-decadal variations can be divided into three distinct periods: first, a rise of temperatures in 1900-1940 (often called as early twentieth-century warming, e.g. Hegerl et al., 2018); secondly, a decrease of temperatures in 1940-1980 (referred as mid-twentieth-century cooling, e.g. Haustein et al., 2019); and finally, the recent warming period since around 1980.

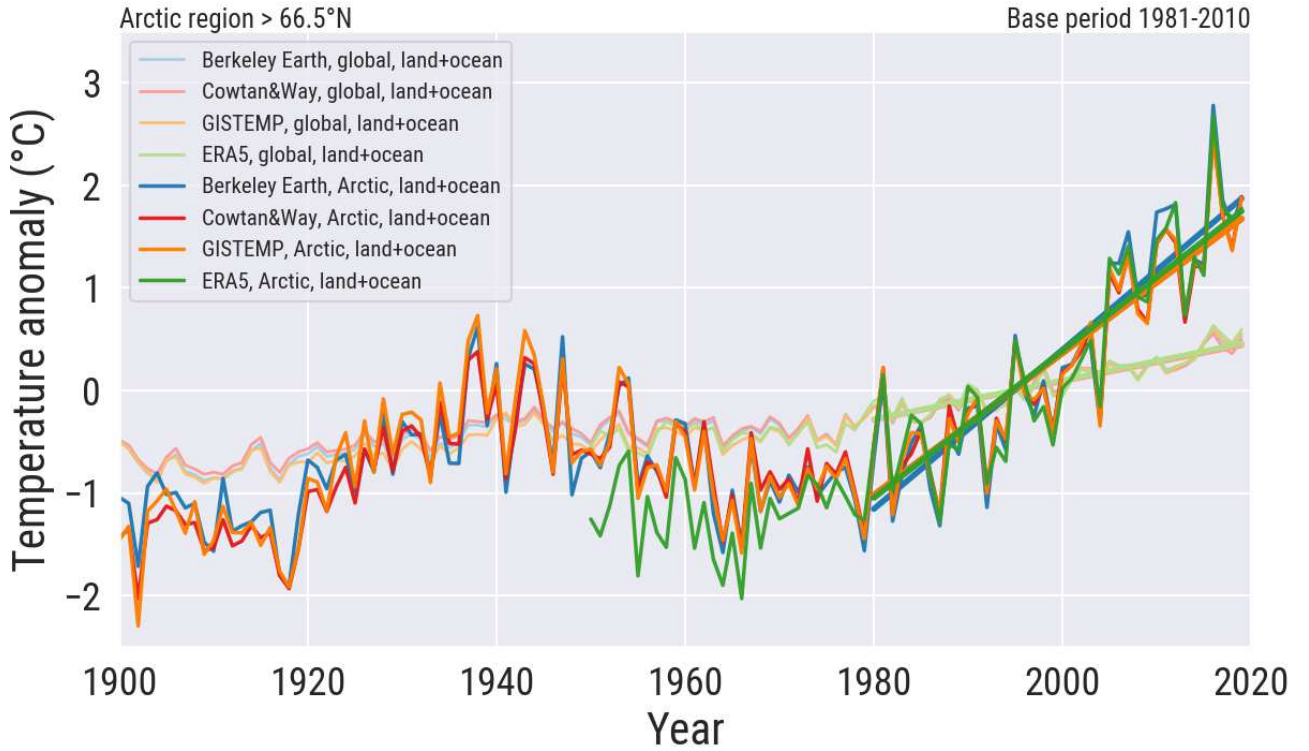


Figure 1: Annual mean temperature anomalies in the Arctic and globally during 1900-2019 derived from the various observational datasets (see the legend). Temperature anomalies have been calculated relative to the 1981-2010 period. Shown are also the linear temperature trends for 1980-2019.

The warming in the Arctic since the 1980s has been particularly strong, and the different datasets are in a close agreement with each other. The agreement between observational data sets and ERA5 is likewise good when land and ocean areas are considered separately (Figs. S1 and S2), although the differences over the ocean are somewhat larger during the pre-1979 period. Due to the good agreement in the 1980-2019 period, we next consider the average of these four datasets as an observational estimate.

The observations indicate that, during 1980-2019, a large fraction of the Arctic Ocean is warming faster than $0.75^{\circ}\text{C decade}^{-1}$ (Fig. 2a), with a clear warming maximum in the Eurasian sector of the Arctic Ocean, near Svalbard and Novaya Zemlya. In this region, the temperature trend over 1980-2019 exceeds $1.25^{\circ}\text{C decade}^{-1}$ (Fig. 2a). Another fast-warming region is the area north of the Bering Strait, with a warming trend of $1^{\circ}\text{C decade}^{-1}$. In contrast, large continental regions in western Siberia and North America do not manifest statistically significant trends in temperatures; however these regions are located in mid-latitudes and are only indirectly affected by AA. The spatial patterns of temperature trends are broadly consistent across the individual observational datasets (Fig. S3), with GISTEMP showing somewhat less pronounced warming maxima near Svalbard and Bering Strait (Fig. S3a) presumably due to different interpolation method than in BEST and CW.

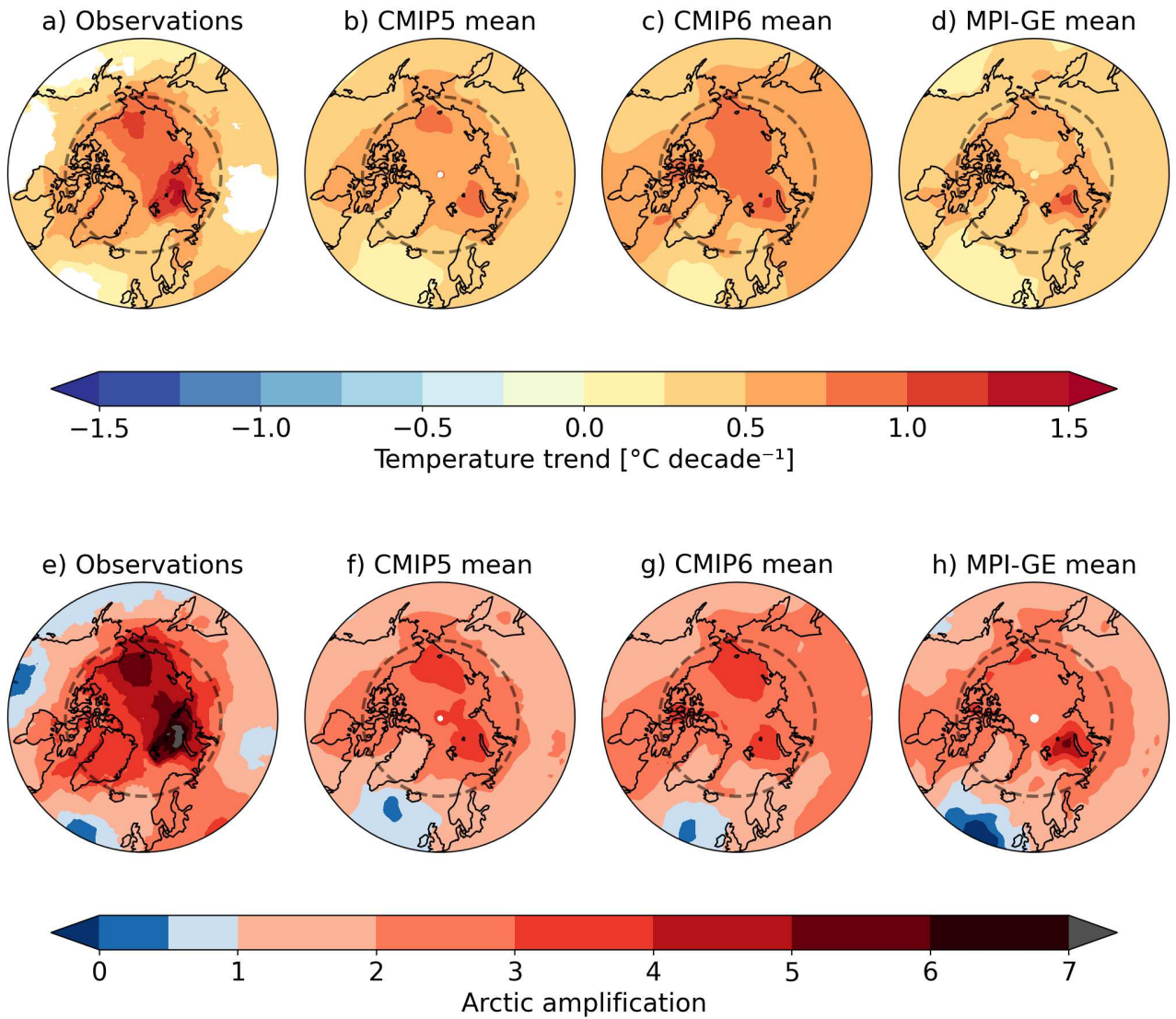


Figure 2: Annual mean temperature trends (upper row) and Arctic amplification (bottom row) for the period 1980-2019 derived from observations (a,e), CMIP5 multi-model mean (b,f), CMIP6 multi-model mean (c,g), and MPI-GE mean (d,h). Dashed line depicts the Arctic Circle (66.5°N latitude). In the upper row, areas without a statistically significant change are masked out. The modelled trends and AA values are combinations of historical simulations (1980-2005 for CMIP5 and MPI-GE, and 1980-2014 for CMIP6) and future projections forced by the RCP8.5 scenario for CMIP5 and MPI-GE, and SSP2-4.5 for CMIP6.

Regarding the simulated temperature trends, CMIP5 models (Fig. 2b) indicate weaker

warming over the Arctic Ocean compared to observations (Fig. 2a). For example, the CMIP5-simulated warming rate near the Svalbard region is less than $1^{\circ}\text{C decade}^{-1}$ while the observations show more than 1.25°C warming per decade.

In the multi-model mean of CMIP6 (Fig. 2c), the magnitude of the warming in the Arctic Ocean is slightly higher than in the CMIP5 models and thus closer to the observations, albeit the localized warming maxima near Svalbard and Bering Strait are certainly underestimated in both model generations. In contrast, the warming outside of the Arctic has in reality been slower than what the CMIP5 and CMIP6 models imply, in particular in western Siberia and the North American continent. MPI-GE (Fig. 2d) indicates slower warming especially in the central Arctic ocean compared to observations (Fig. 2a). In the other parts of the Arctic as well, the warming in MPI-GE mean is clearly underestimated.

When the temperature trends shown in Figs. 2a-d are divided by the average global mean temperature trend of the dataset at each grid-point, we get the spatial maps of 40-year Arctic amplification (AA_{40} ; Figs. 2e-h). Values higher than one indicate that those regions are warming faster than the global average, while values below one indicate a slower warming than the global average. The AA_{40} maps for individual observational datasets are provided in the supplementary material (Fig. S4).

During 1980-2019, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 2e). The most extreme AA values occur in the sea areas near Svalbard, which were locally warming more than seven times as fast as the global average in 1980-2019. The primary reason for such a high amplification ratio is the loss of sea ice, which has been most pronounced in the Barents Sea (Onarheim and Årthun, 2017). Furthermore, it has been found that changes in atmospheric circulation have amplified warming in this area (Wickström et al., 2020; Räisänen, 2021). In general, there are no regions within the Arctic Circle where AA_{40} is smaller than two, apart from the northern North Atlantic.

As already suggested by the temperature trends shown in Figs. 2b-d, modelled AA_{40} values are largely weaker than observed (Figs. 2e-h). In CMIP5 and CMIP6 simulations, AA_{40} reaches

three in the Svalbard and Bering Strait regions (Figs. 2f-g) while in observations these regions are warming more than five times as fast as the global average (Fig. 2e). In MPI-GE (Fig. 2h), AA_{40} reaches locally five in Barents sea, but elsewhere in the Arctic the amplification is underestimated.

We next compare area-averaged trends and AA between observations and models. The observed multi-dataset ensemble-mean temperature trend in the Arctic is $0.73^{\circ}\text{C decade}^{-1}$ and for the globe as a whole $0.19^{\circ}\text{C decade}^{-1}$, with small variations between the individual datasets (Fig. 3a). Using Eq. (1) and the multi-dataset ensemble-mean values for the Arctic and global mean warming trends, we arrive at AA_{40} of 3.9 for the period of 1980-2019. The individual AA_{40} values range from 3.8 in GISTEMP and ERA5 to 4.1 in BEST (Fig. 3b). Looking at monthly values, AA_{40} is strongest in November, reaching a value of 5.4 during 1980-2019 (Fig. S8).

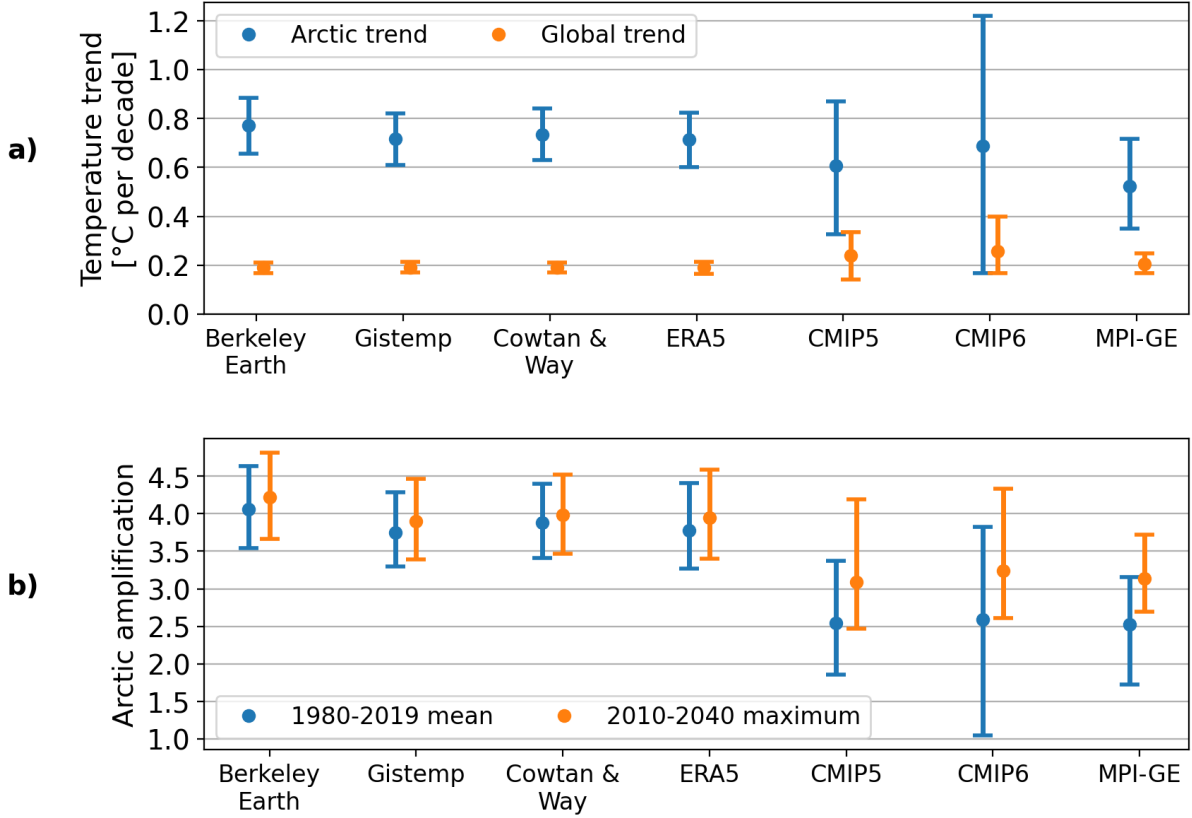


Figure 3: a) Observed and modelled annual temperature trends in the 1980-2019 period in the Arctic (blue) and globally (orange). b) Observed and modelled 40-year Arctic amplification (AA₄₀) ratio calculated for the 1980-2019 period (blue bars), and the maximum AA₄₀ ratio for 40-year periods ending in any year during 2010-2040 (orange bars). For observational datasets, the maximum AA₄₀ ratio (orange bars) is calculated for 40-year periods ending in any year during 2010-2019. The dots represent the central estimate (mean) of the trend (a) or AA₄₀ (b), and the errorbars show the 90 % confidence intervals. See Methods for more explanation for the calculation of the uncertainty estimates.

The CMIP5 multi-model mean warming trend for 1980-2019 is 0.61 K decade⁻¹ for the Arctic and 0.24 K decade⁻¹ for the entire globe (Fig. 3a). The CMIP5 multi-model mean AA₄₀ is 2.5 (Fig. 3b). Thus, while CMIP5 models have underestimated the warming in the Arctic, they have overestimated the global warming rate, resulting in a 36 % underestimation of the ongoing Arctic amplification.

CMIP6 models have simulated the temperature change in the Arctic somewhat more realistically than their predecessors. The multi-model mean warming rate in the Arctic is $0.68 \text{ K decade}^{-1}$ (Fig. 3a), but compared to CMIP5 models, the CMIP6 models exhibit much higher inter-model spread in the trends (Fig. 3a). In line with the higher warming rate in the Arctic, the global mean warming rate in CMIP6 models is slightly higher than in CMIP5 models as well, being $0.25 \text{ K decade}^{-1}$. Due to higher temperature trends both in the Arctic and globally, the mean AA_{40} of 2.6 in the CMIP6 models does not differ much from the CMIP5 ensemble and still underestimates the observed Arctic amplification by 33 % (Fig. 3b). However, due to the considerably larger spread in the warming rates in the Arctic (Fig. 3a), the AA_{40} values in the CMIP6 models feature wider 90 % confidence spread ranging from 1.0 to 3.8.

How large portion of this spread is due to internal variability and what is the role of model uncertainty? To assess the role of internal variability in the AA uncertainty, we use the 100-member MPI-GE, which is the largest available single-model ensemble known to realistically represent the observed variability (Maher et al., 2019). Individual members of MPI-GE historical simulations are initialized from different years of the long preindustrial control run; thus the spread in this ensemble is solely due to internal variability. Compared to the CMIP5 and CMIP6 multi-model means, MPI-GE simulations show lower warming trend in the Arctic, with the central estimate being $0.52 \text{ K decade}^{-1}$ for the 1980-2019 period (Fig. 3a). Consistently with the lower warming rate in the Arctic, the global warming rate in MPI-GE is likewise weaker and thus closer to observations, being $0.21 \text{ K decade}^{-1}$. As a result, the ensemble mean AA_{40} in MPI-GE for 1980-2019 is 2.5, close to both CMIP5 and CMIP6 ensemble means (Fig. 3b). Looking at MPI-GE spread, we find that it explains majority of the total CMIP5 spread, suggesting that the model uncertainty plays a relatively small role in CMIP5 spread during this period. However, model diversity is much larger in CMIP6, with MPI-GE explaining only half of the CMIP6 spread. In particular, a few CMIP6 models simulate AA_{40} values close to those observed, suggesting that these models might be able to capture feedbacks associated with AA well. We analyze the apparently realistic AA values in these models in more detail in the next

section.

Figure 3b clearly illustrates that, in 1980-2019, both CMIP5 and CMIP6 ensembles fail to reproduce the observed AA values, as the multi-dataset ensemble-mean of the observational AA_{40} ratio falls outside of the 90 % uncertainty range of all climate model simulations studied here. However, as we only considered one 40-year time period (1980-2019), a natural follow-up question arising is whether some climate models simulate higher AA at slightly different climate forcing. To investigate this question, we explore the maximum AA_{40} ratio for each climate model simultaneously considering all 40-year periods ending in 2010-2040. This time window was chosen to avoid the nearly ice-free climate conditions later in the 21st century, the comparison of which with the currently-observed values would be meaningless. In this exercise, SSP2.4-5 scenario was used as a continuation for the historical simulations in CMIP6 models, and RCP8.5 scenario in CMIP5 and MPI-GE models, but the selection of the scenario is not expected to affect the results since the role of scenario uncertainty is negligible in the first half of the 21st century (Hawkins and Sutton, 2009; Lehner et al., 2020).

Figure 3b shows that the central estimate of the maximum AA_{40} in the observations ranges from 3.9 in GISTEMP to 4.2 in BEST, with the average maximum being 4.0. In all observational datasets this maximum has occurred during the 1979-2018 period, one year earlier than our baseline period. The central estimate of maximum AA_{40} in CMIP6 models is 3.2, with 90 % inter-model spread ranging from 2.6 to 4.3, thus overlapping with the observed amplification. This result indicates that some model runs are capable of simulating large AA_{40} values comparable to the observed values under slightly different climate forcing, assuming that the climate forcing is a function of time and is similar across models for the same moment in time. However, the model capability to simulate a large AA is partly due to the extension of the period until 2040, when there is less sea ice. Nevertheless, in most cases models cannot simulate high AA_{40} even if we allow for a time gap, and therefore we do have evidence that the model runs generally underestimate the recent Arctic amplification.

Furthermore, Fig. S5 demonstrates that CMIP6 models tend to underestimate AA under

a wide range of different Arctic definitions and time windows. The underestimation is the strongest in the high Arctic ($> 70^\circ\text{N}$, Fig. S5b) and over the ocean (Fig. S7b).

4 The role of Arctic sea ice loss and the hiatus phase in global warming in the modelled Arctic amplification

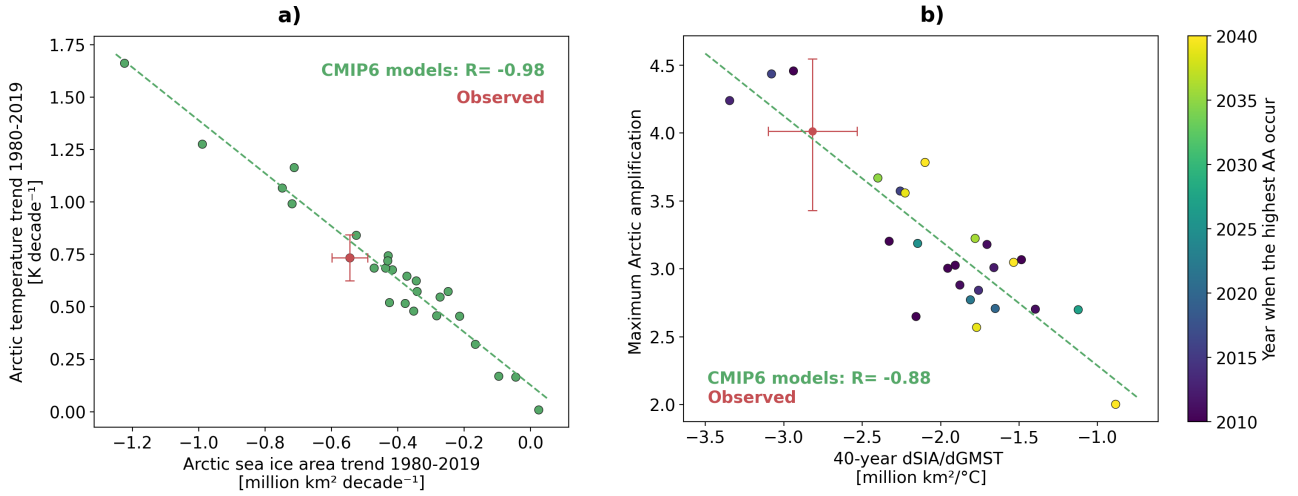


Figure 4: The annual mean temperature trend in the Arctic as a function of Arctic sea ice area trend in CMIP6 models and observations in 1980-2019 (a), the sensitivity of annual mean sea-ice area trend to global annual mean surface temperature (GMST) scattered against the maximum Arctic amplification ratio during 2010-2040 (b). The color of the dots in (b) shows the ending year of the maximum 40-year AA ratio. The errorbars in (a) and (b) show the 90 % confidence intervals.

As evidenced previously, the observed Arctic amplification lies outside the uncertainty range of CMIP5, CMIP6 and MPI-GE ensembles, with most models not capturing the presently observed AA value even when a period gap is allowed (Fig. 3b). We next address the question of what are the potential factors behind underestimated AA in climate models. We focus on CMIP6 models since they show much larger spread than that in CMIP5.

In the CMIP6 models, the absolute warming rate in the Arctic is strongly coupled with the SIA trend (Fig. 4a, green dots), with stronger sea ice loss promoting faster warming and vice versa. Most of the models simulate somewhat weaker sea ice loss than what is observed (red dot in Fig. 4a) but, consistently with Notz and Community (2020), the observed SIA trend is not outside of the CMIP6 model spread.

When looking at the sea ice loss during periods of maximum AA normalized by the corresponding global warming trend in the models and plotted against maximum AA values, the picture becomes different (Fig. 4b). Almost all models simulate too weak sea ice loss relative to their global warming rate, and thus their maximum Arctic amplification ratio in 2010-2040 remains smaller than what is observed (Fig. 4b). However, because SIA loss is not the only factor causing AA, the causal relationship can be also other way around: too weak Arctic amplification in the models can lead to smaller SIA loss for a given amount of global warming. The issue is further complicated by potential model biases in oceanic forcing on sea ice. The oceanic heat flux affects SIA but does not have a direct effect on air temperatures over ice-covered parts of the Arctic Ocean (Koenigk et al., 2020). Only in three models (EC-Earth3, MRI-ESM2-0 and NESM3), the sensitivity of SIA trend to their global warming rate is at same level as in observations, and these model also produce the high AA ratios.

Another potential factor inducing differences between the modelled and observational AA ratios is the hiatus phase in global warming that occurred between about 1998 and 2012 (Medhaug et al., 2017), although in statistical terms, the existence of the hiatus is questionable (Mudelsee, 2019). Nevertheless, in these years global mean temperature nearly ceased to increase, which acts to reduce the denominator of Eq. (1) for the entire period 1980–2019. According to Stolpe et al. (2021), an important contributing factor to the hiatus was the low sea surface temperature in equatorial Pacific Ocean. Nevertheless, the impact of tropical Pacific temperature anomalies did not extend to high northern latitudes where warming continued unabatedly (Fig. 1), keeping the numerator of Eq. (1) large.

According to Box TS.3, Fig. 1a of IPCC AR5 report (Stocker et al., 2013), in the CMIP5

model simulations a hiatus is quite a possible albeit infrequent phenomenon. If the hiatus indeed proves to be an important source for the difference of AA between the model simulations and observations, one can expect that the observed AA will be reduced in the long term, along with the reduction of the ratio of forced to unforced climate change. Indeed, AA calculated using the last 10-15 years is clearly smaller than using longer time windows (Fig. S5).

5 Discussion & conclusions

We present evidence that during the last 40 years the Arctic has been warming nearly 4 times as fast as the entire globe and caution that referring to Arctic warming as to being twice or even three times faster than the global warming is a clear underestimation of the situation during 1980-2019. Our results likewise demonstrate that climate models on average underestimate the Arctic amplification by 33-36 % (Fig. 3b). This is also true for the latest CMIP6 models despite the fact that some of these models better reproduce the absolute warming rate in the Arctic. However, those models which show plausible Arctic warming trend simultaneously have too much global warming. In contrast, those models which simulate reasonable global warming, generally have too weak Arctic warming. Thus, our results show that most climate models are unable to simulate a fast-warming Arctic simultaneously with weaker global warming similar to the observed "global warming hiatus" (e.g. Medhaug et al., 2017).

The reasons for the underestimation of AA in the climate models are not clear. It is likely that internal climate variability, e.g. the early 21st century hiatus in global warming contributes to the observed large AA; however, we show evidence of underestimated AA by models also when we compare observations with a large ensemble that faithfully accounts for the internal variability. Our analysis suggest that one potential cause of the underestimated AA is too weak feedback mechanisms between sea ice melt and atmospheric warming in climate models, which is reflected in their inability to reproduce the vertical structure of observed Arctic warming (Cohen et al., 2020). However, it remains unknown which mechanisms are underestimated in

models. Model uncertainties and deficiencies as well as contrasting results between models have been reported related to numerous subgrid-scale processes acting in the Arctic (Vihma et al., 2014) and in large-scale transports affecting AA (Burgard and Notz, 2017).

Further, we suggest that the inability of climate models to simulate realistic AA may have implications for future climate projections. Specifically, the tug of war between AA and tropical warming over the future changes in storm tracks (Shaw et al., 2016; Peings et al., 2019) projected by climate models may be biased towards the forcing by tropical warming, implicating that both projected storm track changes and associated regional climate changes may be biased. Our results call for more detailed investigation of mechanisms behind AA and their representation in climate models.

6 Methods

6.1 Observational data

For the near-surface temperature, we used the following datasets: NASA’s Goddard Institute for Space Studies Surface Temperature version 4 (GISTEMP; Lenssen et al., 2019), Berkeley Earth temperature dataset (BEST; Rohde and Hausfather, 2020), and Cowtan & Way temperature dataset version 2.0 (CW; Cowtan and Way, 2014). In these datasets, near-surface temperature is based on a combination of 2-m temperature observations over land and sea surface temperature (SST) observations over the ocean.

GISTEMP, BEST and CW were chosen for this study because they interpolate the temperatures into data-sparse regions, which are especially abundant in the Arctic. GISTEMP spatially extrapolates temperatures into unmeasured regions using a 1200-km radius of influence for the stations, while BEST and CW employ kriging-based spatial interpolation. In all these datasets, areas of sea ice are treated as if they were land, and SST observations are used only in the grid points which are ice free all year. Thus, temperatures in both terrestrial and marine Arctic are mostly based on terrestrial station observations.

In addition to the three observational datasets, we used ERA5 reanalysis (Hersbach et al., 2020), which has been produced by the European Centre for Medium-Range Weather Forecasts. We used monthly mean 2-m temperature fields in the native, 0.25° (31 km) horizontal resolution. The first release of ERA5 covers the years from 1979 to present, but a preliminary extension for 1950-1978 was recently released. We used the whole time series, from 1950 to 2019. All the observational temperature datasets used are listed in Table S1.

For Arctic sea ice area (SIA), we used the University of Hamburg Sea Ice Area product (Doerr et al., 2021), which contains time series of the monthly SIA in the Northern Hemisphere by several producers. To get a robust observational estimate, we used the average of the following five products: OSI SAF (Lavergne et al., 2019), NASA-Team (Cavalieri et al., 1997), Comiso-Bootstrap (Comiso et al., 1997), HadISST2 (Titchner and Rayner, 2014) and Walsh dataset version 2 (Walsh et al., 2017).

6.2 Climate model data

We compared the observed temperatures to three different climate model ensembles, which are listed in Table S2. These ensembles are 35 CMIP5 models (Taylor et al., 2012), 32 CMIP6 models (Eyring et al., 2016) and the 100-member Max-Planck Institute Grand Ensemble (MPI-GE) (Maher et al., 2019). All three climate model datasets contained historical simulations (1850-2005 for CMIP5 and MPI-GE, and 1850-2014 for CMIP6) and future projections forced by the RCP8.5 scenario for CMIP5 and MPI-GE, and SSP2-4.5 and SSP5-8.5 scenarios for CMIP6 (Table S2). For CMIP6, the monthly averaged data for 2-meter temperature and sea ice concentration were used; for CMIP5 and MPI-GE, only 2-meter temperatures were considered. Sea ice concentration data were only available from 25 CMIP6 models. Also, there is no data from SSP2-4.5 scenario data for CMIP6 TaiESM1 model. The list of all the used CMIP5 and CMIP6 models can be found from the supplement tables S3 and S4.

6.3 Defining the Arctic amplification

We follow the recommendation of Smith et al. (2019), and define Arctic amplification (AA) as the ratio of Arctic warming to global-mean warming:

$$AA = \frac{dT/dt_A}{dT/dt_G} \quad (1)$$

where dT/dt_A and dT/dt_G are the slopes of linear trends of near-surface temperature, calculated using a least-squares fitting for the annual mean values for the Arctic and global domain. The trends were calculated for different time periods (see Fig. S5a), but the last 40 years (1980-2019, hereafter referred to AA_{40}) was chosen as the primary period of interest, because (i) it captures most of the recent warming period (Fig. 1), and (ii) the reanalysis products, such as ERA5, are known to be more reliable during this period because satellite remote sensing data on atmospheric variables and sea ice concentration have become largely available since 1979 (e.g. Fujiwara et al., 2017).

While different areal definitions for the Arctic exist, we use the area encircled by the Arctic Circle (66.5°-90°N) as the primary definition of the Arctic. We argue that this is the area that most scientists consider as the Arctic (NSIDC, 2020), and it is one of the definitions used by AMAP (AMAP, 2009). The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) defined the Arctic as the region poleward from 65.0°N (Trenberth et al., 2007), and AR5 used 67.5°N (Collins et al., 2013). For a sensitivity assessment, dT/dt_A was also calculated using different definitions for the southern boundary of the Arctic, ranging from 55°N to 80°N (Fig. S5).

6.4 Statistical analysis

For observations, we give the uncertainty ranges in dT/dt_A and dT/dt_G as the 90 % statistical uncertainty range. For CMIP5 and CMIP6 simulations, the uncertainty ranges reflect the 90 % confidence interval (5th-95th percentile range) derived from multi-model ensemble. For MPI-

GE simulations, we use the 90 % confidence interval (5th-95th percentile range) derived from the ensemble members. The statistical significance of the observed trends was estimated at 95 % level ($P < 0.05$) using nonparametric Mann-Kendall test (Kendall, 1948; Mann, 1945) with pyMannKendall python package (Hussain and Mahmud, 2019).

The uncertainty range in observed AA_{40} ratios reflects 90 % confidence intervals which were estimated using the bootstrap method (Efron, 1992). For CMIP5 and CMIP6 simulations, the corresponding uncertainty range is the 90 % confidence interval derived from the multi-model ensemble, and for MPI-GE, derived from the ensemble members. The AA_{40} ratios in climate models were first calculated separately for each model/member and then averaged across them (i.e. as mean ratios, not a ratio of means), thus following the recommendation by Smith et al. (2019).

The uncertainty range in observed SIA trend correspond to the 90 % statistical uncertainty range derived from the regression coefficients of the trends.

7 Data availability

Gistemp data are available from <https://data.giss.nasa.gov/gistemp/>, Berkeley Earth data from <http://berkeleyearth.org/data/>, Cowtan & Way data from <https://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html>, and ERA5 data from <https://cds.climate.copernicus.eu>. CMIP5 and CMIP6 data are available from Earth System Grid Federation (ESGF) archive at <https://esgf-node.llnl.gov/projects/cmip5/> and <https://esgf-data.dkrz.de/search/cmip6-dkrz/>, respectively. MPI-GE data is available under licence from <https://mpimet.mpg.de/en/grand-ensemble/>.

8 Code availability

Python- and R-language scripts used for this analysis are available from Github:

<https://github.com/mikarant/arctic-amplification>

9 Acknowledgements

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10 Author contributions

The study was initialized together by ALi, ALa, MR, and KN. MR prepared the initial draft of the manuscript with the help of AK. MR conducted most of the data analysis and created part of the figures. AK produced the MPI-GE results and contributed to the initial preparation of the manuscript with MR. ALi created half of the figures. KN and KR contributed to the downloading of CMIP model data, and OH calculated the uncertainty estimates of the results. TV and ALa contributed to the commenting of the results and revising of the manuscript. All authors commented the manuscript and discussed the results at all stages.

References

- AMAP (2009). AMAP Assessment 2009: Human Health in the Arctic. *Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway*.
- AMAP (2021). Arctic climate change update 2021: key trends and impacts. Summary for policy-makers. *Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway*.
- Beer, E., Eisenman, I., and Wagner, T. J. (2020). Polar amplification due to enhanced heat flux across the halocline. *Geophysical Research Letters*, 47(4):e2019GL086706.
- Bintanja, R., Graverson, R., and Hazeleger, W. (2011). Arctic winter warming amplified by the thermal inversion and consequent low infrared cooling to space. *Nature Geoscience*, 4(11):758–761.
- Blackport, R. and Screen, J. A. (2020). Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves. *Science Advances*, 6(8):eaay2880.
- Blackport, R. and Screen, J. A. (2021). Observed statistical connections overestimate the causal effects of Arctic sea ice changes on midlatitude winter climate. *Journal of Climate*, 34(8):3021–3038.
- Burgard, C. and Notz, D. (2017). Drivers of Arctic Ocean warming in CMIP5 models. *Geophysical Research Letters*, 44(9):4263–4271.
- Cavalieri, D. J., Parkinson, C. L., Gloersen, P., and Zwally, H. J. (1997). Arctic and antarctic sea ice concentrations from multichannel passive-microwave satellite data sets: October 1978-september 1995 user’s guide.
- Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, 7(9):627–637.

- Cohen, J., Zhang, X., Francis, J., Jung, T., Kwok, R., Overland, J., Ballinger, T., Bhatt, U., Chen, H., Coumou, D., et al. (2020). Divergent consensus on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, 10:20–29.
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., et al. (2013). Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013 - The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 1029–1136. Cambridge University Press.
- Comiso, J. C., Cavalieri, D. J., Parkinson, C. L., and Gloersen, P. (1997). Passive microwave algorithms for sea ice concentration: A comparison of two techniques. *Remote sensing of Environment*, 60(3):357–384.
- Cowtan, K. and Way, R. G. (2014). Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, 140(683):1935–1944.
- Dai, A., Luo, D., Song, M., and Liu, J. (2019). Arctic amplification is caused by sea-ice loss under increasing CO₂. *Nature Communications*, 10(1):1–13.
- Dai, A. and Song, M. (2020). Little influence of Arctic amplification on mid-latitude climate. *Nature Climate Change*, 10(3):231–237.
- Davy, R., Chen, L., and Hanna, E. (2018). Arctic amplification metrics. *International Journal of Climatology*, 38(12):4384–4394.
- Davy, R. and Outten, S. (2020). The Arctic surface climate in CMIP6: status and developments since CMIP5. *Journal of Climate*, 33(18):8047–8068.
- Doerr, J., Notz, D., and Kern, S. (2021). UHH Sea Ice Area Product. <https://doi.org/10.25592/uhhfdm.8559>. Accessed: 2021-06-17.

- Efron, B. (1992). Bootstrap methods: another look at the jackknife. In *Breakthroughs in statistics*, pages 569–593. Springer.
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5):1937–1958.
- Francis, J. A. (2017). Why are Arctic linkages to extreme weather still up in the air? *Bulletin of the American Meteorological Society*, 98(12):2551–2557.
- Francis, J. A. and Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, 39(6).
- Francis, J. A. and Vavrus, S. J. (2015). Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, 10(1):014005.
- Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., Harvey, V. L., Hegglin, M. I., et al. (2017). Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems. *Atmospheric Chemistry and Physics*, 17(2):1417–1452.
- Graversen, R. G. and Burtu, M. (2016). Arctic amplification enhanced by latent energy transport of atmospheric planetary waves. *Quarterly Journal of the Royal Meteorological Society*, 142(698):2046–2054.
- Haustein, K., Otto, F. E., Venema, V., Jacobs, P., Cowtan, K., Hausfather, Z., Way, R. G., White, B., Subramanian, A., and Schurer, A. P. (2019). A limited role for unforced internal variability in twentieth-century warming. *Journal of Climate*, 32(16):4893–4917.
- Hawkins, E. and Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, 90(8):1095–1108.

- Hegerl, G. C., Brönnimann, S., Schurer, A., and Cowan, T. (2018). The early 20th century warming: anomalies, causes, and consequences. *Wiley Interdisciplinary Reviews: Climate Change*, 9(4):e522.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*.
- Hind, A., Zhang, Q., and Brattström, G. (2016). Problems encountered when defining Arctic amplification as a ratio. *Scientific reports*, 6:30469.
- Holland, M. M. and Bitz, C. M. (2003). Polar amplification of climate change in coupled models. *Climate Dynamics*, 21(3-4):221–232.
- Huang, J., Zhang, X., Zhang, Q., Lin, Y., Hao, M., Luo, Y., Zhao, Z., Yao, Y., Chen, X., Wang, L., et al. (2017). Recently amplified arctic warming has contributed to a continual global warming trend. *Nature Climate Change*, 7(12):875–879.
- Hussain, M. and Mahmud, I. (2019). pymannkendall: a python package for non parametric Mann Kendall family of trend tests. *Journal of Open Source Software*, 4(39):1556.
- Jansen, E., Christensen, J. H., Dokken, T., Nisancioglu, K. H., Vinther, B. M., Capron, E., Guo, C., Jensen, M. F., Langen, P. L., Pedersen, R. A., et al. (2020). Past perspectives on the present era of abrupt Arctic climate change. *Nature Climate Change*, 10(8):714–721.
- Kendall, M. G. (1948). Rank correlation methods.
- Kim, B.-M., Hong, J.-Y., Jun, S.-Y., Zhang, X., Kwon, H., Kim, S.-J., Kim, J.-H., Kim, S.-W., and Kim, H.-K. (2017). Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. *Scientific Reports*, 7(1):1–9.
- Koenigk, T., Key, J., and Vihma, T. (2020). Climate Change in the Arctic. In *Physics and Chemistry of the Arctic Atmosphere*, pages 673–705. Springer.

- Krishnan, S., Ekman, A. M., Hansson, H.-C., Riipinen, I., Lewinschal, A., Wilcox, L. J., and Dallafior, T. (2020). The roles of the atmosphere and ocean in driving Arctic warming due to European aerosol reductions. *Geophysical Research Letters*, 47(7):e2019GL086681.
- Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., et al. (2019). Version 2 of the eumetsat osi saf and esa cci sea-ice concentration climate data records. *The Cryosphere*, 13(1):49–78.
- Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E. M., Brunner, L., Knutti, R., and Hawkins, E. (2020). Partitioning climate projection uncertainty with multiple large ensembles and cmip5/6. *Earth System Dynamics*, 11(2):491–508.
- Lenssen, N. J., Schmidt, G. A., Hansen, J. E., Menne, M. J., Persin, A., Ruedy, R., and Zyss, D. (2019). Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres*, 124(12):6307–6326.
- Luo, D., Chen, X., Dai, A., and Simmonds, I. (2018). Changes in atmospheric blocking circulations linked with winter Arctic warming: A new perspective. *Journal of Climate*, 31(18):7661–7678.
- Maher, N., Milinski, S., Suarez-Gutierrez, L., Botzet, M., Dobrynin, M., Kornblueh, L., Kröger, J., Takano, Y., Ghosh, R., Hedemann, C., et al. (2019). The Max Planck Institute Grand Ensemble: enabling the exploration of climate system variability. *Journal of Advances in Modeling Earth Systems*, 11(7):2050–2069.
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica: Journal of the econometric society*, pages 245–259.
- Medhaug, I., Stolpe, M. B., Fischer, E. M., and Knutti, R. (2017). Reconciling controversies about the global warming hiatus. *Nature*, 545(7652):41–47.

- Merikanto, J., Nordling, K., Räisänen, P., Räisänen, J., O'Donnell, D., Partanen, A.-I., and Korhonen, H. (2021). How asian aerosols impact regional surface temperatures across the globe. *Atmospheric Chemistry and Physics*, 21(8):5865–5881.
- Mudelsee, M. (2019). Trend analysis of climate time series: A review of methods. *Earth-science reviews*, 190:310–322.
- Navarro, J. A., Varma, V., Riipinen, I., Seland, Ø., Kirkevåg, A., Struthers, H., Iversen, T., Hansson, H.-C., and Ekman, A. M. (2016). Amplification of Arctic warming by past air pollution reductions in Europe. *Nature Geoscience*, 9(4):277–281.
- Notz, D. and Community, S. (2020). Arctic sea ice in CMIP6. *Geophysical Research Letters*, 47(10):e2019GL086749.
- NSIDC (2020). What is the Arctic? <https://nsidc.org/cryosphere/arctic-meteorology/arctic.html>. Accessed: 2021-02-04.
- Onarheim, I. H. and Årthun, M. (2017). Toward an ice-free Barents sea. *Geophysical Research Letters*, 44(16):8387–8395.
- Peings, Y., Cattiaux, J., and Magnusdottir, G. (2019). The polar stratosphere as an arbiter of the projected tropical versus polar tug of war. *Geophysical Research Letters*, 46(15):9261–9270.
- Pithan, F. and Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, 7(3):181–184.
- Räisänen, J. (2021). Effect of atmospheric circulation on surface air temperature trends in years 1979–2018. *Climate Dynamics*, 56(7):2303–2320.
- Richter-Menge, J. and Druckenmiller, M. L. (2020). The Arctic [in "State of the Climate in 2019"]. *Bulletin of the American Meteorological Society*, 101(8).

- Rohde, R. A. and Hausfather, Z. (2020). The Berkeley Earth land/ocean temperature record. *Earth System Science Data*, 12(4):3469–3479.
- Screen, J. A. and Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, 464(7293):1334–1337.
- Serreze, M., Barrett, A., Stroeve, J., Kindig, D., and Holland, M. (2009). The emergence of surface-based Arctic amplification. *The Cryosphere*, 3(1):11.
- Serreze, M. C. and Francis, J. A. (2006). The Arctic amplification debate. *Climatic change*, 76(3-4):241–264.
- Shaw, T., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C., Hwang, Y.-T., Li, C., O’Gorman, P., Rivière, G., Simpson, I., et al. (2016). Storm track processes and the opposing influences of climate change. *Nature Geoscience*, 9(9):656–664.
- Smith, D. M., Screen, J. A., Deser, C., Cohen, J., Fyfe, J. C., García-Serrano, J., Jung, T., Kattsov, V., Matei, D., Msadek, R., et al. (2019). The Polar Amplification Model Intercomparison project (PAMIP) contribution to CMIP6: Investigating the causes and consequences of polar amplification. *Geoscientific Model Development*, 12(3):1139–1164.
- Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., Bréon, F.-M., Church, J. A., Cubasch, U., Emori, S., et al. (2013). Technical summary. In *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 33–115. Cambridge University Press.
- Stolpe, M. B., Cowtan, K., Medhaug, I., and Knutti, R. (2021). Pacific variability reconciles observed and modelled global mean temperature increase since 1950. *Climate Dynamics*, 56(1):613–634.

- Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., and Meier, W. N. (2012). Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, 39(16).
- Stuecker, M. F., Bitz, C. M., Armour, K. C., Proistosescu, C., Kang, S. M., Xie, S.-P., Kim, D., McGregor, S., Zhang, W., Zhao, S., et al. (2018). Polar amplification dominated by local forcing and feedbacks. *Nature Climate Change*, 8(12):1076–1081.
- Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4):485–498.
- Taylor, P. C., Cai, M., Hu, A., Meehl, J., Washington, W., and Zhang, G. J. (2013). A decomposition of feedback contributions to polar warming amplification. *Journal of Climate*, 26(18):7023–7043.
- Titchner, H. A. and Rayner, N. A. (2014). The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations. *Journal of Geophysical Research: Atmospheres*, 119(6):2864–2889.
- Trenberth, K., Jones, P., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J., Rusticucci, M., et al. (2007). Observations: surface and atmospheric climate change. Chapter 3. *Climate change*, pages 235–336.
- Vavrus, S. J. (2018). The influence of Arctic amplification on mid-latitude weather and climate. *Current Climate Change Reports*, 4(3):238–249.
- Vihma, T., Graverson, R., Chen, L., Handorf, D., Skific, N., Francis, J. A., Tyrrell, N., Hall, R., Hanna, E., Uotila, P., et al. (2020). Effects of the tropospheric large-scale circulation on European winter temperatures during the period of amplified Arctic warming. *International Journal of Climatology*, 40(1):509–529.

- Vihma, T., Pirazzini, R., Fer, I., Renfrew, I. A., Sedlar, J., Tjernström, M., Lüpkes, C., Nygård, T., Notz, D., Weiss, J., et al. (2014). Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: a review. *Atmospheric Chemistry and Physics*, 14(17):9403–9450.
- Walsh, J. E. (2014). Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global and Planetary Change*, 117:52–63.
- Walsh, J. E., Fetterer, F., Scott Stewart, J., and Chapman, W. L. (2017). A database for depicting Arctic sea ice variations back to 1850. *Geographical Review*, 107(1):89–107.
- Wickström, S., Jonassen, M., Vihma, T., and Uotila, P. (2020). Trends in cyclones in the high-latitude north atlantic during 1979–2016. *Quarterly Journal of the Royal Meteorological Society*, 146(727):762–779.
- Woods, C. and Caballero, R. (2016). The role of moist intrusions in winter Arctic warming and sea ice decline. *Journal of Climate*, 29(12):4473–4485.
- Yu, L., Zhong, S., Vihma, T., and Sun, B. (2021). Attribution of late summer early autumn Arctic sea ice decline in recent decades. *npj Climate and Atmospheric Science*, 4(3).

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