AGU ADVANCING EARTH AND SPACE SCIENCES

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2023JD039269

Key Points:

- The early 21st century high values of the AA are caused by a higher temperature trend over the Arctic and a lower global temperature trend
- The CMIP6 models' difficulty in reproducing the observed AA is due to the models' overestimate of the rate of mean global warming after 1990
- The future projection of the AA suggests an increasing AA for about the next decade with a slowly decreasing trend after that

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Chylek, P., Folland, C. K., Klett, J. D., Wang, M., Lesins, G., & Dubey, M. K. (2023). High values of the Arctic Amplification in the early decades of the 21st century: Causes of discrepancy by CMIP6 models between observation and simulation. *Journal of Geophysical Research: Atmospheres*, *128*, e2023JD039269. https://doi.org/10.1029/2023JD039269

Received 19 MAY 2023
Accepted 1 NOV 2023

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High Values of the Arctic Amplification in the Early Decades of the 21st Century: Causes of Discrepancy by CMIP6 Models Between Observation and Simulation

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Abstract Arctic Amplification (AA) in the first decade of the 21st century has reached values between 4 and 5, with a subsequent decrease to current values of about 3.6, while the value was from 2 to 3 during the twentieth century. The ensemble mean of the CMIP6 models has difficulty in reproducing the recently observed high values of the AA. In this report, we identify the main reason for this difficulty to be the CMIP6 models overestimate of the mean global temperature trend since about 1990. The largest values of the AA are observed in winter and spring. A sharp AA peak in 1987 spring was caused by a peak in the Arctic temperature trend occurring at the same time as a dip in the trend of mean global temperature. The winter AA has increased almost monotonically since 1990. Dividing the AA between the Arctic land and ocean areas shows that the ocean area makes a larger contribution to the AA. Our future projection of the AA suggests an increasing AA for about the next decade, followed by a slow decrease to about 3.5 in the 2050s.

Plain Language Summary The Arctic is warming faster than the average warming of the whole earth. The Arctic Amplification (AA) is defined as the ratio of the Arctic to global mean warming rates. Thus, the AA increases when the rate of Arctic warming increases, when the rate of global warming decreases, or when both happen at the same time. For most of the twentieth century, the AA was between 2 and 3. However, during the first few years of the 21st century, the AA has reached over four. The current climate models are not able to reproduce the observed early 21st-century high values of AA. We find that the main reason for this difficulty is the models' overestimate of the global warming rates after 1990.

1. Introduction

The Arctic temperature is increasing faster than the global mean temperature (AMAP, 2021; Bengtsson et al., 2004). Climate models have been used to understand the changing climate in the Arctic region (e.g., Graversen & Wang, 2009; Hahn et al., 2021; Holland & Bitz, 2003). The Arctic Amplification (AA) is usually defined as the ratio of the Arctic temperature trend to the mean global temperature trend (Chylek et al., 2009, 2014; Masson-Delmotte et al., 2006; Pithan & Mauritsen, 2014; Previdi et al., 2021; Serreze & Barry, 2011; Stuecker et al., 2018).

Although the AA has been a topic of considerable research effort, an unambiguous definition of the AA has been lacking. The area of the Arctic has not been agreed upon, and a time span over which the trends are taken has not been defined. The Arctic area over which the averages are calculated varies usually between 60°N and 70°N, with some researchers choosing the Arctic Circle (66.5°N) as a boundary of the Arctic. As a compromise and in agreement with our earlier publications we chose for this report the region between 65°N and 90°N as the Arctic area.

In Chylek et al. (2022), it has been shown that if the time span for which the trends are calculated is larger than 36 years, the steps in AA are averaged out, while for time spans shorter than 17 years, the AA becomes unstable due to the trend of the mean global temperature crossing a zero point. Thus, as in our earlier publication, we use 21-year running temperature trends in this report.

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Writing – review & editing: James D. Klett, Muyin Wang, Glen Lesins, Manvendra K. Dubey

As discussed earlier, climate models have played a major role in the study of the AA (Cai et al., 2021; Graversen & Wang, 2009; Hahn et al., 2021; Holland & Bitz, 2003; Ye & Messori, 2021). A decreasing Arctic sea-ice and ice albedo feedback (Dai et al., 2019; Ding et al., 2019; Johannessen et al., 2016; Kumar et al., 2010; Perovich et al., 2007; Vihma, 2014), and heat transport to the Arctic (Mewes et al., 2019; Piston et al., 2019; Polyakov et al., 2017; Tsubouchi et al., 2020) have been suggested as causes of changing AA.

Although the AA has been considered to vary between about 2 and 3, a few recent papers have brought to light recent greater values of AA of around 4 (Chylek et al., 2022, 2023; Isaksen et al., 2022; Rantanen et al., 2022). Many causes have been suggested to explain the variability of the AA. Nevertheless, its origin and variability are at this point quite uncertain.

In our recent paper (Chylek et al., 2022), we have reported that (a) the AA has increased in two jumps since 1970, (b) the AA reached high values during the early years of the 21st century, and (c) the ensemble-mean of the CMIP6 (Coupled Models Inter-comparison Project Phase 6) simulations do not reproduce high values of the AA in the early 21st century. In that paper, we did show what was happening, but without questioning why.

In this communication, we suggest the reason why the climate models have difficulties in reproducing high AA values in the early years of the 21st century. The reason is that the ensemble mean of the CMIP6 models overestimates the rate of global warming since about 1990. Since the AA is defined as a ratio of the Arctic to the global temperature trend, the overestimation of the trend of global warming will cause the models' simulated AA to be underestimated. Thus, while the observed AA reaches almost 5, the CMIP6 model-simulated AA stays between 2 and 3. When the CMIP6 simulated global temperature trend is replaced by the observed trend in the expression for the AA, the AA nearly reaches the observed value (Figure 3d). We also explain the origin of the steps in AA observed and reported in Chylek et al., 2022, and we make a new projection of the AA up to 2050, which is higher than earlier projections.

2. Data and Methods

Most of the past research has considered AA as the ratio of linear trends of the Arctic and global mean temperature with a typical time scale of 30–50 years. To capture the AA changes on a bi-decadal and shorter time scale, we define the AA as the ratio of the Arctic to the global mean temperature 21-year moving trends (Chylek et al., 2022).

Thus, the AA is given by

$$AA = \mathrm{Trend(ARCT)}/\mathrm{Trend(GL)} \tag{1}$$

where Trend(ARCT) and Trend(GL) stand for the 21-year moving average Arctic and global mean temperature trend.

As described above, the calculated AA depends on the geographic extent of the Arctic. Figure 1a shows how the AA varies when the southern boundary of the Arctic is changed between 60°N and 70°N. This shows that the more the boundary is moved southward, the lower the AA will be. We consider the Arctic to be the area north of 65°N.

The AA also varies depending on which of the available temperature records is used (Figure 1b). When the AA is calculated using the HadCRUT5 (Morice et al., 2021) or the NASA GISS data (Lenssen et al., 2019) with a 1,200 km homogenization radius, the obtained AAs are close to each other. When the HadCRUT temperature data are complemented by the method suggested by Cowtan and Way (2014), the calculated AA within the last few decades is higher, reaching over five, and with the data provided by NOAA v5 the AA is lower. The average of AAs with the use of all four data sets is close to AA calculated from the HadCRUT5 and NASA GISS data (Figure 1b). In the following, we use the HadCRUT5 temperature data to derive the AA and we call it the "observed" AA.

Since the AA is defined as a ratio of two trends, it can increase if the trend of Arctic mean temperature is increasing or if the trend of the global mean temperature is decreasing. The fastest growth of the AA will occur when the Arctic warming trend increases at the same time the global warming trend decreases. Of course, the AA as a ratio of two numbers, is defined only where the denominator (the trend of global temperature) is non-zero. Thus,

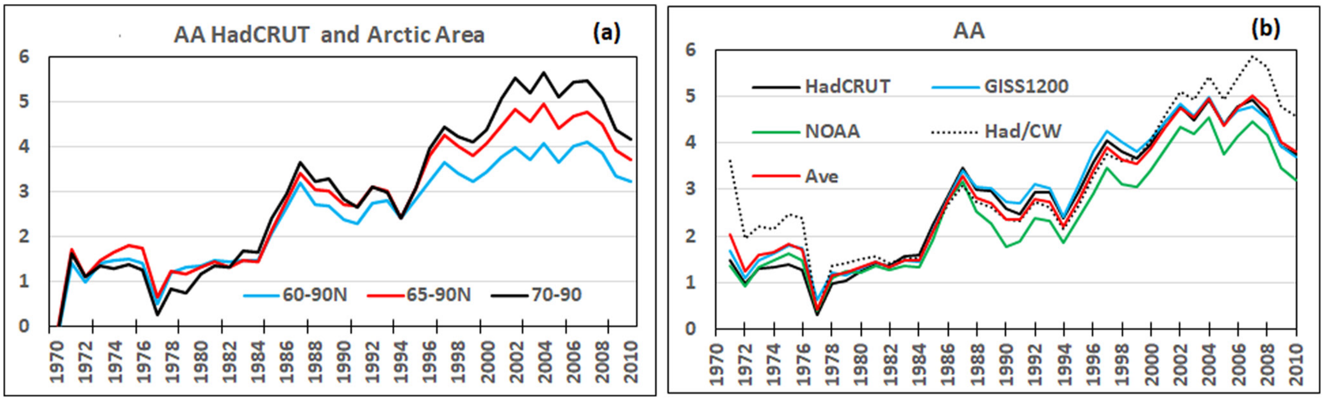

Figure 1. (a) The Arctic Amplification (AA) derived using the HadCRUT5 temperature data and different definitions of the southern boundary of the Arctic region. (b) The AA using the specified temperature data sets and the average AA (red line).

it is customary to define the AA only for the post-1970 years for which both the global and the Arctic temperature trends have been positive so that AA stays positive.

Climate models within the CMIP6 collection have different numbers of realizations for each scenario considered. The individual realizations produced by the same model vary significantly from each other. Most realizations presented in the CMIP6 collection are for the medium scenario SSP2-4.5 (Shared Socioeconomic Pathway 2-4.5), which is thought to represent the middle path between high and low emissions. In the following analysis, we use the SSP2-4.5. We calculate the CMIP6 ensemble mean, where the mean of individual model realizations is obtained first, and after that, the CMIP6 ensemble mean is calculated as a mean of individual models.

To keep the contributions of all models at about the same significance, and to eliminate at least partially the models' internal climate variability, we use all the CMIP6 models that produced at least three realizations of the SSP2-4.5 pathway. This leaves us with the 19 CMIP6 models. To demonstrate that our results are robust, independent of our selection of models, we have repeated our analysis using only the first realization of all models that have at least one SSP 245 scenario. The results are shown in Supporting Information S1.

Several recent papers (Chylek et al., 2022; Rantanen et al., 2022) highlighted the fact that the CMIP6 models have difficulty reproducing the observed early 21st-century high values of the AA. To understand the reason for this, we compare the models' simulated Arctic and global temperature and temperature trends with observations.

In the CMIP6 collection, the historic simulation ended in 2014. Starting in 2015, the CMIP6 data were patched with simulations with the above-described SSP2-4.5 scenario. We use the simulations under the above-described SSP2-4.5 scenario. Most of the CMIP6 models' runs are for this case. The CMIP6 model simulation sets were downloaded from the KNMI Climate Explorer website.

The observed Arctic surface air temperature anomaly defined in our analysis with respect to the based period of 1961–1990 (Figure 2) as well as Arctic temperature trends are reasonably well simulated by the CMIP6 ensemble mean for the SSP2-4.5 scenario, calculated as described above from the mean of individual models. This, however, may be partially an unintentional result of a tuning process rather than due to the good skill of models in replicating key physical processes. Models are generally tuned (via specification of free parameters used to parameterize complicated physical processes) so that the model's simulation of the mean global temperature anomaly and other major climate indicators agree as well as possible with their observed values (e.g., Hourdin et al., 2017). It may happen, for example, that as a result of this tuning some regional temperature anomalies as well as their trends will also be in better agreement with observation.

3. Results

3.1. The CMIP6 Ensemble Mean Simulation

The CMIP6 model simulated the Arctic temperature trend agrees well with the observed trend (Figure 3a). On the other hand, the CMIP6 simulation of the global mean temperature trend (Figure 3b) is not so successful. The

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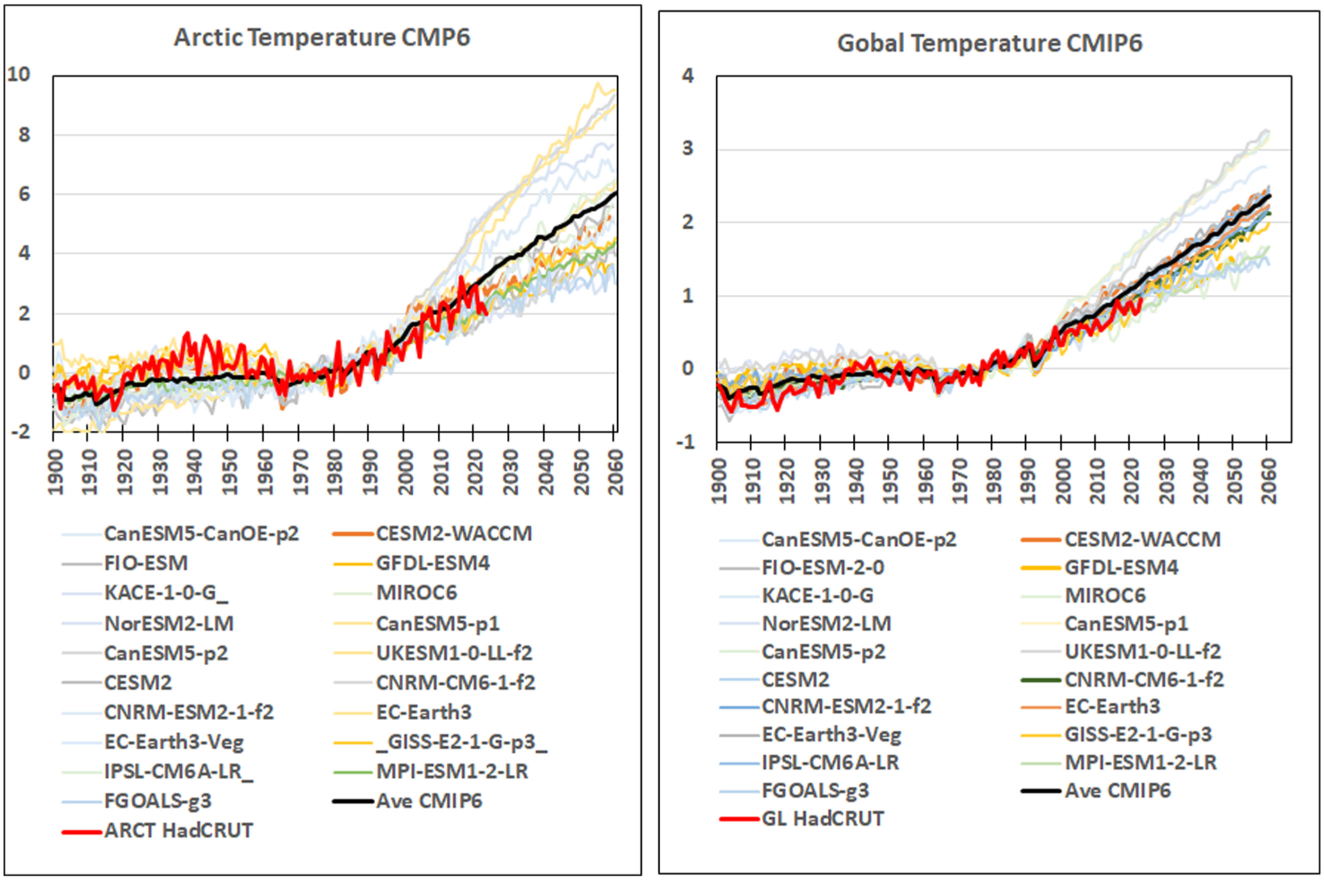

Figure 2. (a) Arctic observed temperature (thick red line), temperature simulated by individual CMIP6 models (thin colored lines), and CMIP6 models mean (thick black line). The models' simulations are extended till the year 2060. The range of models' projections of the Arctic temperature anomaly in the year 2060 is from 3°C to 9°C. (b) The observed mean global temperature (thick red line), mean of CMIP6 simulations (black thick line), and mean of individual models (thin color lines).

CMIP6 models' ensemble mean overestimates the observed mean global temperature trend after 1990. A modest mean global temperature overestimate seen in Figure 2b leads to a significant overestimate of the mean global temperature trend (Figure 3b).

Since the AA is defined as the ratio of the Arctic temperature trend to the mean global temperature trend (Equation 1), the overestimation of the mean global temperature trend after 1990 resulted in an underestimate of the AA, as is the case seen in Figure 3c.

To demonstrate that the underestimate of AA by CMIP6 models is a result of the models' overestimate of the global temperature trend, we define the modified AA where the CMIP6 models' simulated trend of global mean temperature is replaced by the observed global mean temperature trend. This modified AA (defined by Equation 2) is denoted by AA* and shown in Figure 3d.

$$AA^{*} = \text{CMIP6 Arctic Trend}/\text{Observed Global Trend} \tag{2}$$

The modified AA* is in good agreement with the observed AA. The correlation coefficient between the original CMIP6 AA and the observed AA is $r = 0.41$, while $r = 0.89$ between the observed AA and modified AA*.

To estimate the uncertainty of the CMIP6-deduced AA, the standard deviation of the CMIP6 AA (Figure 3c) is calculated from 19 AA individual CMIP6 models used in the current study.

There are five CMIP6 models that simulate considerably higher temperatures and temperature trends than the mean of all models (Figures 2 and 3). These are the three variants of CanESM5, KACE-1-0-G, and UKESM1-0-LL-f2. Since both the Arctic and the global mean temperature trends are significantly overestimated by these models, the AA defined as the ratio of trends is not exceptionally high.

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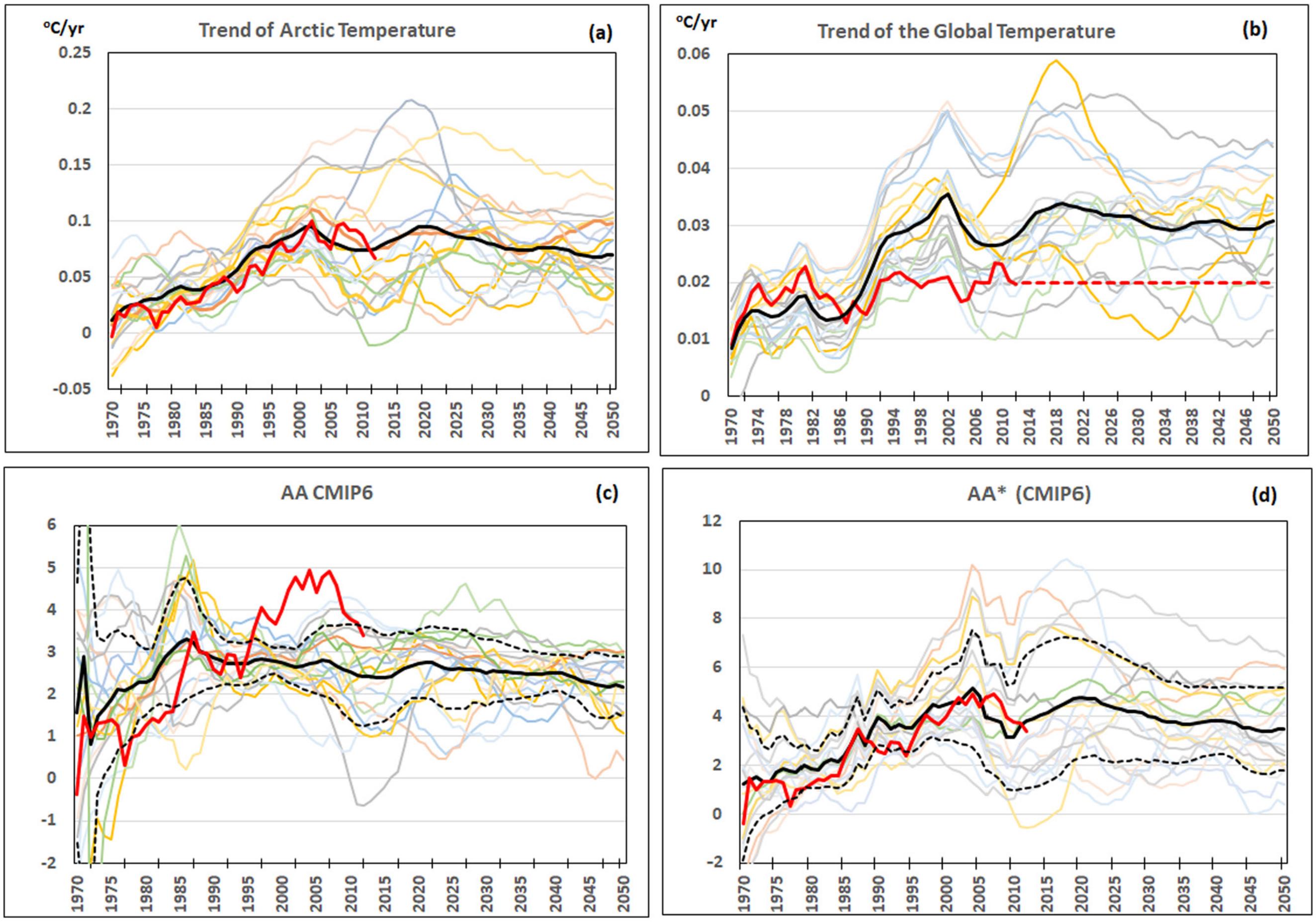

Figure 3. (a) Trends of observed Arctic temperature (thick red line), the mean of the CMIP6 trends simulations (thick black line), and individual models' trends (thin color lines). The temperature trends and Arctic Amplification (AA) in this figure are plotted at the center of the 21-year running average trend. Thus, using the temperature data from 1960 to 2060, we get the range of temperature trends from 1970 to 2050. Panel (b) same as in (a) but for the trend of mean global temperature. The dashed red line is an assumed continuation of the observed trend for the future years needed later for future AA projections. (c) The AA was calculated from the observed temperature (red line), from individual models (thin lines), and their ensemble mean (black line). The AA uncertainty is represented by one standard deviation (black dashed line) estimated from 19 individual models' AA. (d) The modified AA* (thick black line) in which the trend of the CMIP6 models' simulations of the mean global temperature was replaced by the trend of the observed mean global temperature.

In the early years (before 1990), the CMIP6 ensemble mean underestimated the global mean temperature trend, while it overestimated the Arctic mean temperature trend (Figure 3a). Consequently, in this time period, the CMIP6-simulated AA overestimates the observed AA (Figure 3c). On the other hand, the dominant feature of the post-1990 time frame is an overestimation of the global temperature trend by the CMIP6 ensemble mean. As a result, the average simulated AA within this period underestimates the observed AA (Figure 3c).

As has been noted, the main reason that the CMIP6 ensemble mean cannot reproduce the high early 21st century values of the AA is that the CMIP6 models on average overestimate the trend of recent global warming. The models' slight overestimation of the rate of Arctic warming is not sufficient to overcome their greater overestimation of the trend of the global mean temperature.

3.2. Arctic Amplification at a Seasonal Resolution

The seasonal AA provides additional insight into the steep increases of the annual AA seen in 1987 and near the year 2000. The AA at seasonal resolution reaches a maximum of over eight in winter and spring. It had a sharp peak in the spring of 1987 and a much broader peak in winter between years 2000 and 2009 (Figure 4a). The fall AA values are limited to below 6, and summer values are below 4.

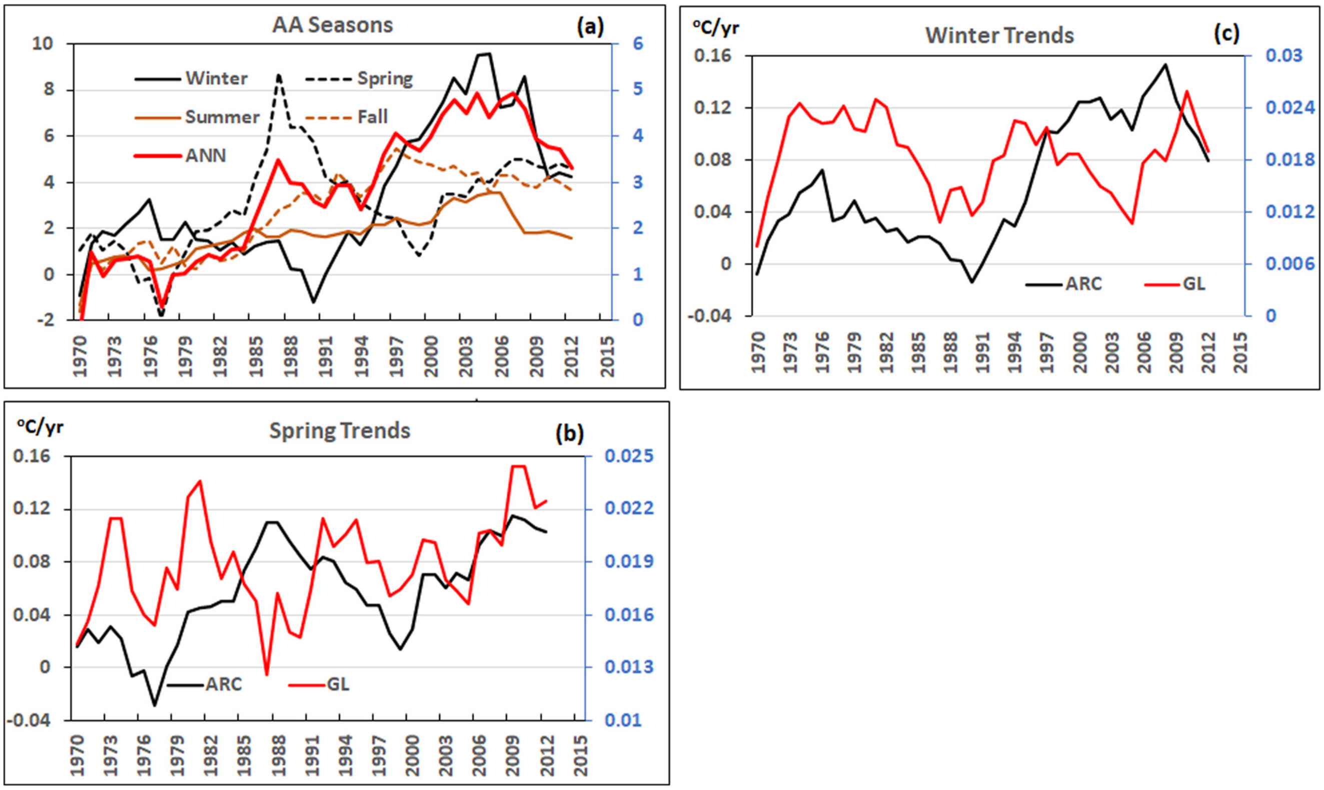

Figure 4. (a) Arctic Amplification (AA) in individual seasons (black and brown lines) are connected with the left-hand side scale, and its annual value (red thick line) with the right-hand side scale. (b) Arctic and global temperature trends in winter, and (c) in spring showing a peak in the 1987 Arctic trend, and a dip in the 1987 global temperature trend.

The annual AA sharp increase in 1987 is produced by a spring peak in the Arctic temperature trend (Figure 4b) occurring at the same time as a sharp dip in the global trend. A broad AA peak in the first decade of the 21st century is due to a gradual increase in the winter temperature trend starting around 1990 (Figure 4c) combined with a gradual decrease of the global temperature trend within the 1995–2005 decade.

3.3. Arctic Amplification Over the Land and Ocean Areas

The observed Arctic land and ocean area temperatures evolve almost parallel to each other during the entire time-interval 1900–2022 (Figure 5a). On the other hand, the global ocean and land mean temperatures evolve parallel to each other during the 1900–1990 time span and then start to diverge quite clearly after 1990 (Figure 5b), much as is shown for unfiltered slightly different data in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Gulev et al., 2021). The main reason for the divergence in land and ocean warming rates is the considerably faster response of land to the relatively sudden increase in the net forcing rate due to increasing greenhouse gases and some decrease in anthropogenic aerosols that started around 1980 (Folland et al., 2018). The global mean temperature response usually used in AA calculations is dominated by the oceans, giving a global mean land and ocean temperature response with a lag of about 4 and 10 years (Boucher et al., 2009; Folland et al., 2018). This explains Figure 5b. However, as noted above, by contrast, the 21-year moving trend of the Arctic mean temperature is not greatly different between the land and ocean points in the Arctic (Figure 5c), probably because the Arctic Ocean warming is additionally affected by the reductions of albedo caused by decreasing sea ice concentrations and extents, a positive feedback of increasing greenhouse gases (e.g., Dai et al., 2019; Ding et al., 2019; Kumar et al., 2010; Matveeva & Semenov, 2022; Notz & Stroeve, 2016; Overland et al., 2011; Screen & Simmonds, 2010).

The split of global warming between the land and the oceans after 1990 shows much faster warming over land leading to a large increase in the temperature trend over land. Figure 5b also shows the global warming slowdown

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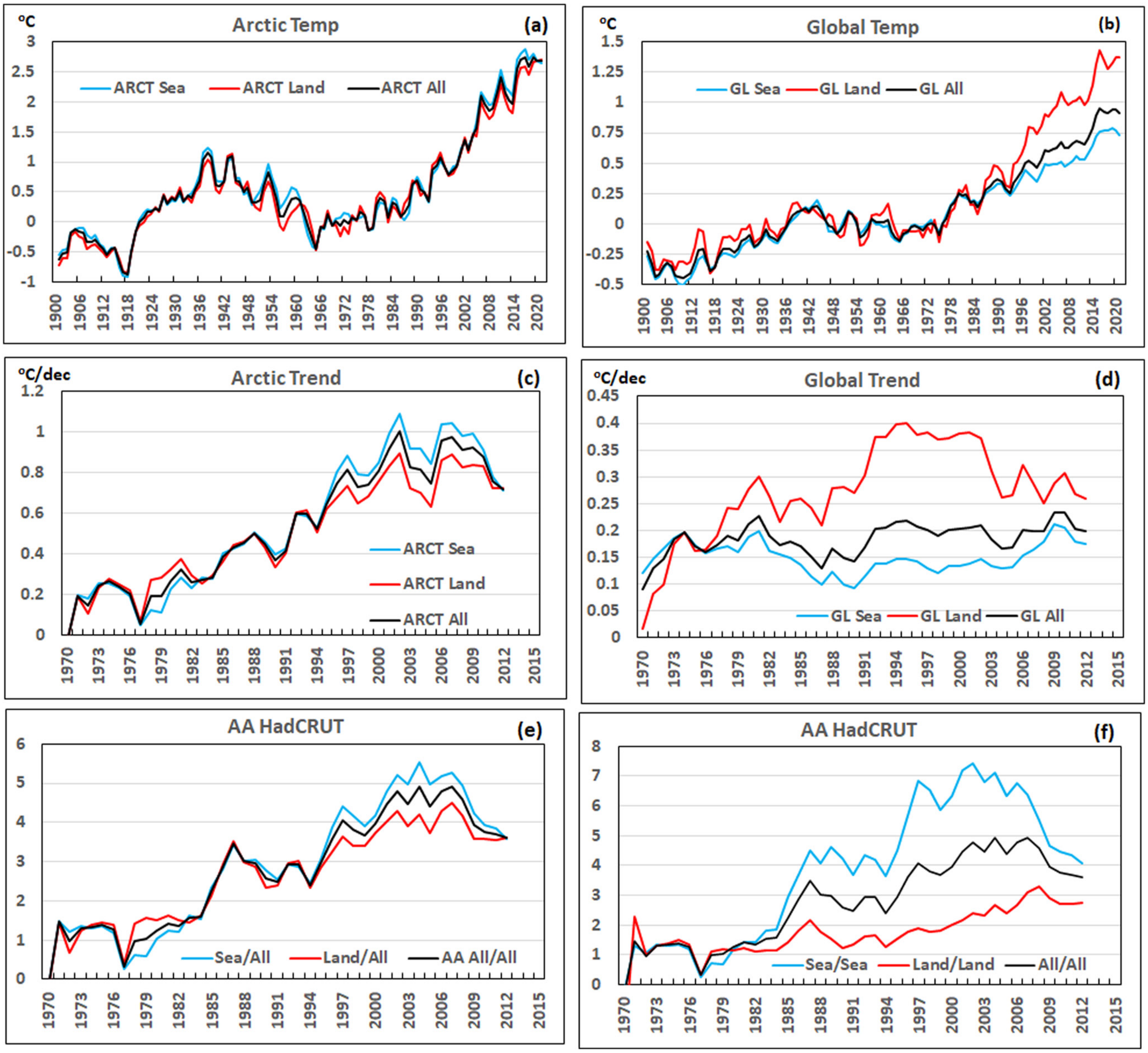

Figure 5. (a) Arctic temperature anomaly according to HadCRUT5 over the sea, land, and the whole Arctic. The annual data are smoothed by a 3-year moving average. Panel (b) Same as in (a), but for global mean temperature anomaly. (c) 21-year moving trends of the Arctic temperature over the sea, land, and the whole Arctic are calculated from annual temperature data. (d) Same as in (c), but for global mean temperature moving. (e) The Arctic Amplification (AA) over the ocean, land, and the whole Arctic was calculated as a ratio of the 21-year moving trends of the Arctic Ocean-area temperature trend, or the Arctic land trend over the trend of global temperature using the HadCRUT5 temperature data. (f) Same as in (e), except using the Arctic Ocean temperature trend over the temperature trend of the global ocean, and similarly for the Arctic temperature trend of the land over the trend of global land temperature. All data are plotted at the middle of the 21-year trends.

from about 2000 to 2013—also known as the "global warming hiatus"—which as suggested by extensive observational and modeling studies, was substantially influenced by the cooling effects of the negative phase of the Interdecadal Pacific Oscillation (IPO), as well as several less important factors that also affected the land component like solar and volcanic forcing (e.g., England et al., 2014; Folland et al., 2018; Fyfe et al., 2016; Kosaka & Xie, 2013; Santer et al., 2014; Trenberth & Fasullo, 2013). However, the rate of warming of the oceans after the early 1980s shows a multidecadal reduction followed by a recovery around 2005 (Figure 4d, blue line), based on a 21-year running trend. This appreciably influences the AA calculated relative to the global mean temperature (Figure 5f) as the oceans contribute more than 70% to this quantity. When referring to global mean temperature, the maximum AA varies between about 4 and 5.5 depending on the component of Arctic temperature used

(Figure 5e). However, when Arctic Ocean temperature and global ocean temperature are used AA reaches at least 7 (Figure 5f) consistent with the reduction in ocean warming rate in Figure 5d and related in part to the state of the IPO. Thus, by separating the AA between the land and the ocean contributions, we find as expected, greater variability in AA over the ocean.

3.4. Future AA Projection

It is not easy to project the future AA behavior. We have seen that the reason that the CMIP6 ensemble mean of model simulations does not reproduce the high AA values in the early years of the 21st century is the models' overestimate of the trend of global mean temperature. The CMIP6 model ensemble mean simulated the 1975–2022 linear trend of Arctic mean temperature within 1% of the observed value, while the simulated trend of the global mean temperature is overestimated by about 26%. When the observed global temperature trend replaces the model-simulated CMIP6 global temperature trend, the agreement between the CMIP6 model-simulated and the observed AA is significantly improved.

Since the CMIP6 ensemble mean is not able to simulate correctly the past AA, we cannot assume that it would nevertheless correctly represent the future trend. However, we have seen that the CMIP6 simulation of the AA using the CMIP6 Arctic temperature trend ratio against the observed global temperature trend has been more successful in approximating the observed AA. Therefore, to estimate future trends, we use the CMIP6 Arctic temperature future projection together with an approximation for the global temperature trend based on past global temperature data. Within the 1975–2022 period, the global temperature increased at the rate of about 0.18K/decade, and we shall assume here that this rate of increase will hold about steady until 2050 (red dashed line in Figure 3b).

Using the above-defined approximation for the mean global temperature trend and the CMIP6 ensemble mean for the Arctic temperature, we obtain the AA* projection to 2050 as shown in Figure 3d. From the current AA value of about 3.6, the AA* is projected to rise up to about 4.3, reaching its maximum value around 2020, with a modest decrease to between 3.5 and 4.0 by 2050. Using the mean global temperature projected by the CMIP6 ensemble mean (solid black curve in Figure 3d), the AA up to 2050 is limited to values between 2 and 3. A similar result was recently reported by Davy and Griewank (2023).

Both studies project that future AA will increase from current values, followed by a decrease toward 2050. This projection assumes the global warming trend remains constant at its current value. Considering the past performance, we assign a higher probability to the AA* path projected by the model with the CMIP6 Arctic temperature trend over an assumed constant future global temperature trend. If the global temperature trend increases in the future, the AA* will be reduced accordingly.

4. Conclusions

The CMIP6 climate models have difficulty reproducing the observed high values of AA in the early 21st century (Chylek et al., 2022; Rantansen, 2022). In this report, we find that the Arctic temperature trend is reproduced by CMIP6 models correctly (Figure 3a); however, the global temperature trend is significantly overestimated by the ensemble mean of CMIP6 models (Figure 3b). A high CMIP6 global temperature trend keeps the CMIP6 AA low (between 2 and 3 instead of between 4 and 5) (Figure 3c). When a high CMIP6 global temperature trend is replaced by an observed trend the AA reaches up to 5 (Figure 3d). Since none of the CMIP6 models can reproduce high AA values in the early years of the 21st century (Figure 3c), it is likely that these high AA values are due to internal climate variability, rather than external forcing.

The AA changed in two steep steps in the late 1980s and again during 1995–2000 (Chylek et al., 2022). The first steep increase of AA in the late 1980s was caused by an increasing rate of Arctic warming and a simultaneous decreasing rate of global warming during the spring season (Figure 4b). The second steep increase in the late 1990s was due to a decade-long increase in the winter trend of Arctic warming (Figure 4c). A recent post-2008 decrease of the AA follows a decrease of the Arctic rate of warming and a simultaneous increase of the global warming rate. By considering separately the AA over land and ocean, we confirm that the AA has been influenced more by temperature changes over the Arctic Ocean than over the land.

Finally, what is the future of the AA? Will it continue to rise to even higher values? That is not likely. Our analysis suggests an increasing AA for about the next decade, followed by a slight decrease until about 2050.

Data Availability Statement

No new data were used in this work. All the CMIP6 runs are available at the World Meteorological Organization, European Climate Assessment and Data set, at the link https://climexp.knmi.nl/selectfield_cmip6.cgi?id=someone@somewhere. The observed HadCRUT5 temperature time series were downloaded from https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=hadcru.

Acknowledgments

The research presented in this report was supported in part by the Laboratory Directed Research and Development program of Los Alamos National Laboratory under project 20200035DR (PI M. Dubey). M. Wang is supported by the Arctic Research Program of the NOAA Global Ocean Monitoring and Observation (GOMO) office through the Cooperative Institute for Climate, Ocean, & Ecosystem Studies (CIOCES) under NOAA Cooperative Agreement NA20OAR4320271, Contribution No. 2021-1173, and PMEL contribution number 5327.

References

AMAP. (2021). *Arctic climate change update 2021: Key trends and impacts. Summary for policy-makers*. Arctic Monitoring and Assessment Programme (AMAP).

Bengtsson, L., Semenov, V., & Johannessen, O. (2004). The early twentieth-century warming in the Arctic – A possible mechanism. *Journal of Climate*, *17*(20), 4045–4057. https://doi.org/10.1175/1520-0442(2004)017<4045:tetwit>2.0.co;2

Boucher, O., Lowe, J. A., & Jones, D. (2009). Implications of delayed actions in addressing carbon dioxide emission reduction in the context of geo-engineering. *Climate Change*, *92*(3–4), 261–273. https://doi.org/10.1007/s10584-008-9489-7

Cai, S., Hsu, P.-C., & Liu, F. (2021). Changes in polar amplification in response to increasing warming in CMIP6. *Atmospheric and Oceanic Science Letters*, *14*(3), 200043. https://doi.org/10.1016/j.aosl.2021.100043

Chylek, P., Folland, C., Klett, J. D., Lesins, G., & Dubey, M. K. (2023). Arctic amplification in the Community Earth System Models (CESM1 and CESM2). *Atmosphere*, *14*(5), 820. https://doi.org/10.3390/atmos14050820

Chylek, P., Folland, C., Klett, J. D., Wang, M., Hengartner, N., Lesins, G., & Dubey, M. K. (2022). Annual mean Arctic Amplification 1970–2020: Observed and simulated by CMIP6 climate models. *Geophysical Research Letters*, *49*(13), e2022GL099371. https://doi.org/10.1029/2022GL09937

Chylek, P., Folland, C. K., Lesins, G., Dubey, M. K., & Wang, M. (2009). Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, *36*(14), L14801. https://doi.org/10.1029/2009GL038777

Chylek, P., Klett, J. D., Lesins, G., Dubey, M. K., & Hengartner, N. (2014). The Atlantic Multi-decadal Oscillation as a dominant factor of oceanic influence on climate. *Geophysical Research Letters*, *41*(5), 1689–1697. https://doi.org/10.1002/2014GL059274

Cowtan, K., & 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. https://doi.org/10.1002/qj.2297

Dai, A., Luo, D., Song, M., & Liu, J. (2019). Arctic amplification is caused by sea-ice under increasing CO_2. *Nature Communications*, *10*(1), 121. https://doi.org/10.1038/s41467-018-7954-9

Davy, R., & Griewank, P. (2023). Arctic amplification has already peaked. *Environmental Letters*, *18*(8), 084003. https://doi.org/10.1088/1748-9326/ace273

Ding, Q., Schweiger, A., L'Heureux, M., Steig, E. J., Battisti, D. S., Johnson, N. C., et al. (2019). Fingerprints of internal drivers of Arctic sea-ice loss in observations and model simulations. *Nature Geoscience*, *12*(1), 28–33. https://doi.org/10.1038/s41561-018-0256-8

England, M., McGregor, S., Spence, P., Meehl, G. A., Timmermann, A., Cai, W., et al., (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, *4*(3), 222–227. https://doi.org/10.1038/nclimate2106

Folland, C. K., Boucher, O., Colman, A., & Parker, D. (2018). Causes of irregularities in trends of global mean surface temperature since the late 19th century. *Science Advances*, *4*(6), eaao5297. https://doi.org/10.1126/sciadv.aao5297

Fyfe, J., Meehl, G. A., England, M. H., Mann, M. E., Santer, B. D., Flato, G. M., et al. (2016). Making sense of the early-2000s warming slowdown. *Nature Climate Change*, *6*(3), 224–228. https://doi.org/10.1038/nclimate2938

Graversen, R., & Wang, M. (2009). Polar amplification in a coupled climate model with locked albedo. *Climate Dynamics*, *33*(5), 629–643. https://doi.org/10.1007/s00382-009-0535-6

Gulev, S., Thorne, P. W., Ahn, J., Dentener, F. J., Domingues, C. M., Gerland, S., et al. (2021). Changing state of the climate system. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.)*Climate change 2021: The physical science basis. Contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change* (pp. 287–422). Cambridge University Press. https://doi.org/10.1017/9781009157896.004

Hahn, L. C., Armour, K. C., Zelinka, M. D., Botz, C. M., & Donohoe, A. (2021). Contributions to polar amplification in CMIP5 and CMIP6 models. *Frontier in Earth Science*, *9*, 710036. https://doi.org/10.3389/feart.2021.710036

Holland, M., & Bitz, C. (2003). Polar amplification of climate change in coupled models. *Climate Dynamics*, *21*(3–4), 221–232. https://doi.org/10.1007/s00382-003-0332-6

Hourdin, F., Mauritsen, T., Gettelman, A., Golaz, J. C., Balaji, V., Duan, Q., et al. (2017). The art and science of climate model tuning. *Bulletin of the American Meteorological Society*, *98*(3), 589–602. https://doi.org/10.1175/bams-d-15-00135.1

Isaksen, K., Nordli, Ø., Ivanov, B., Køltzow, M. A. Ø., Aaboe, S., Gjelten, H. M., et al. (2022). Exceptional warming over the Barents area. *Scientific Reports*, *12*(1), 9371. https://doi.org/10.1038/s41598-022-13568-5

Johannessen, O., Kuzmina, S., Bobylev, L., & Miles, M. (2016). Surface air temperature variability and trends in the Arctic: New amplification assessment and regionalization. *Tellus*, *68*(1), 28234. https://doi.org/10.3402/tellusa.v68.28234

Kosaka, Y., & Xie, S.-P. (2013). Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, *501*(7467), 403–407. https://doi.org/10.1038/nature12534

Kumar, A., Perlwitz, J., Eischeid, J., Quan, X., Xu, T., Zhang, T., et al. (2010). Contribution of sea ice loss to Arctic amplification. *Geophysical Research Letters*, *37*(21), L21701. https://doi.org/10.1029/2010GL045022

Lenssen, N., Schmidt, G., Hansen, J., Menne, M., Persin, A., Ruedy, R., & Zyss, D. (2019). Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres*, *124*(12), 6307–6326. https://doi.org/10.1029//2018JD029522

Masson-Delmotte, V., Kageyama, M., Braconnot, P., Charbit, S., Krinner, G. C., Ritz, C., et al. (2006). Past and future polar amplification of climate change: Climate model inter-comparisons and ice-core constraints. *Climate Dynamics*, *26*(5), 513–529. https://doi.org/10.1007/s00382-005-0081-9

Matveeva, T. A., & Semenov, V. A. (2022). Regional features of the Arctic sea ice area changes in 2000–2019 versus 1979–1999 periods. *Atmosphere*, *13*(9), 1434. https://doi.org/10.3390/atmos130914

Mewes, D., Mewes, C., & Jacobi, C. (2019). Heat transport pathways into the Arctic and their connections to surface air temperature. *Atmospheric Chemistry and Physics*, *19*(6), 3927–3937. https://doi.org/10.5194/acp-19-3927

Morice, C. P., Kennedy, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., et al. (2021). An updated assessment of near-surface temperature change from 1850: The HadCRUT5 dataset. *Journal of Geophysical Research*, *126*(3), e2019JD032361. https://doi.org/10.1029/2019JD032361

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*, *354*(6313), 747–750. https://doi.org/10.1126/science.aag2345

Overland, J., Wood, K., & Wang, M. (2011). Warm arctic—Cold continents: Climate impact of newly open Arctic Sea. *Polar Research*, *30*(1), 15787. https://doi.org/10.3042/polar.v30i0.15787

Perovich, D. K., Light, B., Ricken, H., Jones, K. F., Runciman, K., & Nghiem, S. V. (2007). Increasing solar heating of the Arctic Ocean and adjacent sea, 1979–2005. Attribution and role of ice-albedo feedback. *Geophysical Research Letters*, *34*(19), L19505. https://doi.org/10.1029/2008GL034007

Pistone, K., Eisenman, I., & Ramanathan, V. (2019). Radiative heating of an ice-free Arctic Ocean. *Geophysical Research Letters*, *46*(13), 7474–7480. https://doi.org/10.1029/2019GL082914

Pithan, F., & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, *7*(3), 181–184. https://doi.org/10.1038/ngeo20714

Polyakov, I., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., et al. (2017). Greater role of Atlantic inflows on sea ice loss in the Eurasian basin of the Arctic Ocean. *Science*, *356*(6335), 285–291. https://doi.org/10.1126/science.aai8204

Previdi, M., Smith, K., & Polvani, L. (2021). Arctic amplification of climate change: A review of underlying mechanisms. *Environmental Research Letters*, *16*(9), 093003. https://doi.org/10.1088/1748-9326/ac1c29

Rantansen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Santer, B., Bonfils, C., Painter, J. F., Zelinka, M. D., Mears, C., Solomon, S., et al. (2014). Volcanic contribution to decadal changes in tropospheric temperature. *Nature Geoscience*, *7*(3), 185–189. https://doi.org/10.1038/ngeo2098

Screen, J., & Simmonds, I. (2010). The central role of diminishing sea ice in recent arctic temperature amplification. *Nature*, *464*(7293), 1334–1337. https://doi.org/10.1038/nature09051

Serreze, M., & Barry, R. (2011). Processes and impact of Arctic amplification: A research synthesis. *Global and Planetary Change*, *77*(1–2), 85–96. https://doi.org/10.1016/j.gloplacha.2011.03.004

Stuecker, M. F., Bitz, C. M., Armour, K. C., Proistosescu, C., Kang, S. M., Xie, S. P., et al. (2018). Polar amplification dominated by local forcing and feedbacks. *Nature Climate Change*, *8*(12), 1076–1081. https://doi.org/10.1038/s41558-018-0339-y

Trenberth, K. E., & Fasullo, J. T. (2013). An apparent hiatus in global warming? *Earth's Future*, *1*, 19–32. https://doi.org/10.1002/2013ef000165

Tsubouchi, T., Vage, K., Hansen, B., Larsen, K., Osterhus, S., Johnson, C., et al. (2020). Increased ocean heat transport into the Nordic Seas and Arctic Ocean over period 1993–2016. *Nature Climate Change*, *11*(1), 21–26. https://doi.org/10.1038/s41558-020-00941-3

Vihma, T. (2014). Effect of Arctic sea ice decline on weather and climate: A review. *Surveys in Geophysics*, *35*(5), 1175–1214. https://doi.org/10.1007/s10712-014-9284-0

Ye, K., & Messori, G. (2021). Inter-model spread in the wintertime Arctic amplification in the CMIP6 models and the important role of internal climate variability. *Global and Planetary Change*, *204*, 103543. https://doi.org/10.1016/j.gloplacha.2021.103543