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Key Points:

- Annual mean Arctic Amplification (AA) within the period 1970–2020 changed in steep steps around 1986 and 1999. It reached values over 4.0
- Even those CMIP6 models best at reproducing the AA did not reproduce the second sudden increase near 1999
- We conjecture that the first AA sharp increase is due to external forcing, while the second is due to internal climate variability

Supporting Information:

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

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Annual Mean Arctic Amplification 1970–2020: Observed and Simulated by CMIP6 Climate Models

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Abstract While the annual mean Arctic Amplification (AA) index varied between two and three during the 1970–2000 period, it reached values exceeding four during the first two decades of the 21st century. The AA did not change in a continuous fashion but rather in two sharp increases around 1986 and 1999. During those steps the mean global surface air temperature trend remained almost constant, while the Arctic trend increased. Although the "best" CMIP6 models reproduce the increasing trend of the AA in 1980s they do not capture the sharply increasing trend of the AA after 1999 including its rapid step-like increase. We propose that the first sharp AA increase around 1986 is due to external forcing, while the second step close to 1999 is due to internal climate variability, which models cannot reproduce in the observed time.

Plain Language Summary The rate of Arctic warming varied in time, while the rate of global warming was nearly constant over the period 1960–2020. This led to a variable Arctic Amplification (AA) defined as a ratio of the Arctic warming trend to mean global warming trend. In addition, the Arctic experienced sudden changes in the rate of warming with step-like changes in annual mean Arctic Amplification around the years 1986 and 1999. Climate models do not capture the second observed sharp increase of the AA. We suggest that the first AA increase around 1986 is primarily due to external forcing (increasing concentration of carbon dioxide) while the second sharp increase around 1999 is dominated by internal climate variability which current models cannot capture accurately within the time scale of the physical phenomena.

1. Introduction

The Arctic region has experienced a larger warming trend than most of the rest of the globe in recent decades. Thus, since 1970, Arctic surface air temperature has been rising several times faster than the global mean temperature (Figure 1a), leading to decreasing Arctic sea-ice cover and melting of the Greenland ice sheet. This is generally referred to as Arctic Amplification (AA) (Chylek et al., 2009, 2014; Masson-Delmotte, 2006; Pithan and Thorsten, 2014). The AA is seasonally variable, reaching its maximum values in winter and a minimum in summer (Johannessen et al., 2016; Lesins et al., 2012). It has been shown that the Arctic influences the climate all over the world (Overland et al., 2011; Pistone et al., 2019; Screen, 2013; Tang et al., 2013). The associated sea level rise, particularly from melting of the Greenland Ice Sheet, is also of concern for many coastal areas.

Arctic climate is subject to human-made forcing by atmospheric greenhouse gases (Dai et al., 2019; Notz & Stroeve, 2016) and anthropogenic aerosols (Booth et al., 2012; Chylek et al., 2016), as well as to natural forcing (mainly changes in solar irradiance and volcanic activity). Unforced climate variability involves atmospheric and oceanic variability (Bengtsson et al., 2004; Chylek et al., 2014; Ding et al., 2019) and naturally occurring changes in atmospheric aerosols and carbon dioxide. It is not easy to untangle individual contributions. Our current understanding of climate change and its future projections depends in large part on simulations by climate models.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) in general underestimate the AA (Previdi et al., 2021). The CMIP6 models reproduce broadly the observed pattern of surface Arctic warming (Hahn

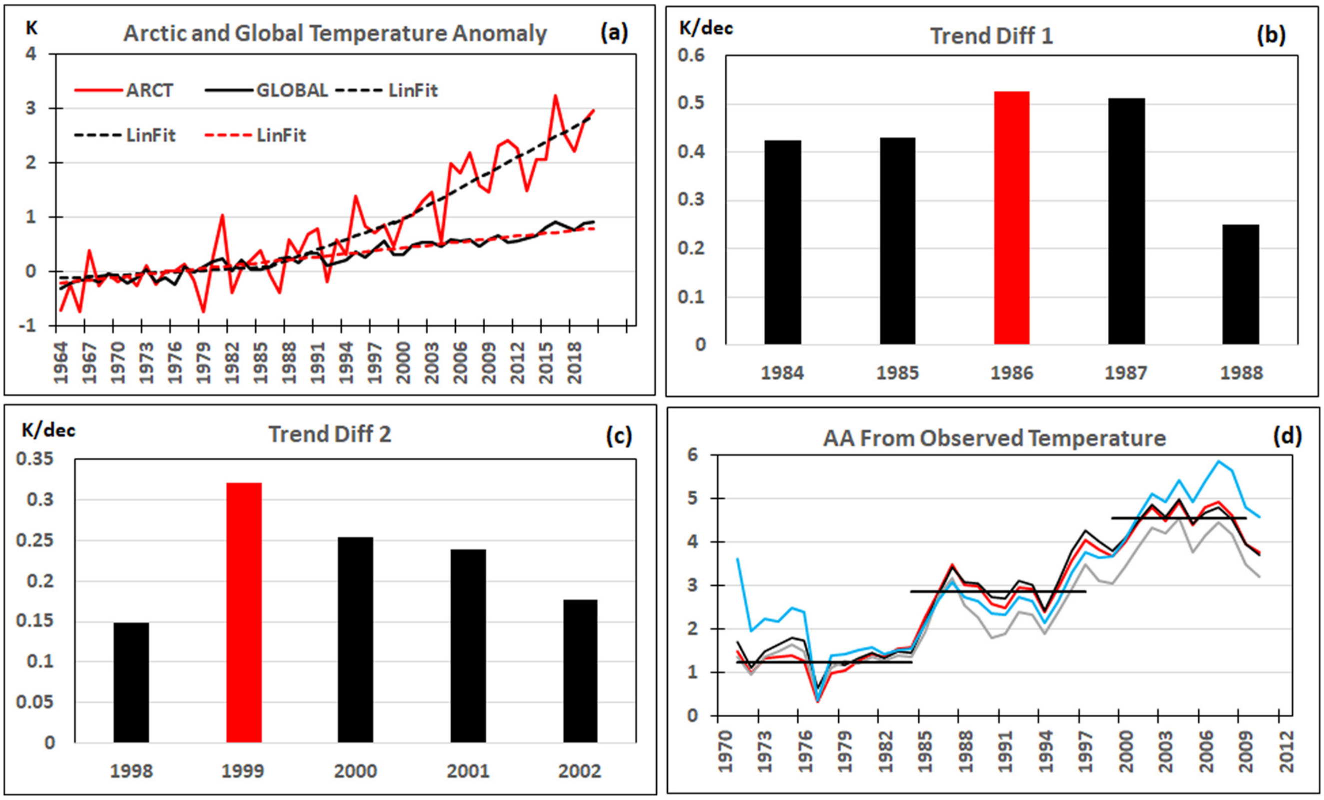

Figure 1. (a) Annual Arctic and global mean temperature anomaly, with respect to 1961–1990 mean, according to HadCRUT5.0 (black and red solid lines) and their piece-wise linear approximations (dashed lines LinFit). (b and c) The maximum (red columns) difference between 21 years moving trends after and before the breaking point identifies 1986 and 1999 as times of changing trends in mean Arctic temperature. (d) The values of Arctic Amplification index obtained using the HadCRUT5.0 (red), GISS (black), NOAA NCEI (gray), and HadCRUT/CW (blue) data, and their step-like approximation (black horizontal lines).

et al., 2021). They identified the surface albedo feedback and lapse rate feedbacks to be major contributors to Arctic warming.

Climate model projections of future climate changes are essential for planning any mitigation of expected changes and developing adaptation strategies.

In this communication we show that AA within the time-span 1970–2020 did not change continuously, but rather in (near) discrete steps, and that the AA index reached values exceeding 4.0 (where the rate of Arctic warming is four times higher than the rate of global warming) during the first decade of the 21st century.

2. Data and Methods

The NASA GISS temperature set with 1,200 km smoothing radius (Lenssen et al., 2019) provides an AA record almost identical to HadCRUT5.0 (C. Morice et al., 2021), while the Had/CW (HadCRUT4 data complemented by the procedure suggested by Cowtan & Way, 2014) data shows the highest AA, and the NOAA NCEI (National Centers for Environmental Information) the lowest.

For the temperature records in the rest of this paper, we use HadCRUT5.0 data as it arguably contains the most widespread information from Arctic air temperature stations and the most up to date correction of biases in sea surface temperature. Relative to HadCRUT4 the HadCRUT5 provides improved accuracy and increased land coverage (by 9%). HadCRUT5 also contains a significant improvement in the infilled Arctic area compared that of HadCRUT4. The station database has been expanded such that the number of those stations with sufficient data to estimate temperature anomalies has grown from 4,842 in CRUTEM.4.0.0.0 (as used in C. P. Morice et al., 2012) to 7,983 in CRUTEM5 (Osborn et al., 2021).

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We consider the region 65°N–90°N as being the Arctic. All temperature data (1960–2020) were downloaded from the KNMI Climate Explorer website (https://climexp.knmi.nl/start.cgi) and from the UK Met Office data set at https://www.metoffice.gov.uk/hadobs/hadcrut5. The global temperature anomaly changes relatively slowly within the considered time span 1960–2020. In contrast, the Arctic warming increased rather sharply over this period with superimposed sudden changes of trend. A visual inspection of temperature time series (Figure 1a) suggests change-points of the trend of Arctic temperature near the years 1985 and 2000. To determine more objectively the points of changing trend we first select the years from 1984 to 1988 and years from 1998 to 2002 as possible change-points and we calculate the 21-year trend before and after the considered year. Then we calculate the difference of trends before and after each of the considered years. The year for which this difference is the largest within a consider time span is taken as a year of change of trend. The results indicating the years of 1986 and 1999 as years of changing trend are shown in Figures 1b and 1c. Statistical procedures and the statistical significance of the break-points can be found in the Supporting Information S1. The dashed lines in Figure 1a represent piece-wise linear approximation to the temperature anomaly data (composite of linear approximations before, after and between the points of trend change).

3. Arctic Amplification

Arctic Amplification indicates how much faster the warming is in the Arctic region is compared to overall global warming. Although many papers study AA, it has no generally accepted definition. We define, for the purposes of the following analysis, the AA index as the ratio of the 21-year moving trend centered on the year of interest of the Arctic surface temperature anomaly to the 21-year moving trend of global temperature anomaly. The AA behavior does not change significantly if the number of years is changed between 17 and 27 years. The longer time period (>27 years) leads to smoothing of the AA and removal of the step-like behavior, while the shorter period (<17 years) leads to an unstable AA due to frequent fluctuations of the sign of the trend. The average AA calculated as a mean of AAs using the length of trend interval between 17 and 27 years is shown in Figure S1 in Supporting Information S1.

Although there are differences between individual temperature data sets (HadCRUT, GISS, NOAA, and HadCRUT/CW), each of them leads to periods of almost constant AA, interspersed with periods of fast change (Figure 1d). All temperature anomalies are shown with respect to the 1961–1990 mean.

Figure 1d shows that the post 1970 values of the AA index can be seen to be composed of three periods during which it can be approximated by a constant, and with steep increases in between. The values of the AA are close to 1.5 during the first constant period, and approximately 3.1 and 4.4 during the second and the third constant periods. As stated previously, we consider the Arctic region to be the area within 65°N–90°N. When this area is extended to 60°N–90°N our qualitative results remain unchanged; however, the maximum value of the AA is reduced by about one unit (see Figure S1b in Supporting Information S1).

4. Arctic Amplification and CMIP6 Models

4.1. Methodology

We use the observed HadCRUT5 temperature data and the CMIP6 model simulations. The data are downloaded from the KNMI Climate Explorer website. The temperature time series (1960–2020) of global temperature and the Arctic region (65–90°N) are obtained using the KNMI Climate Explorer software. Points of changing trends in the temperature anomaly are identified and their statistical significance determined as described in Supporting Information S1. The AA is calculated as the ratio of the 21 years moving linear trend of Arctic to global temperature anomaly with the year of interest being at the center of 21 years as described in Section 3.

The total Arctic or global temperature anomaly is calculated as the difference between the 2010–2020 average and the reference 1961–1990 temperature. We also calculate the correlation coefficient for years 1970–2010 between the model-calculated AA and the AA deduced using the HadCRUT5 temperature data.

CMIP6 models are arranged in order of decreasing correlation coefficient and assigned the order number: A. Then models are re-arranged in order of increasing absolute value of the difference between the model and observed Arctic warming and assigned an order number: B. The final order number or a skill level of a model is taken as: 2A + B, giving the correlation coefficient twice the weight compared to the model Arctic warming. Although this

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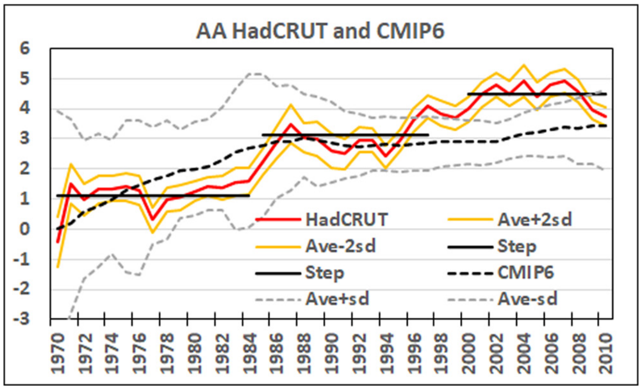

Figure 2. The Arctic Amplification (AA) (red line) and its two standard deviations (yellow lines) uncertainties calculated from the mean HadCRUT5 temperature data and its one hundred realizations, together with the AA from the ensemble mean of CMIP6 simulations with the first member of each model (black dashed line) and its one standard deviation uncertainties (gray dashed lines). The observed near constant periods of the AA are shown as horizontal solid black lines.

may seem somewhat arbitrary, our aim is to estimate the true shape of the AA more than the skill in simulating the observed Arctic warming.

4.2. AA of Ensemble Mean of CMIP6 Simulations

We use simulations by 39 climate models (see Table S1 in Supporting Information S1) available within the CMIP6 collection with the Shared Socioeconomic Path 2–4.5 (SSP2-4.5) scenario to obtain the mean global and Arctic (65°N–90°N) temperature. There are only minor differences in 1960–2020 CMIP6 global mean temperatures between using just one member per model or all available members. However, future differences become significant for mean Arctic temperature, where for example, in 2040 the difference between the two Arctic mean temperatures is projected to be about 0.8°C. To give all models an equal weight, in this report we consider the mean temperatures obtained by using one member per model. The resulting AA index for the CMIP6 simulations with one member (the first member) per model is shown in Figure 2 together with the AA index obtained from the observed HadCRUT5.0 temperature data. The estimates of standard deviations were obtained from 100 realizations of the HadCRUT temperature data, and from the first member of individual models of the CMIP6 simulations.

The HadCRUT5.0 uses 2m-temperature over land and SST over the ocean, while climate models use near-surface temperature all over the globe. This may introduce bias to the AA because SSTs are warming slower than the air above it. To investigate this potential bias, we have compared the AA calculated using the HadCRUT5 temperature and ERA5 temperature reanalysis. Using the ERA5 the step-like fashion of AA is preserved in time with only small changes in magnitude.

Climate change in the Arctic contains contributions from both natural climate variability and the externally forced climate change (Ding et al., 2019). In the ensemble mean of 39 CMIP6 models, the internal climate variability is expected to be averaged out such that the result represents mostly the externally forced variability. Although the CMIP6 ensemble mean captures correctly the rise of the AA index to over 3.0 in the 1980s, it misses the subsequent rise to over 4.0. Instead, the models suggest a slow variation of the AA index around 3.0. The observed AA increase between 1970s and 1980s (Figure 2) includes likely a significant externally forced contribution, while the 1990s–2000s increase, which is not seen in the ensemble mean of CMIP6 models, is likely to be dominated by internal climate variability.

4.3. AA of Individual CMIP6 Simulations

The AA variability of the individual model realizations (Figure S1d in Supporting Information S1) is generally much larger than the variability of the AA obtained from the observed data. While the observed AA within the years 1970–2010 is within the range $1 < AA < 5$, the individual model simulations have a much wider range of AA $-6 < AA < 6$. An example of three realizations by the ACCESS-ESM1-5 climate model is shown in Figure S1d in Supporting Information S1.

We next analyze the first realizations of the 39 individual CMIP6 model runs. The distribution of the correlation coefficients between the mean HadCRUT5 AA and each model AA range from a highly significant correlation $r = 0.86$, to a highly significant anti-correlation $r = -0.89$ (Figure 3a). The division of positive and negative correlations is nearly symmetric with 18 models providing positive and 21 negative correlations. The average of the individual correlation coefficients is 0.03, suggesting random internal climate variability dominates individual model simulations.

To investigate the randomness of individual realizations within a given CMIP6 model we consider the first and second realizations. We have 29 models with at least two realizations of temperature anomaly from which we calculate the AA. There are a few models with a significant correlation between the first and second model realizations and the HadCRUT5 AA. These models include the three Canadian models (CanESM5-CanOE-p2, CanESM5-p1, and CanESM5-p2) and KACE-1-0 (Figure 3b). These models have likely a component of the

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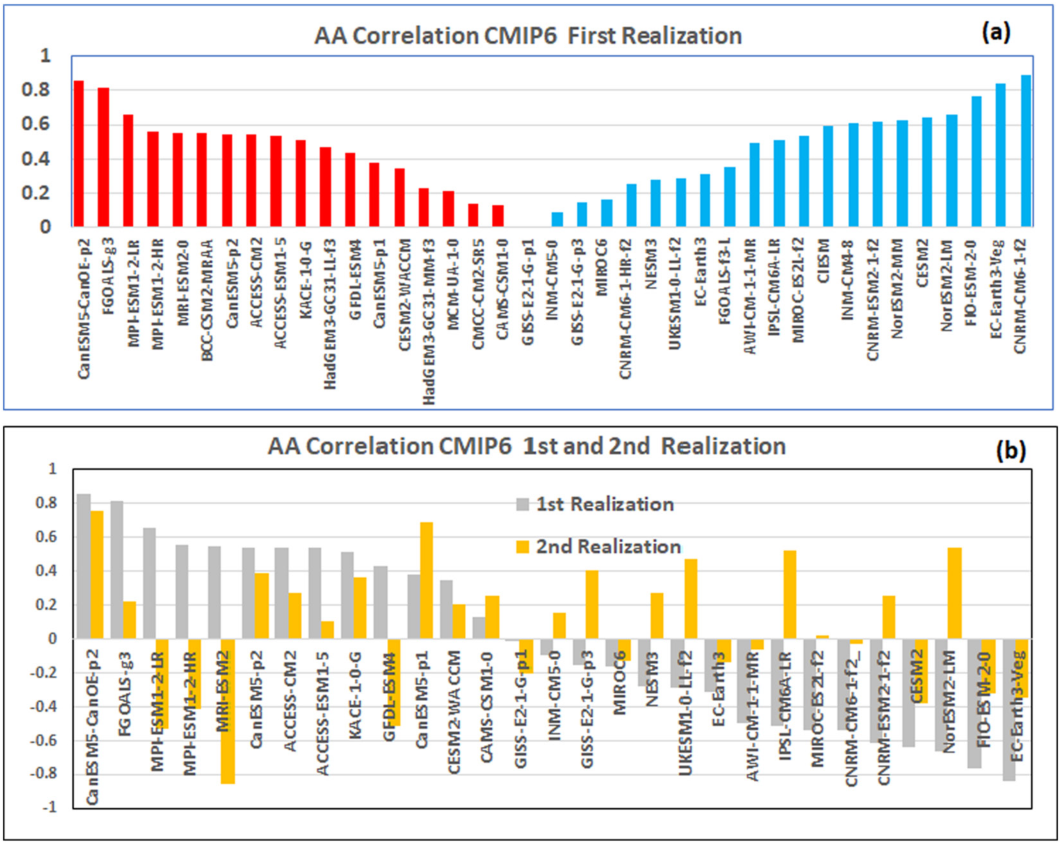

Figure 3. Correlation coefficient 1970–2010 between the Arctic Amplification (AA) calculated from the observed (HadCRUT5) temperatures and the first realization of the model simulations. Red columns show a positive correlation, blue columns show a negative correlation. (b) The same for the first and second model realizations. Gray columns show correlation coefficient between the observed AA and the first model realizations; the yellow columns between the second realization and observed AA.

model that shows a stronger response to external forcing compared to the models' internal variability resulting in a similarity of individual realizations.

To confirm the dominance of the external forcing over internal climate variability in these models we consider the 10 temperature realizations produced by the CanESM model. Among the 10 AA time series calculated from these realizations, nine have a positive statistically significant correlation with the AA obtained from the HadCRUT5 data, with an average correlation coefficient $r = 0.48$ for the 10 individual realizations. This confirms that the simulation of temperature variability in this model is dominated by external forcing with a relatively small contribution from internal climate variability.

For the remaining models, we find no significant correlation with the HadCRUT5 AA for both the first and second model realizations, indicating that there is a substantial randomness due to internal climate variability within each model.

4.4. AA of Model Ensemble Mean of Five Simulations

In the light of these results, to further analyze the AA using an ensemble mean of individual models, we select the CMIP6 models having at least five realizations of Arctic and global temperatures. This gives 16 CMIP6 models.

We follow the procedure as described in Section 4.1. Most of the models (ensemble mean of the first five realizations) significantly underestimate Arctic warming from its average over 1961–1990 to the one over 2010–2020 (Figure 4a). By contrast the mean global temperature increase over this period is reproduce reasonably well by the majority of models (Figure 4c), most with a relatively small error (error <0.15°C). The exceptions are the

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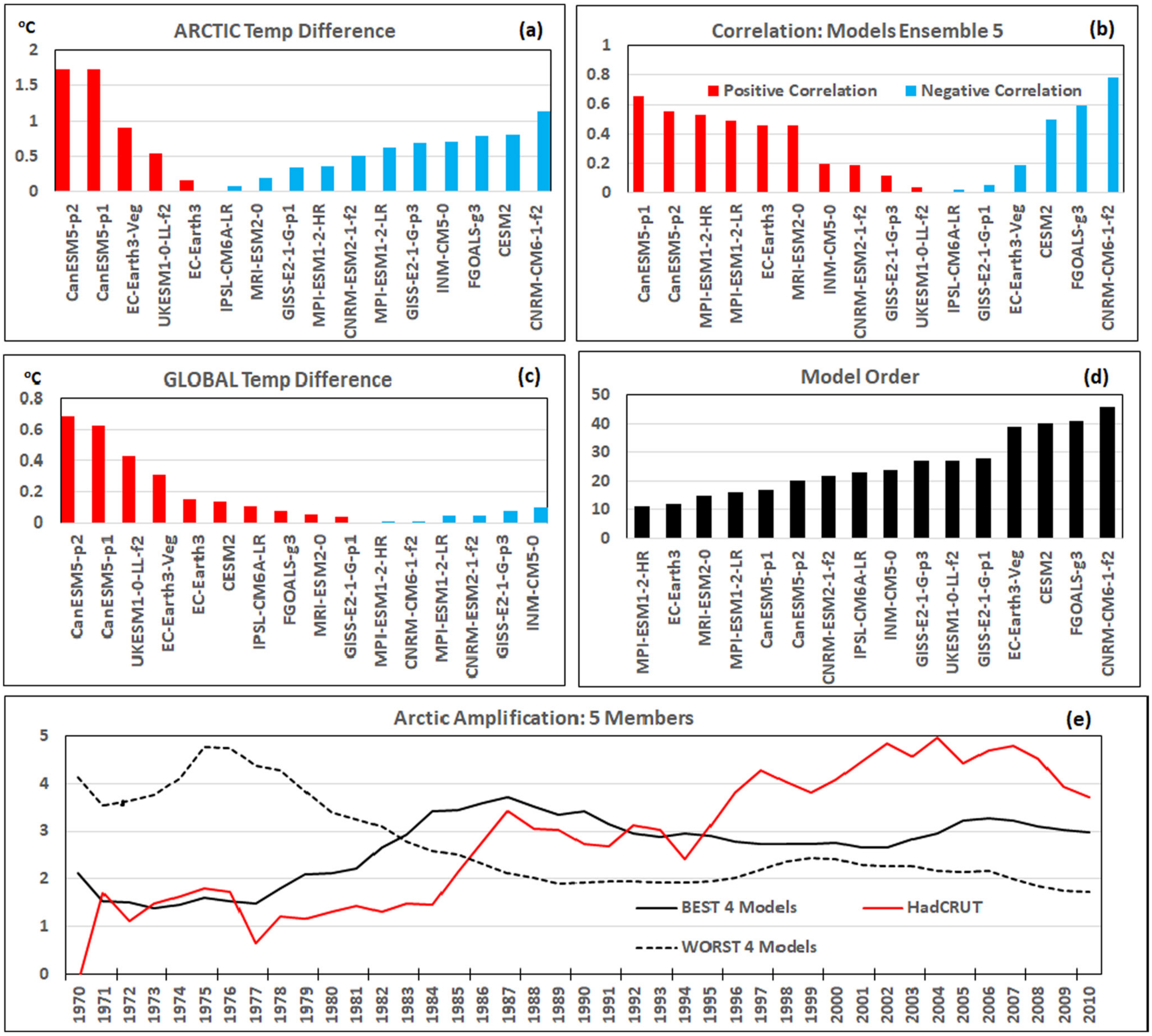

Figure 4. CMIP6 model simulations using the ensemble mean of the first five realizations of each model. (a)The Arctic temperature difference between the model simulated and observed warming between the mean of 2010–2020 and 1961–1990. The red columns are positive differences and the blue columns are negative differences. (b) The same for mean global temperature. (c) Correlation coefficient between the AA calculated using the model and the HadCRUT5 temperature data. (d) Models' order (skill measure) using the procedure described in the text. (e) The AA according to the HadCRUT5 data (red line), the average of Arctic Amplification (AA) of the four models with the lowest order number (the highest skill—the best four models) shown as a solid black line, the AA as an average of the four models with the highest order number (the worst skills—the worst four models) as a dotted gray line.

Canadian models (CanESM5-p1 and CanESM5-p2), which significantly overestimate both Arctic as well as global warming (Figures 4a and 4c).

Six models show a statistically significant correlation (Figure 4b) between observed and model produced AA. To account for both the correlation coefficient and the ability to reproduce the observed Arctic warming, we assign to each model the skill measure defined in Section 4.1. We arrange the models according to the assigned skill measure from the lowest to the highest (Figure 4d). The best four models include MPI-ESM1-2-HR, EC-EARTH3, MRI-ESM2-0, and MPI-ESM1-2-LR.

The AA calculated as the average of four best models is shown in Figure 4e. Its correlation coefficient with the HadCRUT5 AA is $r = 0.57$. These models reproduce the first AA step from 1970s to mid-1980s, although this is not as steep as it appears in the observed HadCRUT5 AA. We deduce that at least a part of this first AA increase is produced by an external forcing in these models. However, even these best models are not able to reproduce the second increase from 1990s to 2000s. We suggest that this second AA increase is due to internal climate variability. This is in agreement with a similar conclusion concerning the internal climate variability and the recent decline of Arctic sea ice (Ding et al., 2019).

To show the range of model AAs, the average AA of the four models with the worst skill measure (the highest order number) is also shown (Figure 4e). A decreasing value of the AA is a result of a significant underestimate of the Arctic warming. The worst models show no increase in the AA with time, and even the best models show no increase after the mid-1980s.

Our results do not depend significantly on the choice of a number of realizations (five in our case) for the Arctic and global mean temperatures. We have repeated the described procedure using three instead of five model realizations. In this case we have 26 CMIP6 models available. As shown in Figure S2 in Supporting Information S1, the best and the worst four models with just three realizations are the same models as those found in the case of five realizations, but not in the same order.

5. Summary and Discussion

We found that the observed AA index in the early decades of the 21st century reached values exceeding 4.0 (Figure 1), while during the last few decades of the twentieth century, its value was between 2.0 and 3.0. The observed AA has not increased since 1970 in a smooth way, but rather in two sharp increases around the years 1986 and 1999.

Since the largest change in Arctic temperature occurs in winter, it cannot be a direct albedo effect of regional aerosols, since solar radiation is much reduced or even absent in the Arctic in wintertime. Accordingly, the main radiative feedback is likely related to the down-welling longwave radiation. This suggests that the increased AA could be related to increased low-level cloudiness and increased water vapor. This may be a consequence of reduced summer and early fall sea-ice coverage resulting in a warmer ocean and increased evaporation, leading to higher low-level cloudiness in the following winter. Another cause may include an increase in heat transported into the Arctic by the atmosphere and ocean (Polyakov et al., 2017; Tsubouchi et al., 2020).

There seems to be no single cause for these relatively sudden increases, but the likely contributing causes include sea-ice and water-vapor feedbacks combined with changes in atmospheric and oceanic heat transport into the Arctic. Further research is needed to show to what extent atmospheric circulation changes forces Arctic temperature and AA. Are the Arctic temperatures and the related AA actually linked to atmospheric circulation variations that are mainly themselves forced by regional Arctic sea ice variations?

Although there has been a significant increase in the AA index during the past approximately 50 years, future climate changes are expected to lead to lower values of the AA index than those recently observed due to decreasing temperature gradients between the tropical and Arctic regions. In the meantime our key result is that the ensemble mean of the CMIP6 simulations does not reproduce the observed AA behavior. Even the best CMIP6 models capture only the first AA increase around 1986, while they miss the second sharp increase around 1999. We conjecture that the first increase was dominated by external forcing (e.g., increasing concentration of greenhouse gases), while the second AA increase around 1999 had a significant contribution from internal climate variability. This climate variability cannot be reproduced by present climate models in proper (observed) time.

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 & 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 = hadcrut5.

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