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Brief Report

Arctic Amplification in the Community Earth System Models (CESM1 and CESM2)

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Abstract: We compare the Arctic amplification (AA) produced by the two Community Earth System Models CESM1 and CESM2, members of the CEMIP5 (Coupled Models Intercomparison Project phase 5) and CEMIP6 collections, respectively. We find that the CESM1 model reproduces the recent high values of the AA deduced from the observed temperature much better than the CESM2. The correlation coefficient within the 1970–2012 time period between CESM1-simulated AA and the observed one is 0.47, while the CESM2 simulation leads to an anticorrelation of r = −0.53. Even the more successful model (CESM1) is not able to reproduce recent high AA values of 4–5. The main cause of this failure is the model's overestimate of the rate of increase in the mean global temperature in years post 1990. When the CESM1 model's simulated trend of the mean global temperature is replaced in the expression for the AA by the observed temperature trend, the correlation coefficient increases from 0.47 to 0.75. The CESM1 model is among the best north American models in AA simulation while the CESM2 model is among the least successful.

Keywords: Arctic amplification; Arctic climate; climate models; CESM1 and CESM2

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1. Introduction

The faster rise in Arctic near-surface air temperature compared to the global average is known as Arctic amplification [1–7]. The observed AA, defined as the ratio of the Arctic temperature trend to the global trend, had values between two and three during the last few decades of the 20th century. However, the AA has reached values over four during the first decades of the 21st century [8–10]. It has also become apparent [8,10] that the climate models within the CMIP6 (Coupled Model Intercomparison Project phase 6) collections do not reproduce the observed rise in AA. However, the reasons why models are not able to reproduce the recent high values of AA has not been explained. Although several causes of the changing AA have been suggested, it is not clear which may contribute most, or which may be most responsible for recent high AA values. The suggested possible causes of changing AA include decreasing Arctic Sea ice [11–16], changes in atmospheric and oceanic circulation [17–19], the Atlantic Multi-Decadal Oscillation and Pacific Decadal Oscillation [1,20,21], and increases in water vapor and cloudiness.

The goals of this communication are (1) to investigate how two versions of the National Center for Atmospheric Research (NCAR) climate model (CESM1 from the CMIP5 collection, and its updated version CESM2 from the CMIP6 collection) perform in reproducing the observed AA, and (2) to suggest a possible cause why models have difficulties in reproducing high AA values in the early 21st century. Although we concentrate first on the NCAR climate models, we extend our investigation to include all US and Canadian models involved in CMIP5 and CMIP6 model assemblies. Understanding the AA and variability of the Arctic and global climate is essential for the future forecast of sea levels and other possible global consequences of Arctic warming.

The sources of data are listed in Section 2, Section 3 presents the methodology, Section 4 describes the main results, and Section 5 contains the discussion and conclusions.

2. Data

All the data we used are publicly available. They include the observed global and Arctic temperature anomaly, as well as the anomaly projected by the considered CMIP6 and CMIP5 climate models. There are several datasets of global and Arctic temperature. They include the temperature anomaly produced by the UK Met Office in collaboration with the University of East Anglia, known as the HadCRUT dataset, the NASA GISS set that provides two temperature datasets distinguished by the radius of homogenization (250 km or 1200 km), the dataset produced by the NOAA Centers for Environmental Information, and the HadCRUT temperature dataset complemented by Cowtan and Way [22]. All of these datasets lead to a very similar AA within the 1970–2022 times period [8]. The HadCRUT5.0 and NASA GISS 1200 km datasets are very close to each other, as well as close to the average of all four considered datasets. Thus, we considere it justified to use the HadCRUT5.0 temperature anomaly as representing the observed temperature anomalies of the global and Arctic near-surface air temperature. The simulated temperature anomaly data for all models were downloaded from the KNMI Climate Explorer website (https://climexp.knmi.nl/start.cgi), accessed 6 November 2022, and the observed HadCRUT5.0 data were downloaded from the UK Met Office website at https://www.metoffice.gov.uk/hadobs/hadcrut5, accessed 1 November 2022. Within the CMIP6 collection, the SSP2-45 scenario was used, whereas the Representative Concentration Pathways 45 (RCP45) was used for CMIP5. We used only the models with five or more runs of the considered scenarios. To weight each model equally, for models with more than five runs, we considered only the first five runs.

The CESM models [23] are state-of-the-art fully coupled models composed of atmosphere, ocean, and sea ice model components. The final version of CESM1 has been available since 2010, whereas the modified version, CESM2, has been available since 2018 to simulate the present, past, and future climate. The atmospheric component of the model underwent a major modification from CESM1 to CESM2.

3. Methods

We were interested in comparing the AA deduced from the observed temperature data with the AA deduced from the models' simulations. We defined the AA as the ratio of 21 year running trends of the Arctic temperature to the trend of global temperature [8]. The Arctic was defined as the Earth's surface north of latitude 65° N. All temperature anomaly data were taken relative to the 1961–1990 mean. While the temperature anomaly depended on the mean with respect to which the temperature anomaly was taken, the trends and the AA were independent of that choice. In the figures, the temperature trends and the AA are plotted with respect to the center of the used 21 year interval. Thus, for example, the AA composed of the trends from 2000–2020 are plotted at the value of the center of this interval, i.e., the year 2010.

4. Results

4.1. Community Earth System Models CESM1 and CESM2

We wished to compare the models' simulated AA with each other and with the AA derived from the observed temperatures within a time period of accelerated global warming. The global mean temperature anomalies with respect to the 1961–1990 mean, determined from the observed HadCRUT5.0 temperature data and from the CESM1 and CSEM2 [23–25] simulated temperatures, are shown in Figure 1a. Although there were considerable differences in the early part of temperature record, our main interest was in the time period post 1960. After 1990, the slope of the CESM2 simulated temperature anomaly was considerably steeper than that of the CESM1 simulation, as well as that of the observed temperature. This led to a higher CESM2 simulated temperature, especially during the early years of the 21st century.

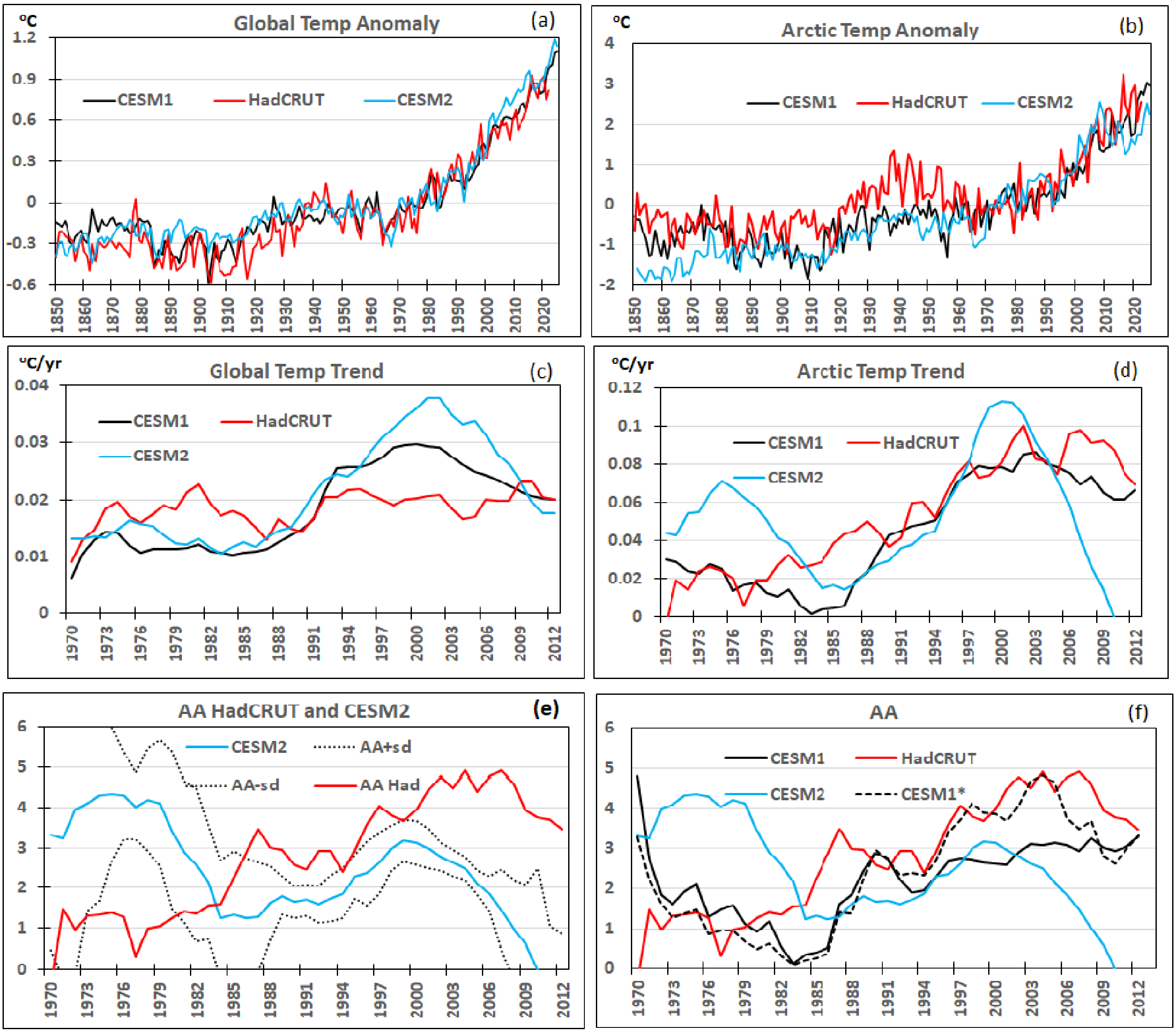

Figure 1. (**a**) Global temperature anomalies according to the HadCRUT observational data (red line), simulated by the NCAR CESM1 model (black line) and by the CESM2 model (blue line). Note the significant CESM2 overestimate in the early decade of the 21st century. (**b**) The same for the Arctic (65-90 N) temperature anomaly. (**c**) The 21 year running trends of the HadCRUT, CESM1, and CESM2 global mean temperature anomalies. (**d**) The 21 year running trends of the HadCRUT, CESM1, and CESM2 Arctic temperature anomalies. (**e**) The HadCRUT AA (red color) and the CESM2 AA (blue color) together with the CESM2, together with one standard deviation of uncertainty. (**f**) The Arctic amplification deduced from the HadCRUT (red line), CESM1 (black line), and CESM2 (blue line). The black dashed line (CESM1*) is the apparent AA when the CESM1 global temperature trend (black line in panel **c**) is replaced by the observed (HadCRUT) temperature trend (red line in panel **c**).

The Arctic temperature (Figure 1b) again showed considerable discrepancies in early years between the CESM1 and CESM2 simulations and the HadCRUT5.0 observed temperature anomaly. It is apparent that the CESM1 simulations were closer to the observed temperatures than the CESM2 simulations in both the global and the Arctic temperature anomalies (Figure 1a,b).

The trend of the observed global mean temperature in the time period post 1970 was less variable than the models' simulations (Figure 1c). The standard deviations of the HadCRUT, CESM1, and CESM2 global temperature trends were 0.0030, 0.0073, and 0.0088, respectively. The maximum difference during the time period post 1990 between the simulated and observed mean global temperature trend was around 85% in the case of CESM2, whereas it was close to 50% for CESM1. In the Arctic, in the period post 1990, there was quite good agreement between the Arctic temperature trend and the CESM1 simulation (Figure 1d), while the CESM2 temperature simulation overestimated the observations during the early 2000, followed by a large underestimate after the year 2005. The resulting Arctic amplification deduced from observed and CESM2 simulated temperature anomalies are shown in Figure 1e, together with one standard deviation of uncertainty. The CESM2 uncertainty was estimated from the five models' individual realizations. Whenever the trend of global temperature reached zero, the AA became very large and ill-defined (infinite). This happened in one of the five CESM2 realizations. Three years (1983–1985) of AA simulated with this one realization were deleted to remove the very large AA values.

The HadCRUT5.0 AA showed two steep steps around 1986 and 1999, as previously reported [8], with a change in AA from around one in the 1970s to almost five during the first decade of the 21st century. The CESM2 result showed no resemblance to the AA deduced from the observed temperature data. The correlation coefficient between the observed and CESM2 simulated AA was negative ($r = -0.53$). Although the results for the earlier version of the Community Climate System Model, CCSM4, are not shown, they were similar to those of the CESM2 model.

The CESM1 simulation agreed much better with the observed AA than the CESM2 simulation (Figure 1f). The CESM1 correlation coefficient with the observed AA was $r = 0.47$. The main deviation from the observed AA was a significantly lower AA around the year 1985 and again within the 1990–2012 time period compared to the observed AA. The first underestimate of AA (1980–1990) was due to an underestimate of the Arctic temperature trend, which reached close to zero near the middle 1980s. The second underestimate in the period post 1990 was not due to an underestimate of the Arctic trend, but to an overestimate of the trend of global warming after 1990 (Figure 1c). To support this statement that the overestimate of the global warming was the cause of the model's underestimate of the AA, we show the "modified" AA (denoted as CESM1* in Figure 1f), where the modeled CESM1-simulated global warming trend was replaced by the observed trend. Subsequently, the underestimate of AA during the years post 1990 was eliminated (dotted curve in Figure 1f), and the correlation coefficient increased from $r = 0.47$ to $r = 0.75$.

The difference between the AA simulated by the CESM2 and CESM1 is surprising, since the CESM2 is generally considered to be an improved version of the CESM1 model that should provide a better simulation [23,24]. The disagreement between the CESM2-simulated AA, the CESM1-simulated AA, and that deduced from the observed temperature was caused by a too high global warming after 1990 and a too high climate sensitivity of the CESM2 model [25]. This resulted in a higher CESM2-simulated global temperature trend compared to CESM1 and to the observed global temperature. The climate sensitivity of the CESM2 model is listed at 5.15 K [24], which is outside the estimated most likely climate sensitivity of CMIP6 models of 1.5–4.5 K. The climate sensitivity of CESM2 is about 1.5 K higher than that of CESM1 [25]. A recent independent analysis [26] placed the climate sensitivity between 1.55 and 3.20 K (5–95% range) with a median value of 2.16 K. The high climate sensitivity of CESM2 is also not supported by paleoclimate data [27].

The models' overestimation of mean global temperature had two major sources, namely, the prescribed climate forcing and the feedbacks [23,24]. Anthropogenic forcing due to greenhouse gases is prescribed in both models; however, the forcing due to natural, anthropogenic, and volcanic aerosols is modeled differently in the individual models. In the models, the aerosols affect climate sensitivity mainly through the microstructure and lifetime of the simulated clouds.

4.2. Other US and Canadian Models

There are other models designed by climate research centers in the US and Canada. The correlation coefficients within the 1970–2012 time period between the AA produced by a given model and the AA derived from the observed temperature data (HadCRUT5) are shown in Figure 2a. A significant positive correlation, in addition to that obtained from CESM1, was produced only by the Canadian model CanESM5. However, the CanESM5 model significantly overestimated both the global and the Arctic temperature anomalies within the 1970–2022 time period (Figure 2b,c). This should disqualify the CanESM5 model from being used for study of the Arctic climate change in both the past and the future. The third model with a non-negligible positive correlation was the GFDL ESM4 (Figure 2a). Although its correlation coefficient (r = 0.40) was lower than those of NCAR CESM1 and CanESM5 (r = 0.47), its global and Arctic 1970–2022 warming was not far from the observed values. We also note that the CMIP6 ensemble mean of all models led to a relatively high correlation coefficient of around 0.5 with the AA deduced using the observed HadCRUT data.

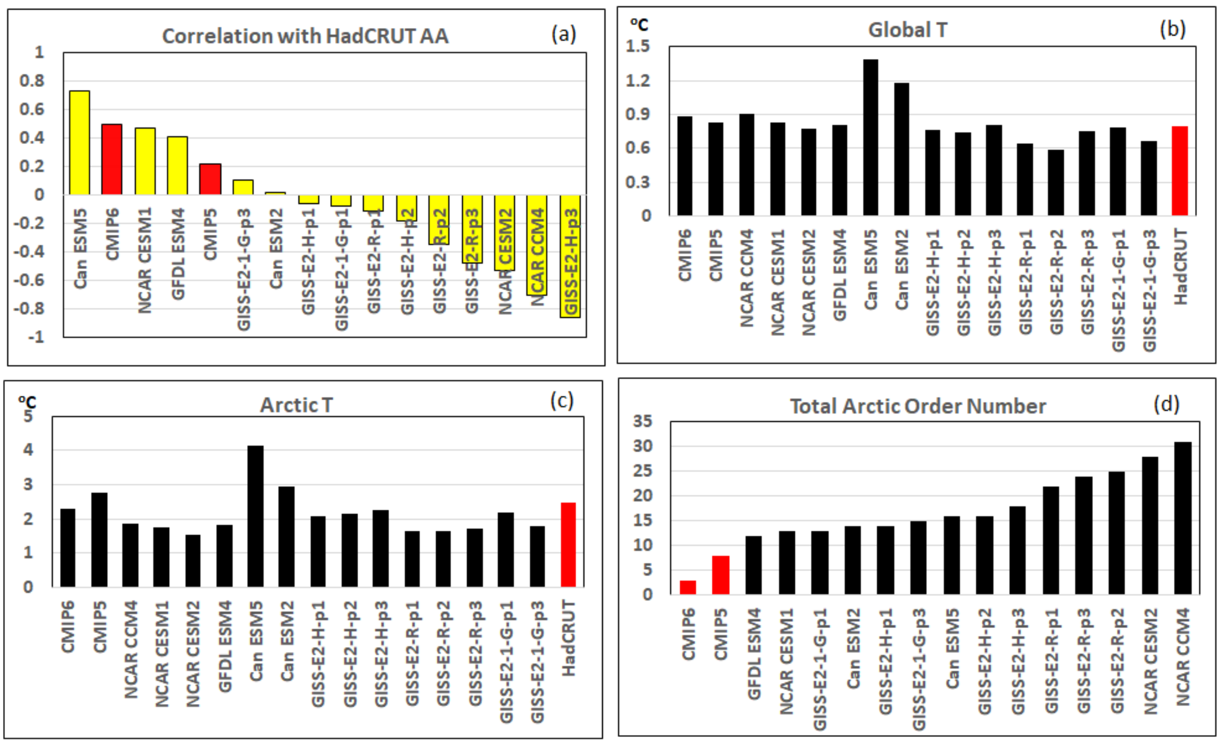

Figure 2. (**a**) Correlation coefficients between the Arctic amplifications deduced from the temperature anomalies simulated by the 14 North American CMIP6 climate models (yellow color) and the AA deduced from the observed (HadCRUT) temperature anomalies. The correlation coefficients are also shown for the ensemble mean temperatures of CMIP6 and CMIP5 models (red color). (**b**) Global warming between decades 1970–1980 and 2010–2020 by individual models (black color), CMIP6 and CMIP5 ensemble means, and the HadCRUT data (red colomn). (**c**) The same for the Arctic warming. (**d**) The total order number (defined in the text) of the 14 considered models (black color) and the CMIP6 and CMIP5 ensemble means (red color).

Figure 2 summarizes the results of our analysis. The models were arranged in the order of decreasing correlation coefficient and assigned a correlation order number. Subsequently, the models were rearranged in terms of the absolute difference between Arctic 1970–2022 warming produced by the model and the observed warming, and then assigned an Arctic warming order number. Lastly, the two order numbers were added to obtain the total order number as shown in Figure 2d.

Concerning the development of models within the same research center, we can note that the NCAR CESM1 (member of the CMIP5 collection) occupied first place among the considered 14 North American models, while the CCSM4 from CMIP5 and the CESM2, a member of the CMIP6 collection, were models with the highest total order number (Figure 2d). The AA shape of the CESM2 was quite close to that of the CCM4 (not shown), while the CMIP5 CESM1 model was, at least in the Arctic region, far more successful. This suggests that the CMIP6 models may, in general, be different from, but not necessarily better than, their CMIP5 predecessors. The modeling improvements between CMIP5 and CMIP6 may lead to improvement of some climate characteristics, while producing worse results in others. Although the CESM1 model is better than CESM2 as far as the AA simulation is concerned, the ensemble mean of all CMIP6 models produces an AA closer to the observed AA than the ensemble mean of all CMIP5 models (Figure 2).

Although the CanESM5 improved the correlation with the observed AA compared to CanESM2 (Figure 2a), it also increased model overestimates of global and Arctic warming. The NASSA GISS models (CMIP5 and CMIP6) showed good agreements with the observed global and Arctic warming during 1970–2022 (Figure 2b,c); however, they showed no significant correlation with the AA derived from the observed temperatures (Figure 2a).

5. Discussion and Conclusions

Climate change in the Arctic affects the sea level, as well as the global climate. The advantage of comparing the AA instead of temperature anomalies is that the AA as a ratio of the Arctic to global warming trends does not depend on the time period selected for normalization of anomalies. Thus, the dispute as to whether the temperature records should be normalized to the same values within the 1850–1880 or 1961–1990 time periods is avoided.

Comparing the AA simulations by the NCAR CESM1 and CESM2 climate models (Figure 1f), we found that the CESM1 model provides an AA that is much closer to the AA obtained from the observed (HadCRUT5.0) temperature data. Thus, the earlier version of the model within the CMIP5 collection is far superior to its latest version included in the CMIP6, as far as AA is concerned. Evidently, the later version of the CESM model, at least in some climate indicators, may be considerably worse than the earlier version. We believe that this is important information to make note of, the recognition of which might help model developers improve their future model modifications.

In spite of a positive correlation between the CESM1 simulation and the observed temperature, the model still could not reproduce the high observed AA values during the early years of the 21st century. Although one may naïvely expect this to be due to the model's underestimate of the Arctic warming trend, this turned out not to be the case (Figure 1d). The reason for the large AA underestimate in the early years of the 21st century was the model's overestimate of the global warming rate after 1990 (Figure 1c) by both CESM2 and CESM1. This overestimate of the global warming trend in the CESM1 simulation reached a maximum value close to 50%, while the overestimate by CESM2 was even more serious, reaching up to 85% (Figure 1c). The fact that many of the CMIP6 models overestimate the global warming trend is well known [28]. A suggested main reason is stronger feedbacks, especially cloud feedback. A recent publication [29] suggested that only CMIP6 models with the Equilibrium Climate Sensitivity (ECS) below 4.0 should be used, especially for regional studies. The CESM2 model's ECS is 5.15.

Comparing all the models produced by the four leading climate research centers of the US and Canada, we found that the NCAR CESM1 model provides the most accurate Arctic warming rate and AA compared to the AA derived from the observed temperature data. The other two NCAR models, the CCSM4 (CMIP5) and CESM2 (CMIP6), are on the opposite end of the scale.

Future overestimates of the global mean temperature trend can be avoided if modelers tune not only the global mean temperature to the historic one, but also the mean global temperature trend to that of the observed mean global temperature.

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