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Brief Report

Why Does the Ensemble Mean of CMIP6 Models Simulate Arctic Temperature More Accurately Than Global Temperature?

Petr Chylek [1,*], Chris K. Folland [2,3,4], James D. Klett [5], Muyin Wang [6,7], Glen Lesins [8] and Manvendra K. Dubey [1]

1 Los Alamos National Laboratory, Earth and Environmental Sciences, Los Alamos, NM 87545, USA
2 School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
3 Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden
4 Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, QLD 4350, Australia
5 PAR Associates, Las Cruces, NM 87545, USA
6 Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, WA 98105, USA
7 Pacific Marine Environmental Laboratory, Seattle, WA 98105, USA
8 Department of Physics and Atmospheric Science, Dalhousie University, Halifax, NS B3H 4J5, Canada
* Correspondence: chylek@lanl.gov

Abstract: An accurate simulation and projection of future warming are needed for a proper policy response to expected climate change. We examine the simulations of the mean global and Arctic surface air temperatures by the CMIP6 (Climate Models Intercomparison Project phase 6) climate models. Most models overestimate the observed mean global warming. Only seven out of 19 models considered simulate global warming that is within ±15% of the observed warming between the average of the 2014–2023 and 1961–1990 reference period. Ten models overestimate global warming by more than 15% and only one of the models underestimates it by more than 15%. Arctic warming is simulated by the CMIP6 climate models much better than the mean global warming. The reason is an equal spread of over and underestimates of Arctic warming by the models, while most of the models overestimate the mean global warming. Eight models are within ±15% of the observed Arctic warming. Only three models are accurate within ±15% for both mean global and Arctic temperature simulations.

Keywords: Arctic; global warming; climate CMIP6 models; selection of models

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1. Introduction

Each year, we have more data available to test simulations provided by the ensemble of climate models. Climate models are used to project future climate to inform society and the government about likely future climate changes. The climate system is complicated, composed of the atmosphere, ocean, land, and cryosphere with hundreds of individual processes on many spatial and temporal scales, from single cloud droplets to ocean currents. Such a system cannot be modeled exactly.

In the Arctic, the warming is faster than the global average. In addition to the temperature rising, presumably due to the increasing concentration of atmospheric greenhouse gases, the Arctic temperature shows a significant multidecadal variability [1–4]. Some of this variability can be attributed to internal climate variability and some to the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation [5–8].

Early climate models [9] neglected many small-scale processes, while the latest models include some of these [10]. However, with each new process included in a model, the model uncertainty also increases, and the range of the models' results increases. Thus, while the latest models include a greater number of considered processes, the range of projections by individual models has also increased.

The most basic variable representing climate change is the mean global near-surface air temperature. The Arctic is of special interest, since here, the warming is larger than the global mean. And, the melting of the Greenland ice sheet could contribute to rising sea levels. The Arctic Amplification [11–15] reached its peak values in the early decades of the 21st century [16,17].

Climate modeling is carried out under the coordination of the World Climate Research Program. Several directed climate-change studies and their projections were organized under the Coupled Models Intercomparison Projects (CMIPs). The three most recent model intercomparisons are CMIP3 [18,19], CMIP5 [20,21], and CMIP6 [22,23].

Some reports have been concerned about the suitability of the CMIP6 models to reproduce the observed climate. A publication authored by a large group of modelers and other climate scientists [24] warned against using the ensemble mean of all CMIP6 models in climate-change studies since some of the models run clearly "too hot". On the other hand, another report [25] found that the CMIP6 projection of recent warming has been slightly conservative.

In this report, we investigate the capabilities of models to reproduce both mean global and Arctic temperatures and how this capability has changed over time from CMIP3 to CMIP6. For the mean global temperature, we find that the ensemble means of CMIP3 and CMIP5 simulations are closer to the observations than the ensemble mean of the CMIP6 models. Uninformed use of CMIP6 simulations and projections may, therefore, lead to exaggerated results that might create more doubt than necessary about our capability to avert an undesirable climate change.

2. Data and Methodology

Model simulations are publicly available on several websites. We use the KNMI Climate Explorer data at the website https://climexp.knmi.nl/start.cgi (accessed on 16 January 2024) to download the models' results for the CMIP3, CMIP5, and CMIP6 projects. We use the historical simulation combined with the projections using the "middle-of-the-road" forcing scenarios. These are the SRES A1B, RCP4.5, and SSP2-4.5 scenarios for CMIP3, CMIP5, and CMIP6, respectively. These scenario acronyms refer respectively to special report in emission scenarios [26], representative concentration pathways [27], and shared socioeconomic pathways [28]. Although the RCP 60 has been designated by some as being most similar to A1B, only a few models use RCP 60. The RCP 45 is next in similarity to the A1B, and most of the models have several runs for the RCP 45 scenario. Thus, we, as do many other authors, consider RCP 45 to be suitable for comparison to A1B. It is acknowledged that no exact comparison between the CMIP3 and higher-order CMIP models is possible.

For the analysis of simulations by individual CMIP6 models, we consider all models that have three or more SSP2-4.5 scenario runs within their ensemble collection. These simulations use the historical climate up to the year 2014 and the SSP2-4.5 scenario afterward. To treat all CMIP6 models in the same way, we use the first three simulations of each model and calculate their average.

For this study, we assume the observed temperature record given by the UK Met Office HadCRUT5.0 filled in data available at the website https://www.metoffice.gov.uk/hadobs/hadcrut5/ (accessed on 16 January 2024). The HadCRUT5.0 temperature data are calculated from the monthly average near-surface temperature relative to the 1961–1990 mean on a $5^\circ \times 5^\circ$ lat/lon grid [29].

The Arctic region is considered to be the Earth (land and ocean) north of the latitude of 65° N. Most research papers set the southern border of the Arctic between 60 and 70° N. In this report, we consider the Arctic an area north of latitude 65° N. This is in the middle of the commonly used range, and it is in agreement with our earlier publications [16,30]. It contains the land and ocean that is covered by ice for a part of the year. As a quantitative measure of the skill of the simulations, we compare the average of the Arctic or global temperature in the 2014–2023 period with respect to the average of the reference period 1961–1990. The World Meteorological Organization (WMO) recommends 30 years to define the average climate. Following WMO recommendations [31,32], 1961–1990 is used as the reference period for observing long-term climate development. We also separated models with simulated warming within ±15% of the observed Arctic or global warming. The only reason for selecting the 15% accuracy is that we considered 10% to be too restrictive and 20% to be too wide.

Our previous study [16,30] has shown that the trend period selected should be between 17 and 35 years, since for a shorter window, the Arctic Amplification becomes unstable due to the trends passing through zero. For trends longer than 35 years, the interesting trend variability is being averaged out. To be consistent with our previous studies, we used 21 years for the temperature trend.

3. Results

3.1. Ensemble Means of CMIP3, CMIP5, and CMIP6

Considering the ensemble means of all CMIP3, CMIP5, and CMIP6 simulations of the Arctic temperature anomaly, we find that the CMIP3 simulation underestimates the observed temperature during the first two decades of the 21st century (Figure 1a). The underestimate is smaller with the ensemble mean of the CMIP5 models, and the underestimate is changed to overestimate with the CMIP6 models. The average underestimate of Arctic warming in the 2014–2023 decade with respect to the 1961–1990 mean is 0.59 °C by the mean of CMIP3 models and 0.18 °C by CMIP5. The CMIP6 models lead to an overestimate of 0.15 °C. Thus, in the Arctic, the progression from earlier to later models improves the models' ability to reproduce the observations. Although the models cannot reproduce well the Arctic warming in the early years of the past century and the following cooling up to the 1970s, which might be due to natural variability, the CMIP6 ensemble mean is still generally closer to the observed temperature change than the earlier CMIPs.

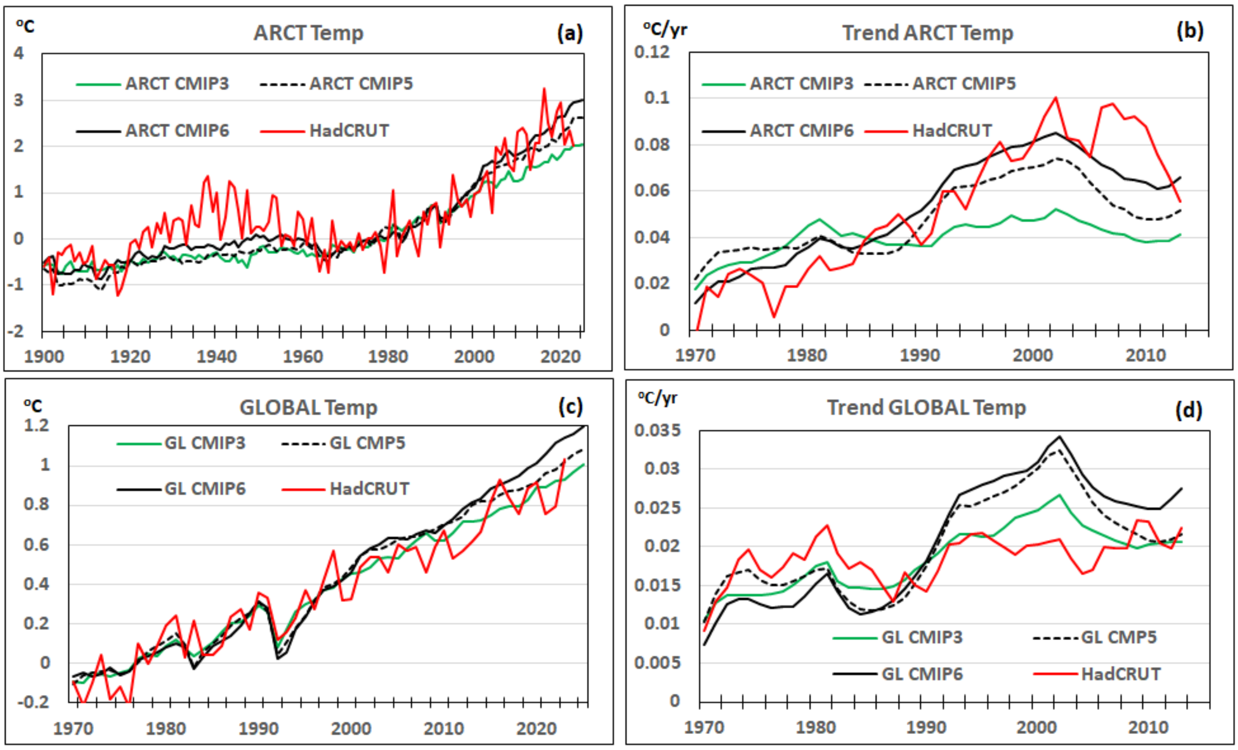

Figure 1. (**a**) The observed Arctic temperature anomaly (red line) together with the ensemble means of the CMIP3 models (green line), CMIP5 models (black dash line), and CMIP6 models (solid black line). (**b**) The 21-year centered trends of the Arctic observed temperature, updates yearly (red), CMIP3 mean simulation (green), CMIP5 mean simulation (dashed black), and CMP6 (solid black). (**c**) The same as in panel a but for global mean temperature anomaly. (**d**) The same as panel b but for global mean temperature trends.

However, for the mean global temperature anomaly (Figure 1c), the situation is just the opposite. The CMIP3 ensemble mean is the closest to the observed mean global temperature, while the CMIP6 simulation shows a large global warming overestimate since the 2000s [30]. The average underestimate of global warming in the 2014–2023 decade with respect to the 1961–1990 mean is 0.01 °C by the mean of the CMIP3 models, while the CMIP5 and CMIP6 models lead to an overestimate of global warming by 0.06 °C and 0.14 °C, respectively.

The differences between the annual mean Arctic and global temperature in CMIP simulations are also observed in the annual mean temperature trends. For the Arctic temperature trend (Figure 1b), successive CMIP simulations are generally closer to the trend derived from the observed data. For the mean global temperature (Figure 1d), by contrast, successive CMIP simulations are generally farther away from the observed trend. However, the differences between the CMIP5 and CMP6 temperature trends are not statistically significant.

To quantify each set of CMIP temperature overestimates or underestimates, we calculated their 2014–2023 average temperature and its differences from the observed 1961–1990 average. In the Arctic, successive CMIP sets approach the observed one, while in the case of the mean global temperature, the differences grow with later sets of CMIP simulations.

3.2. Simulations by Individual CMIP6 Models

For each of the 19 CMIP6 models with at least three SSP2-4.5 scenario runs, we first calculate the average of the first three simulations. After that, we calculate the warming between the decadal average of 2014–2023 and the 1961–1990 reference period. The results for the Arctic temperature are shown in Figure 2a and for the mean global temperature in Figure 2b. In the following, we consider models with simulated temperatures to be within ±15% of the observed temperature.

The average Arctic warming of the considered 19 CMIP6 models is 2.55 °C, while the observed warming, HadCRUT5.0, is 2.42 °C. This is a relatively small overestimate of 5%. However, the range of Arctic warming suggested by the models is large (Figure 2a), from 1.41 °C (CNRM-ESM2) to 4.50 °C (CanESM5). Thus, a relatively good agreement of the ensemble mean between the CMIP6 simulated and observed average Arctic temperature is arguably a cancellation among each individual members rather than the result of proper consideration of physical processes by individual models.

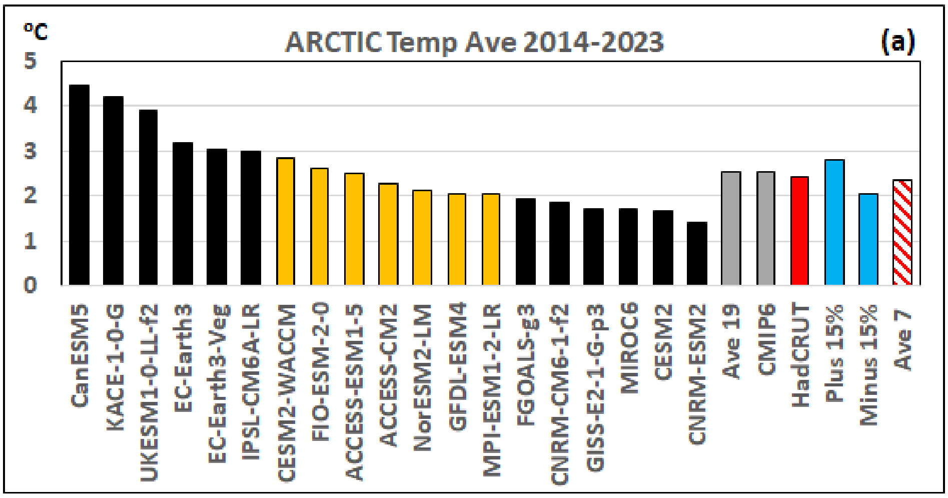

Figure 2. *Cont.*

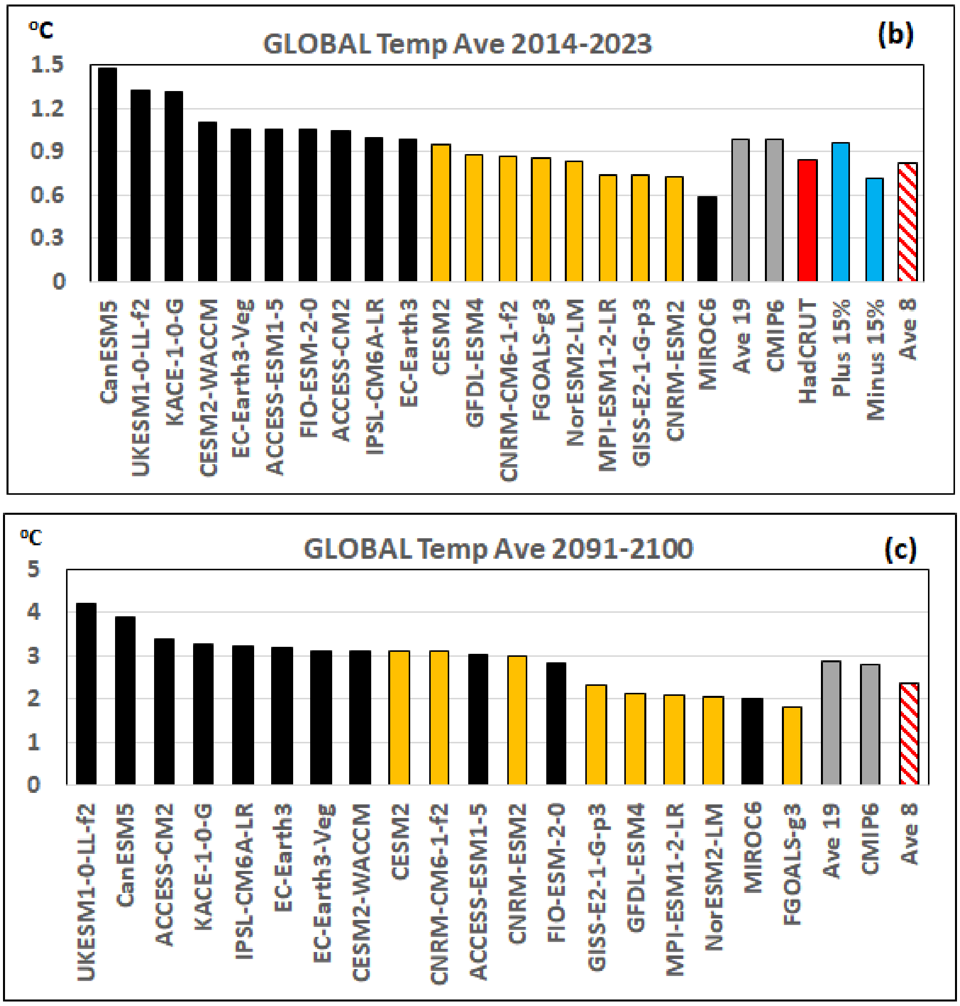

Figure 2. (**a**) The Arctic warming between the average of the years 2014–2023 and the mean of 1961–1990 simulated by the 19 CMIP6 models (black and yellow columns). The CMIP6 mean and the mean of the considered 19 models are in gray columns, and the observed HadCRUT5.0 warming is in the red column. The range of ±15% from the observed temperature is shown in blue columns. The seven CMIP6 models with the simulated 2014–2023 mean Arctic warming within ±15% of the observed value are shown in yellow columns. The average warming by these selected models is in the red-striped column. (**b**) The same for the mean global warming. (**c**) Projection of the 2091–2100 average mean global temperature with respect to the 1961–1990 mean by the 19 considered CMIP6 models.

The mean global warming of the 19 CMIP6 models is 0.97 °C compared to the observed warming of 0.84 °C. This is an overestimate of about 15%. The range of 19 considered models is from 0.58 °C (MIROC6) to 1.48 °C (CanESM5).

Thus, the Arctic warming, as simulated by the mean of CMIP6 models, is more accurate than the mean global warming. This is, however, due to the cancellation of overestimation and underestimation by individual models of the Arctic, which does not occur in the simulated global mean temperature case.

The average of all CMIP6 models is not suitable for simulating the mean global temperature. This has been recently acknowledged by a large group of climate modelers and other climate researchers [24]. Despite this, some researchers used the CMIP6 ensemble mean to simulate the mean global temperature [25] and to make an assessment of future climate changes. A number of these publications report warming and other climate-related effects “higher than we thought”. This indicates an unwise use of the CMIP6 models with likely overly pessimistic results.

Using the results shown in Figure 2, we can make a selection of more accurate CMIP6 models suitable for the future projection of the Arctic and mean global temperature. If we limit our consideration to models that can simulate the annual mean temperature anomalies within ±15% of the observed value, we have seven models for the Arctic and eight models for the global mean temperature. This is still a reasonable number of models to capture realistic future projections. These models are denoted in Figure 2a,b by yellow columns. We note that a different set of models is within ±15% of the observed warming for the Arctic compared to the mean global temperature. Thus, for studying climate change, for each variable of interest and each separate region of Earth, it may be necessary to choose a different set of models. Different model sets are more accurate for different variables in different regions of the globe [33,34].

The selection of the seven CMIP6 models for the Arctic (Figure 2a) leads to Arctic warming between the decade of 2014–2023 and the 1961–1990 reference of 2.34 °C, compared to the observed warming of 2.42 °C. For mean global warming, with the selection of the eight models (Figure 2b), we get an average of the CMIP6 simulations of 0.81 °C compared to the HadCRUT5.0 suggested warming of 0.84 °C.

Our selection of the seven models that simulate the 2014–2023 average of the Arctic temperature and eight models for the mean global temperature both within ±15% is just an example of how suitable models can be identified. Using the data presented in Figure 2, and similar calculations for other variables and other regions, users can make their own selection of models for the best agreement with the requirements of the investigated topic.

3.3. Projection of the Warming up to 2100

The projection of mean global warming relative to the 1961–1990 average by the 19 selected CMIP6 models up to the year 2100 is shown in Figure 3. Each model's projections are shown in thin colored lines. The range of projected warming by individual CMIP6 models in the year 2100 is broad, varying from 1.8 °C to 4.3 °C. Such an uncertainty is likely too wide to be useful. The average of the 19 models (the thick brown line) is about 2.96 °C in the year 2100. The ensemble mean of all the CMIP6 models (not shown) is similar at 2.88 °C.

If we accept the criterion that we use only the models that are within ±15% of the observed average 2014–2023 warming, we have the eight models shown in Figure 2b. Using the average of these eight models, we have a 2100 projected warming of 2.41 °C. Thus, the 19 selected models, or the mean of all the CMIP6 models, overestimate the projected 2100 mean global warming by about 0.5 °C or by 23% compared to the eight more accurate models. This is a result of using the moderate SSP2-4.5 scenario. The overestimate in temperature is even larger, 0.92 °C, with the SSP5-8.5 scenario (not shown) used in some research reports studying the consequences of future increases in atmospheric greenhouse gases.

The projected Arctic warming up to the year 2100 is seen in Figure 4. The range of projections by the 19 selected CMIP6 models spans over 9 °C from about 4 °C (NorESM2-LM) to 13 °C (UKESM1-0-LL-f2). The ensemble mean of these models in 2100 is an Arctic warming of 7.4 °C relative to the reference of the 1961–1990 average. If we use only the seven models identified within ±15% of the observed Arctic warming in 2023 (Figure 2a), we have a slightly reduced warming of 6.6 °C. The difference between these projected warmings is only about 12%, which is about half of the 23% difference found for the mean global temperature. The models have considerable uncertainty in simulated temperature, even in the case of current warming. Therefore, the projection to 2100 has to be considered highly uncertain, considering the large range of projected temperature by individual models plus the uncertainty in the emission scenarios.

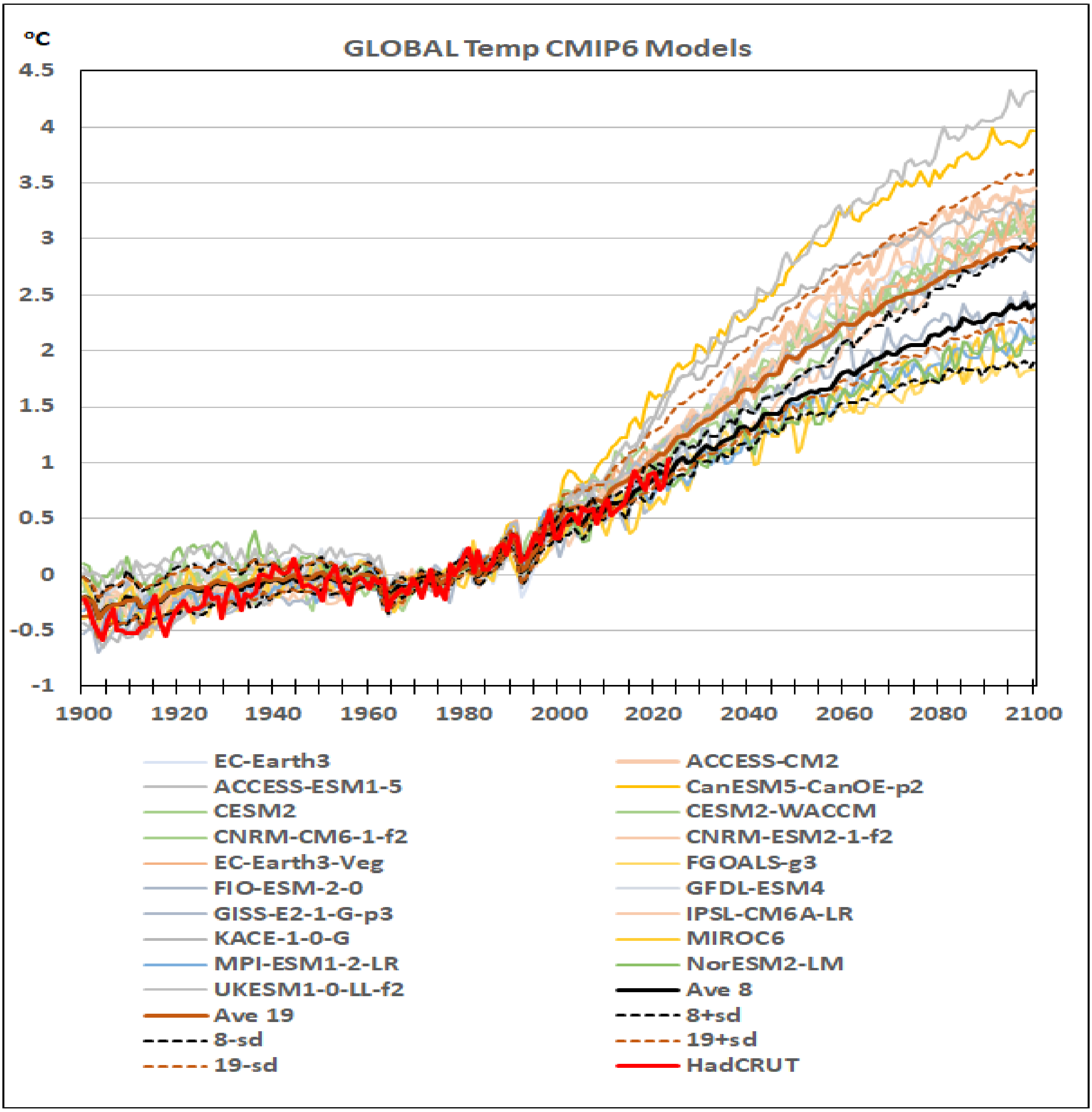

Figure 3. The projection of the mean global temperature up to the year 2100 by the 19 individual CMIP6 models (thin color lines). The average warming of the considered 19 models is shown as thick brown lines. The average of eight models identified within ±15% of the observed warming is shown as a black line. The dashed lines are boundaries of ±one standard deviation from the mean. The observed warming (HadCRUT5.0) up to 2023 is shown as a red line.

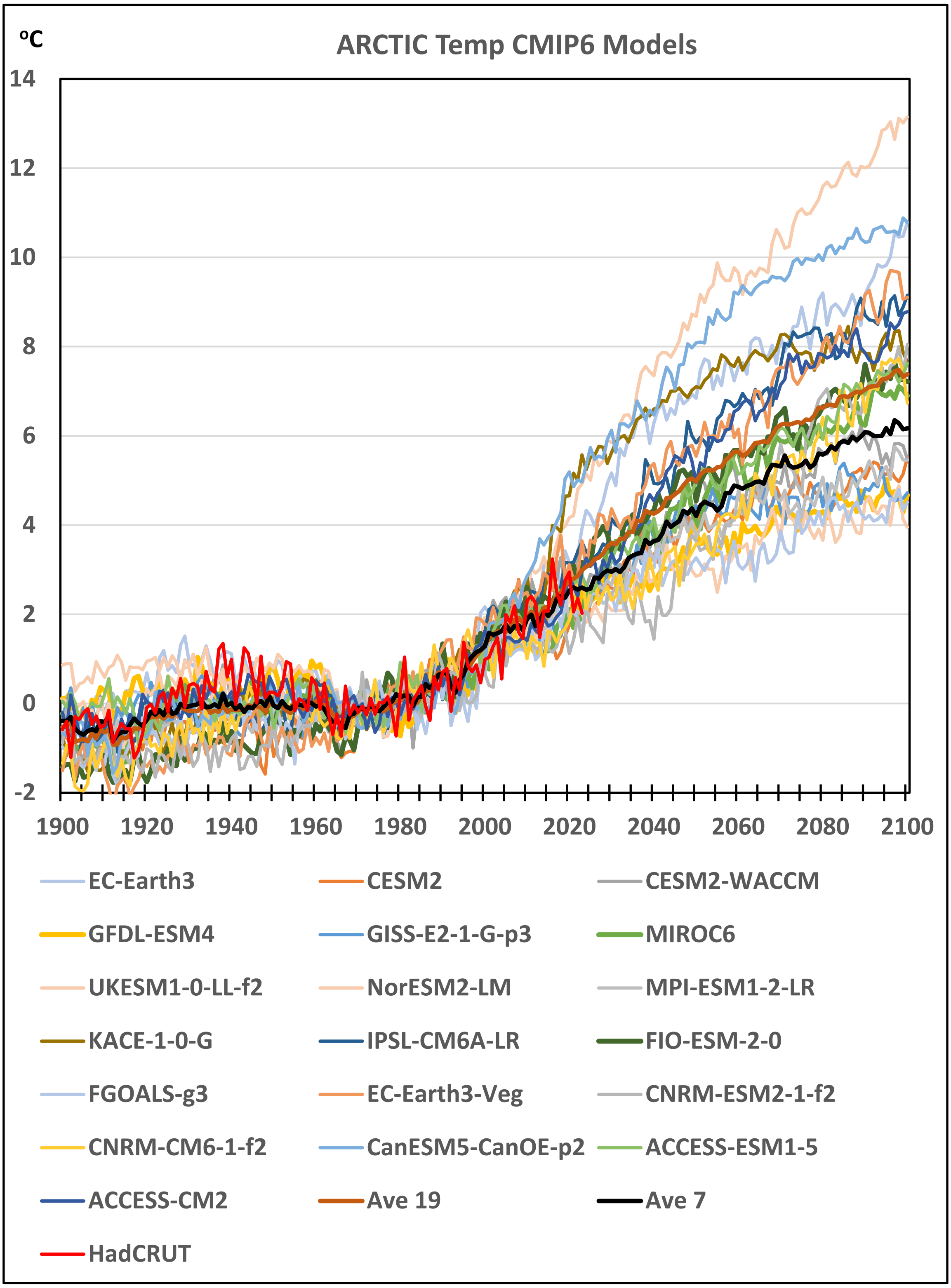

Figure 4. The projection of the Arctic temperature up to the year 2100 by the 19 CMIP6 models. The average warming of the considered models is shown as thick brown lines. The average of seven models identified within ±15% of the observed warming (Figure 2a) is shown as a black line. The observed warming (HadCRUT5.0) up to 2023 is shown as a red line.

4. Summary and Conclusions

The mean global temperature as simulated by the 19 considered CMIP6 climate models shows 10 models (Figure 2b) that simulate the warming between the average for 2014–2023 and 1961–1990, which is more than 15% higher than the observed warming. On the other hand, only one model produces a simulation that is more than 15% below the observed warming. This leads to a too-high global warming simulated by the ensemble mean of the CMIP6 models over this period. Therefore, the mean of the CMIP6 models should not be used in studies of future climate. There are eight CMIP6 models within ±15% of the observed warming over this period. These models, or their subsets, should provide a better assessment of past and future climate. This procedure of model selection was optional in CMIP5 and CMIP3. However, it becomes mandatory for the CMIP6 collection. The reason is that ensemble averages of global warming in CMIP3 and CMIP5 were close to the observed warming, while with the CMIP6 models, the global warming is significantly overestimated when the ensemble mean of all models is used.

A different set of seven models (Figure 2a) provides a simulation of Arctic surface warming within ±15% of the observed Arctic warming. Three of these models are common to both the Arctic and global sets. Arctic warming is simulated by the ensemble mean of the CMIP6 models more accurately than the mean global temperature. This is because models overestimating and underestimating Arctic warming are more symmetrically distributed (Figure 2a), so their errors cancel, which is not the case for mean global warming. The list of acceptable models according to the considered criterion (±15%) is provided in Table 1. Only three models, GFDL-ESM4 [35], MPI-ESM1-2-LR [36], and NorESM2-LM [37], satisfy the condition of being within ±15% of the observed warming for both Arctic and global warming.

Table 1. The set of CMIP6 models simulating surface temperature increase in 2014–2023 compared to the mean of 1961–1990 within ±15% of the observed average of the global (left column) and the Arctic (middle column) temperature. The right column shows the three models belonging to both sets.

CMIP6 Models ±15% Global (GL) Temp	CMIP6 Models ±15% Arctic (ARCT) Temp	CMIP6 Models ±15% GL and ARCT Temperature
GFDL-ESM4	GFDL-ESM4	GFDL-ESM4
MPI-ESM1-2-LR	MPI-ESM1-2-LR	MPI-ESM1-2-LR
NorESM2-LM	NorESM2-LM	NorESM2-LM
CNRM-ESM2	ACCESS-ESM1-5v	
CNRM-CM6	ACCESS-CM2	
FGOALS-g3	FIO-ESM-2-0	
CESM2	CESM2-WAACM	
GISS-E2-1-G-p3		

Accordingly, for each different region of interest, and for each climate variable of interest in climate studies, the accuracy of all CMIP6 models should be determined, and a suitable subset of models selected. Even an exact agreement between the past simulated and observed temperature does not guarantee reliable future predictions. The past agreement is only a necessary condition for an accurate future projection; it is not a sufficient condition. However, the models that cannot reproduce well the past are not suitable for future projections. Also, if there were periods of internal climate variability [38,39], this would inevitably cause some differences between model-simulated and observed temperatures that are not caused by incorrect responses to anthropogenic warming scenarios.

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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, accessed on 16 January 2024. The observed HadCRUT.5.0.2.0 analysis summary temperature time series were downloaded from https://www.metoffice.gov.uk/hadobs/hadcrut5/data/HadCRUT.5.0.2.0/download.html, accessed on 16 January 2024.

Conflicts of Interest: The authors declare no conflicts of interest.

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