Letter

Future projections of temperature and precipitation for Antarctica

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Abstract

Antarctica directly impacts the lives of more than half of the world’s population living in the coastal regions. Therefore it is highly desirable to project its climate for the future. But it is a region where the climate models have large inter-modal variability and hence it raises questions about the robustness of the projections available. Therefore, we have examined 87 global models from three modelling consortia (Coupled Model Intercomparison Project Phase 5 (CMIP5), Coupled Model Intercomparison Project Phase 6 (CMIP6), and NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP)), characterized their fidelity, selected a set of ten models (MM10) performing satisfactorily, and used them to make the future projection of precipitation and temperature, and assessed the contribution of precipitation towards sea-levels. For the historical period, the multi-model mean (MMM) of CMIP5 performed slightly better than CMIP6 and was worse for NEX-GDDP, with negligible surface temperature bias of approximately 0.5 °C and a 17.5% and 19% biases in the mean precipitation noted in both CMIP consortia. These biases considerably reduced in MM10, with 21st century projections showing surface warming of approximately 5.1 °C–5.3 °C and precipitation increase approximately 44%–50% against ERA-5 under high-emission scenarios in both CMIP consortia. This projected precipitation increase is much less than that projected using MMM in previous studies with almost the same level of warming, implying approximately 40.0 mm yr⁻¹ contribution of precipitation towards sea-level mitigation against approximately 65.0 mm yr⁻¹.

1. Introduction

Although the Antarctic landmass is geographically isolated from the rest of the world, it profoundly influences the earth’s climate system (Parish et al 1994). The vast ice sheet of the continent controls the earth’s energy balance, regulates the hydrological cycle, and affects the atmospheric and oceanic circulations in the Southern Hemisphere (Singh et al 2016, Tewari et al 2021a, 2021b, 2021c). As the world’s biggest freshwater reservoir, with a sea-level equivalent of 57.9 ± 0.9 m (Mortlighem et al 2020), the mass of its constantly changing ice sheet is directly related to increasing sea levels. The precipitation and surface temperature plays a crucial role in the Antarctic hydrological cycle and determines the evolution of its ice sheet through the surface mass balance. These two variables are critical input parameters for the regional dynamic ice sheet models, and these models require their reliable estimates to study the ice sheet dynamics. However, due to long isolation from the rest of the world, limited observations, and scattered measuring stations over the region, the climatology of its precipitation is subjected to large uncertainties. In the absence of proper observational records for the entire continent, reanalysis data (Bromwich et al 2011, Palerme et al 2017) and global climate models (GCMs) (Agosta et al 2015) provide spatiotemporally climatological records as an input to the regional scale models adapted for the region, which in turn allows a better assessment of the surface mass balance and the dynamics of its ice sheets.

These GCMs have been widely used in the past decades (IPCC 2013) to evaluate the climate and changes in the precipitation over Antarctica. However, the reliability of these models is a major concern.
since most of them fail to correctly capture the climatology of temperature and precipitation over the region (Connolley and Bracegirdle 2007, Monaghan et al 2008, Palerme et al 2017). The precipitation projections from these models also vary significantly; for example, the relative precipitation change for the Antarctic continent among the Coupled Model Intercomparison Project Phase 5 (CMIP5) models ranges from 1.8%–43% when computed between 1986–2005 and 2080–2099 in the RCP 8.5 scenario (Palerme et al 2017). Similarly, the average surface warming over the region is projected to be around 1.8 °C–5.8 °C towards the end of the century. The models thus differ widely in capturing the mean value, trend, and seasonality of these variables over Antarctica with biases varying in space and amongst models, thereby posing enormous challenges for the scientific community in making reliable climate change projections (Agosta et al 2015). Recent studies based on the latest generation of models available in the Coupled Model Intercomparison Project Phase 6 (CMIP6) reported similar issues in representing precipitation over the region despite the advancement in model physics (Roussel et al 2020). These biases in GCMs are most likely caused by their low resolutions and a lack of polar-specific physics.

Since projections for precipitation and temperature from these climate models are valuable forcing fields for determining the future sea-level changes from the regional dynamical ice sheet models, these models must reproduce their past climatology satisfactorily to provide reliable future projections. A simple and most widely used tool to reduce the biases in individual models is to use the multi-model mean (MMM) for projections (Harrison et al 1995, Jain et al 2019). However, the effectiveness of MMM varies depending upon the diagnostic variable of interest, and in cases when there is a large bias in MMM, a targeted analysis is required to identify the best set of models that simulate the past climatology satisfactorily for making reliable projections (Mishra et al 2018, Pathak et al 2019).

Climate change has been one of the external factors that have caused drastic changes over Antarctica in the past decades. The record warming signals observed over different parts of the continent in recent years (Clem et al 2020, Stammerjohn and Scambos 2020) make it one of the most vulnerable places on earth against the climate change. Due to the sensitivity of the polar systems against climate feedbacks, Antarctica’s contribution to a warming planet and rising sea levels could be catastrophic (Rintoul et al 2018). The response of the Antarctic Ice sheet to the warming of the Atmosphere and Oceans in the future will determine the fate of rising sea levels. Dynamic Ice sheet models predict a rapid rise in the global sea levels by 0.5 centimeters per year after around the year 2060 from Antarctica alone (DeConto et al 2021) if no policy changes are made. However, studies also indicate that the enhanced precipitation due to the climatic changes will partially offset this sea-level rise (Frieler et al 2015, Favier et al 2017, Tewari et al 2021a). The precipitation enhancement would be a result of the thermodynamic and dynamic changes caused in response to the greenhouse emissions, among which the thermodynamic changes would dominate the response (Uotila et al 2007, Grieger et al 2016). Hence quantitative assessment of temperature and precipitation projection becomes essential to improve the reliability of their projections. The projections will be meaningful only from the models that can simulate the past climatology satisfactorily. The efforts will help us estimate the implications on sea levels caused by an enhancement in precipitation due to warming over the region and help policymakers design appropriate climate adaptation strategies.

To fulfil this requirement of improved climate projections of precipitation and surface temperature over the whole of Antarctica, the present study aims to evaluate the state-of-the-art GCMs available in different modelling consortiums, namely, CMIP5, CMIP6, and NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) over Antarctica. The proficiency of the models to reproduce the climatology of precipitation and surface temperature is first assessed for the historical period (1950–2005). Based on the evaluation of the models to represent the past climatology using pattern correlation coefficient (PCC) and root mean square error (RMSE) as the statistical measures, ten best performing models are selected for future projections. The details of the datasets, the methodology used, and the key findings are discussed in the following sections.

2. Data and methods

The models from the CMIP 5 and 6 coordinated by the World Climate Research Program and NEX-GDDP data, obtained by downscaling CMIP5 models (Thrasher et al 2012), are evaluated in the present study. The monthly mean precipitation and surface air temperature from 29 CMIP5, 38 CMIP6, and 21 NEX-GDDP models (as listed in table 1) have been analyzed over the whole Antarctic continent (from the pole but excluding ice shelves). One ensemble member per model (the first) was used for which the monthly mean output coverage for precipitation and temperature was complete. The recently released ERA5 data by the European Center for Medium-Range Weather Forecasts based on the historical observations combined with the Integrated Forecasting System model and its data assimilation system (Hersbach et al 2020, Bell et al 2021) is used as a reference for the model evaluation. It has an enhanced spatial and temporal resolutions compared to its predecessor ERA-Interim data and the entire dataset extends back to
1950, which helps to overcome/mitigate the multidecadal variability and allows to evaluate models more accurately as the forced response to greenhouse gas increases. ERA-Interim data produces the closest match among the various other reanalysis products available (Bromwich et al. 2011, Nicolas and Bromwich 2011, Behrangi et al. 2016) over Antarctica with the limited observational records. It has recently been reported that ERA5 has a superior performance compared to the former in representing the precipitation rate (Tetzner et al. 2019, Naakka et al. 2021) and it also satisfactorily represents the surface temperature with a low bias and a high correlation coefficient above 0.95 over all of the observational stations present in the region (Gossart et al. 2019, Zhu et al. 2021) and therefore it was selected for the present study.

The performances of various models in the modelling consortium are assessed based on the uncentered PCC and the RMSE to evaluate the agreements and biases between the models and the reanalysis data. The PCC is determined to gauge the degree of resemblance between the modelled field and the ERA5 climatology, while RMSE is used to measure the error in the modelled climatology in various consortia. The climate model outputs have been interpolated to a quarter degree resolution using the bilinear interpolation for making them consistent with the quarter degree ERA5 data. For the historical period (1950–2005), the set of models with the highest PCC and at the same time the precipitation rate lying within $\pm20\%$ of the ERA5 precipitation rate were selected as the best ten models in both CMIP5 (CMIP5-MM10) and CMIP6 (CMIP6-MM10) datasets (represented by bold italics font in table 1). This enabled us to identify the models that are at least consistent with the past climatology over the region, which is necessary although not sufficient to make reliable future projections. For future projections, we considered the high emission scenario (RCP 8.5 scenario in CMIP5 and SSP5-8.5, which is the nearest equivalent to RCP-8.5 in CMIP6), for which

### Table 1. List of CMIP5, CMIP6 and NEX-GDDP models used in this study. The best performing models in CMIP6 and CMIP6 have been highlighted by italics and bold font.

| S. No. | CMIP6 models | CMIP5 models | NEX-GDDP models |
|--------|--------------|--------------|-----------------|
| 1      | ACCESS-CM2   | ACCESS 1-0   | ACCESS 1-0      |
| 2      | ACCESS-ESM1-5| BNU-ESM      | BNU-ESM         |
| 3      | AWI-ESM-1-1-LR | CCSM4       | CCSM4           |
| 4      | BCC-ESM2-MR  | CESM1-BGC    | CESM1-BGC       |
| 5      | CAMS-ESM1-0  | CNRM-CM5     | CNRM-CM5        |
| 6      | CESM2        | CSIRO-Mk3-6-0| CSIRO-Mk3-6-0   |
| 7      | CESM2-WACCM  | CanESM2      | CanESM2         |
| 8      | CMCC-CM2-SR5 | GFDL-CM3     | GFDL-CM3        |
| 9      | CNRM-CM6-1   | GFDL-ESM-2G  | GFDL-ESM-2G     |
| 10     | CNRM-CM6-1-HR| GFDL-ESM-2M  | GFDL-ESM-2M     |
| 11     | CNRM-ESM2-1  | IPSL-CM5A-LR | IPSL-CM5A-LR    |
| 12     | CanESM5      | IPSL-CM5A-MR | IPSL-CM5A-MR    |
| 13     | EC-Earth3    | Miroc5       | Miroc5          |
| 14     | EC-Earth3-Veg| MIROC-ESM    | MIROC-ESM       |
| 15     | FGOALS-f3-L  | MIROC-ESMchemy| MIROC-ESM-chemy|
| 16     | FGOALS-g3    | MPI-ESM-LR   | MPI-ESM-LR      |
| 17     | FIO-ESM-2-0  | MPI-ESM-MR   | MPI-ESM-MR      |
| 18     | GFDL-CM4     | MRI-CGCM-3   | MRI-CGCM-3      |
| 19     | GFDL-ESM4    | NorESM1-M    | NorESM1-M       |
| 20     | GISS-E2-1-G  | bcc-csm-1-1  | bcc-csm-1-1     |
| 21     | HadGEM3-GC31-LL | inmcm4      | inmcm4          |
| 22     | IITM-ESM     | ACCESS1-3    | ACCESS1-3       |
| 23     | INM-CM4-8    | CESM1-CAM5   | CESM1-CAM5      |
| 24     | INM-CM5-0    | CESM1-WACCM  | CESM1-WACCM     |
| 25     | IPSL-CM6A-LR | EC-EARTH     | EC-EARTH        |
| 26     | KACE-1-0-G   | FGOALS-g2    | FGOALS-g2       |
| 27     | MCM-UA-1-0   | FIO-ESM      | FIO-ESM         |
| 28     | MIROC6       | GISS-E2H-CC  | GISS-E2H-CC     |
| 29     | MIROC-ES2L   | HadGEM-AO    | HadGEM-AO       |
| 30     | MPI-ESM1-2-HR|             |                 |
| 31     | MPI-ESM1-2-LR|             |                 |
| 32     | MRI-ESM2-0   |             |                 |
| 33     | NEM3         |             |                 |
| 34     | NorESM2-LM   |             |                 |
| 35     | NorESM2-MM   |             |                 |
| 36     | TaiESM1      |             |                 |
| 37     | UKESM1-0-LL  |             |                 |
the radiative forcing by the greenhouse gases, aerosols, and other emissions in the year 2100 totals to 8.5 Wm$^{-2}$. The linear trends are computed using the Theil-Sen estimator, and the statistical significance is computed using the Mann-Kendall test applied at a 99% confidence level.

3. Results

The climatological mean annual surface air temperature and precipitation rate over Antarctica from ERA-5 and different modelling consortia are shown in figures 1(a) and (b), respectively. It is evident that the NEX-GDDP models overestimate the surface temperatures (by 13 °C–15 °C) and underestimate the precipitation rate by 40 mm d$^{-1}$ with a quite narrow inter-model spread, thereby performing poorly over the region. None of the models in the group reproduces the observed climatology as the bias correction technique applied on the parent CMIP5 models used gridded observations by Sheffield et al (2006), which are mostly available in the lower latitudes over the land surface only. Thus, the NEX-GDDP consortium models do not provide any robust projections over Antarctica and hence are not considered in the subsequent analysis. CMIP 5 and CMIP 6 models, on the contrary, display a wide spectrum in simulating the surface temperature and precipitation over the region. 20 out of the 29 CMIP5 models and 23 out of the 38 CMIP6 models, which are written in italics in table 1 lie within the range of ±20% of the ERA-5 precipitation rate. It is noted that EC-EARTH shows better performance among all the other models in CMIP5 consortium and closely captures the climatology of the precipitation rate (PCC = 0.926, RMSE = 0.589 mm d$^{-1}$) and temperature (PCC = 0.986, RMSE = 1.77 °C) over the region, while in CMIP6 GFDL-CM4 has a better performance (PCC = 0.933, RMSE = 0.488 mm d$^{-1}$ for precipitation and PCC = 0.989, RMSE = 2.91 °C for temperature, respectively). Although the MMM captures the climatological value of temperature over the continent, the precipitation rate is highly overestimated in both CMIP consortia (approximately 17.5% in CMIP5 and 19% in CMIP6). The selection of the best ten performing models (represented by bold letters in table 1) significantly improves the representation of the climatology of both precipitation and temperature as is evident from the box plots and the RMSE vs. PCC plots (in figures 1(c) and (d), respectively). These models identified as the best models in the CMIP 5 consortium also belong to the group of models previously identified by Agosta et al (2015) with an aim to evaluate the models for regional modelling of the surface mass balance. In general, it can be observed from table 1 that the models belonging to the same modelling groups (for example, ACCESS, GFDL, MPI-ESM, CESM) and having similar modelling components, have similar performances over the region due to similarity in model physics. The surface temperature and the precipitation rate from the identified models approach the climatological values of −35.8 °C and 164.86 mm yr$^{-1}$, respectively, as observed in the ERA 5 dataset in both modelling consortia. The representation of precipitation gets significantly improved in MM10 ensemble compared to MMM, and the PCC changes from 0.89–0.93 in CMIP 5 and 0.926–0.947 in CMIP6, accompanied by a reduction in RMSE. The representation of surface temperature is also marginally improved as reflected from PCC, which increases from 0.983–0.986 in CMIP 5 and from 0.991–0.993 in CMIP 6 by considering MM10 instead of MMM. Thus, the MM10 reliably captures the climatology of the surface temperature and precipitation in CMIP models compared to the MMM, which is also true for the seasonal variation (see supplementary figures 1 and 2 (available online at stacks.iop.org/ERL/17/014029/mmedia)). Thus, we use the ensemble of the best models (MM10) for the projection of temperature and temperature over the region.

The time evolutions of the temperature and precipitation using MM10 for the RCP 8.5 scenario simulations in CMIP5 and SSP-585 pathways in CMIP6 are shown in figures 2(a) and (b), respectively. It can be noted that the average temperature rises over the continent in the 21st century (i.e. in the year 2099) ranges approximately from 5.1 °C–5.3 °C in CMIP5-MM10 and CMIP6-MM10, compared to the ERA-5 climatology. This warming rate is consistent with the warming rate predicted by using the MMM of CMIP5 and CMIP6 models reported in the literature for the region (Palerme et al 2017, Bracegirdle et al 2020). The warming towards the end of the century (2070–2100) relative to the historical period (1950–2005) is larger than 4 °C in both the ensemble means (see supplementary figure 3), indicating an intense warming to be expected over the region towards the end of the century, which would increase the melting rate of its ice sheet. The robust warming signal in both MMM and MM10 projections highlights the adverse effect that warming could have on the continent if the emissions are left unchecked. Spatially this warming signal is uniformly spread out in all the seasons and is more profound over the continent’s interiors compared to the coastal regions (see supplementary figure 4), which is in line with the recent observations indicating that the Southern Pole is warming at a much alarming rate than the other regions (Clem et al 2020). From the projections of precipitation using MM10 over the continental landmass, it was noted that the projected precipitation enhancement for the 21st-century in CMIP5 and CMIP6 consortia is approximately 44%–50% of the climatological mean (ERA-5 data), which is considerably lower than the enhancement projected using MMM (approximately 54%–66%). Further, the
precipitation changes towards the end of the century relative to the historical period show significant differences in MMM and MM10 (supplementary figure 3) and are correlated with the corresponding temperature changes (correlation coefficient \(\sim 0.93\)). The precipitation enhancement in projections was found to be prominent in the Southern Hemispheric winters and was relatively more over the coastal margins than in the continental interiors due to the orographic effects of the ice sheets (supplementary figure 5).

The projected mean precipitation sensitivity towards the end of the century using the MM10 is estimated to be around 7.7% K\(^{-1}\), which is much larger than the global mean of around 2% K\(^{-1}\) (Held and Soden 2006). The projections under the SSP-585 pathways in CMIP6-MM10 corroborate the CMIP5-MM10 projections, which signifies the robustness of the response under an adverse warming. Under such a scenario, one should therefore expect higher sea-level contribution by the Antarctic than that projected by
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Figure 2. Long term changes in surface air temperature and precipitation rate over the Antarctic landmass. (a) Mean value of surface air temperature (in °C) and (b) precipitation rate (in mm yr⁻¹) in CMIP5-MM10 and CMIP6-MM10 models projected from the best ten models. The shaded areas represent the standard deviation of the ensemble MM10 mean.

MMM as the expected mitigation by an increase in the precipitation would be much lower. The evolution of the Antarctic precipitation in the 21st century could also be used to assess its contribution towards the sea level [as 360 Gt of ice is equivalent to 1 mm in sea level (Alley et al. 2005)]. Following the methodology of Palerme et al. (2017) the contribution of Antarctic precipitation towards sea-level mitigation during the 21st century (from 2015–2099) is estimated to be approximately 40 mm yr⁻¹ using the MM10, which is approximately 60% of the value obtained using MMM in both CMIP5 and CMIP6 consortia (supplementary figure 6).

Since the trends provide important information about the climate change, we next investigate the future spatial trends of temperature and precipitation over the region in figure 3. The ensemble mean projections of temperature from both CMIP5-MM10 and CMIP6-MM10 models highlight a significant decadal warming trend over Antarctica of 0.4 °C–0.8 °C per decade, which is more pronounced in CMIP6-MM10. The highest warming with values more than 0.7 °C per decade is noted over the interiors of the continent, which suggests that the high decadal warming trend observed over the Southern Pole in the past decades will hasten further over the interior regions of the Antarctic ice sheet under a high emission scenario. For precipitation, the trend values are significant only over the coastal regions with a decadal enhancement of approximately 18.0 mm, which is much higher than the mean precipitation trend over the continent. The
precipitation increase over the coastal areas would result from an enhancement in the moisture transport towards the poles in a warming world by the synoptic-scale events (Dalaiden et al., 2020). The precipitation enhancement is also well correlated with the surface warming and the enhanced evaporation from the sea-ice retreat (supplementary figure 7). The inner regions of the continent show a marginal enhancement, which mostly occurs due to an increase in the surface evaporation as the high orography of the ice sheet prevents the moisture-laden winds from the lower latitude to penetrate inland.

4. Discussion

By evaluating the fidelity of the models in simulating the precipitation and temperature over Antarctica among different modelling consortia, the following broad conclusions can be drawn. The downscaled models in the NEX-GDDP datasets do not perform well over the continent, and their MMM values are far away from the observed climatology and hence are unsuitable for making projections over the continent. On the other hand, the CMIP5 and CMIP6 consortium models display a wide spectrum in representing the temperature and precipitation over the region. Their MMM performs better than most of the individual models in the group in simulating the climatology of these variables over the region; however, there are large biases of the order of 28–31 mm yr\(^{-1}\) of (RMSE 0.58 mm d\(^{-1}\)) in simulating the annual precipitation rate over the continent. The precipitation bias in MMM of CMIP6 models shows no significant improvement in comparison to the MMM of the CMIP5 models despite the advancement in model physics, which indicates that the polar climate over Antarctica is still not well represented in most of the
CMIP6 models. The analysis shows that much of the existing biases in the annual and seasonal cycle of CMIP5-MMM and CMIP6-MMM are considerably reduced when we use the ensemble mean of the best model identified over the region.

The future projections using the best models identified among both CMIP5 and CMIP6 modelling groups predict a rise in the surface temperature over Antarctica, which is more intense over the Southern Pole in comparison to the coastal regions. This indicates that the recent warming signal observed over the South Pole in the past three decades, which is a manifestation of the global warming (Clem et al 2020) will continue to increase in the future under the adverse warming scenario. Both CMIP5-MM10 and CMIP6-MM10 projections show that the decadal trends for the surface temperature over Antarctica will be quite high (0.7 °C) compared to the global average, which is consistent with the values projected by the MMM. There is a slight difference of around 0.11 °C per decade over the continent’s interior in the MM10 projections by both the consortia but the overall difference in the average surface temperature projected towards the end of the 21st century is negligible. The annual precipitation rate is also projected to get enhanced, with the coastal areas receiving more precipitation approximately 6–18 mm per decade due to their orographic obstruction forcing the incoming winds to liberate the enhanced moisture due to warming around the periphery of the continent. The precipitation increases over the entire continental landmass in the 21st century is projected to be around 36%–40% of the climatological mean in MM10, which is much lower than the enhancement projected using MMM approximately 48%–56% of CMIP5 and CMIP6 consortia, respectively. Overall, an enhanced contribution of Antarctica towards the rising sea levels is expected, as the rate of warming is similar to that projected by the MMM, but the precipitation increase is considerably reduced, implying more serious repercussions on the global sea levels than previously estimated using MMM if emissions increase at a rapid pace.

Thus, the present results suggest that the selection of the ensemble mean of the best performing models over Antarctica instead of MMM will help in alleviating the uncertainties associated with the climatological representation of precipitation and temperature over the region, and it can be used for driving the regional models to estimate reliable projections for the changes in the sea levels. The climatologically projected changes from these models show a gradual increase in the surface temperature over the continent, accompanied by an enhanced precipitation. However, the compensation by the surface mass gain through precipitation is almost half of that assessed by the MMM in the previous studies. This behaviour emphasizes the possibility of an increase in the Antarctic contribution to the rising sea levels towards the end of the century and raises challenges before the policymakers to develop faster mitigation strategies to achieve the climate target.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: The data from CMIP5 and CMIP6 models are available at the Earth System Grid Federation (ESGF) (https://esgf-index1.ceda.ac.uk/). The NEX-GDPP data can be found at (https://ds.nccs.nasa.gov/thredds/catalog/bypass/NEX-GDPP/catalog.html). The ERA5 atmospheric reanalysis data can be acquired via their portal (https://apps.ecmwf.int/data-catalogues/era5/).

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