Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2023, 11, 1-19
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Antarctic Sea Ice Concentration in the Brazilian Earth System Model Simulations

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How to cite this paper: Casagrande, F., Finotti, E., Souza, R. B., Moura, R., & Leonardo, N. F. (2023). Antarctic Sea Ice Concentration in the Brazilian Earth System Model Simulations. *Journal of Geoscience and Environment Protection, 11,* 1-19.
https://doi.org/10.4236/gep.2023.119001

Received: July 11, 2023
Accepted: August 29, 2023
Published: September 1, 2023

Abstract

Sea ice is an important and complex component of the Earth's system, acting as both an indicator and an amplifier of climate change. Here, we investigated the ability of the Brazilian Earth System Model (BESM-OA2.5) and four state-of-the-art climate models participating in the fifth phase of the Coupled Model Intercomparison Project, Version 5 (CMIP5) to represent the Antarctic Sea Ice Concentration (SIC) seasonal cycle. We validated the sea ice model's performance using satellite data from 1980 to 2005 and calculated the skill and RMSE of each model. BESM-OA2.5 results for melt-freeze transitions in the Southern Ocean are consistent with CMIP5 models and satellite data. In February, when the sea ice reaches its annual minimum, the BESM-OA2.5 has the best fit among the models. However, in September, when the Antarctic sea ice reaches its annual maximum, the SIC simulated by BESM-OA2.5 indicated the largest area covered by ice compared to satellite, particularly on the Polar Front. Similar results were found in the CMIP5 models evaluated here. We suggest that the large bias simulated in the Polar Front is related to the inability of the sea ice model to represent the complex ocean- atmosphere-sea ice interactions. The subject is considered a hot topic in climate change studies and lacks conclusive answers.

Keywords

Southern Ocean, Climate Models, Satellite, CMIP5 Simulations, Climate Validation

1. Introduction

Sea ice is a critical component of the Earth's system and plays a fundamental role in the global climate, acting as a driver, indicator, and amplification of climate change (Notz et al., 2016; Meredith et al., 2019). It is an essential element of the cryosphere, reflecting most of the incident solar energy back to space and regulating the Earth's energy balance (Pithan & Mauritsen, 2014; Meredith et al., 2019). The changes in sea ice area, thickness, and concentration also affect the ocean and atmospheric circulation on a wide range of spatial and temporal scales, and the effects in mid-latitude are still poorly understood (Ferrari et al., 2014; England et al., 2020; Zhu et al., 2023). According to England et al. (2020), the Antarctic sea ice retreat could lead to changes in tropical atmospheric circulation, precipitation, and temperature patterns, with the largest impact occurring in the Pacific and Atlantic regions, and substantial implications for global climate.

Contrasting with the Arctic, which has experienced an unprecedented, rapid, and drastic sea ice retreat in recent decades, the Antarctic sea ice has shown a slightly positive trend (1979-2018). However, this trend has been reversed to a significant retreat since 2014 (Parkinson, 2019; Gorenstein et al., 2022), with the Antarctic sea ice area reaching its lowest level on record in 2023 (Liu et al., 2023). The Antarctic sea ice decrease has been so pronounced that it is sufficient to eliminate the positive trend constructed over the past 40 years (Parkinson, 2019).

The reasons behind this reversal are still the subject of debate and research, the scientific community has attributed them to the following reasons: 1) ozone depletion (Turner et al., 2009; Marshall et al., 2014); 2) response to CO_2 forcing (Meredith et al., 2019; Liu et al., 2023); 3) El Niño-Southern Oscillation (Stammerjohn et al., 2008; Crosta et al., 2021); 4) Interdecadal Pacific Oscillation (Meehl et al., 2016; Liu et al., 2023); 5) Amundsen Sea Low (Liu et al., 2023); 6) increase freshwater input over Southern Ocean from the ice shelf melting (Bintanja et al., 2013, 2015; Pauling et al., 2017); and 7) changes in wind and sea surface temperature (Purich et al., 2016; Blanchard-Wrigglesworth et al., 2021) and natural variability (Meehl et al., 2016; Zhang et al., 2019; Singh et al., 2019). Ludescher et al. (2019) suggest that this is the first indication of a tipping point in Antarctic sea ice characteristics toward an even greater diminishment of sea ice in the coming years. The 2023 lowest Antarctic sea ice record highlights the question of whether the recent change is a brief anomaly or an early precursor to a transition to a long-term decline. The hypothesis is supported by CMIP climate model projections, which show fast sea ice retreat for the 2100 future global climate projections (Meredith et al., 2019; Roach et al., 2020; Liu et al., 2023; Casagrande et al., 2023).

Over the last few decades, the observed changes in the polar regions and their impacts on mid-latitudes have drawn the attention of the scientific community, and climate models have been crucial in understanding these processes. Coupled Global Climate Models (CGCMs) and Earth System Models (ESMs) are essential tools for studying past, present, and projected future climate change, helping scientists better understand the global climate system and the complex nature of the interactions between the ocean, atmosphere, land, and cryosphere. However, even with the advances in both CGCMs and ESMs over the last decades, accurate sea ice simulation is still considered a challenge, particularly in the Southern Ocean (Roach et al., 2020; Meredith et al., 2019).

The Coupled Model Intercomparison Project (CMIP), coordinated by the World Climate Research Programme (WCRP), is a collaborative effort among climate scientists to improve our understanding of climate change. CMIP provides multi-model output publically available in a standardized format, allowing the comparison of different climate models under similar conditions (same numerical experiment, defined via protocols) with natural, unforced variability or in response to anthropogenic forcing. The project has made essential scientific contributions to the Intergovernmental Panel on Climate Change (IPCC) (Taylor et al., 2012; Eyring et al., 2016; Touzé-Peiffer et al., 2020). Over 20 groups around the world have contributed to CMIP5, running more than 40 CGCMs and ESMs. The models are developed independently and include different physical parameterizations.

The development of the Brazilian Earth System Model (BESM) is an effort of several institutions and researchers coordinated by the National Institute for Space Research (INPE) to build a multidisciplinary research framework with the intent of understanding the causes of global climate change, its effects, and its impacts on society (Nobre et al., 2013). The BESM also contributes to CMIP, Phase 5 (CMIP5) with short-term and long-term simulations (Nobre et al., 2013). The sea ice component in the BESM model was previously investigated by Casagrande et al. (2016, 2021) for the Arctic region, however, the ability of the BESM-OA model to simulate Antarctic sea ice changes remains unknown and is the subject of this paper.

Global climate models generally provide significantly more accurate simulations of the Arctic than the Antarctic (Shu et al., 2015). Turner et al. (2015) suggest that the primary reason is the inability of climate models to reproduce the observed sea ice retreat until 2014.

According to Meredith et al. (2019), realistic Antarctic sea ice simulations are still a scientific challenge due to the high no-linearly of the sea ice physical process. The sea ice models need to be able to accurately simulate the dynamical and thermodynamic interaction of the complex coupled processes between ocean, atmosphere, ice sheet, and sea ice, which determine the resulting sea ice distribution and movement (Notz, 2012; Notz et al., 2013; Luo et al., 2023). Notz (2012) suggests that without such understanding, a trustworthy projection of future changes will not be possible. Sea ice changes are not only scientifically interesting, but they also have important environmental, geopolitical, and economic implications (Oppenheimer et al., 2019; Meredith et al., 2019; IPCC, 2021).

Here, we evaluated the historical simulations (1980-2005) of BESM, Coupled Version 2.5 (BESM-OA2.5), and the other four climate models participating in the CMIP5 to represent the regional distribution of the Sea Ice Concentration

(SIC) seasonal cycle and validate the results with satellite data. The paper is structured as follows: First, we present the method and the data sources. Then, we analyze the Antarctic SIC seasonal cycle and the spatial pattern, comparing the BESM-OA2.5 historical simulations to satellite observations and other CMIP5 models. Finally, we discuss the results, present our conclusions, and lay out our recommendations for future work.

2. Methods

2.1. Data Source

This study uses long-term simulations from five General Circulation Models (GCMs) and Earth System Models (ESMs), including BESM-OA V2.5, participating in CMIP5. The numerical experiment design follows the CMIP5 Taylor Protocol (Taylor et al., 2012). The long-term simulations started from multi-century preindustrial control (quasi-equilibrium) integration and included an interactive representation of the ocean, atmosphere, sea ice, and land (Taylor et al., 2012).

The historical simulation used here is a long-term simulation that runs from 1850-2005 forced by observed atmospheric CO_2 (Taylor Protocol, Taylor et al., 2012). To validate and compare the model simulations with satellite, all datasets were regridded using a bilinear interpolation from each original grid to a 1.0 × 1.0 lat/lon grid in the period 1980-2005—end of the long model integrations starting in the 1850s (and also the match period between model simulations and satellite data available).

To validate the Antarctica SIC outputs (1980-2005), we used passive microwave-derived monthly data sets from Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite, the Special Sensor Microwave/Imager (SSM/I), Special Sensor Microwave Imager/Sounder (SSMI/S), and instruments on the Defense Meteorological Satellite Program's (DMSP), distributed by National Snow and Ice Data Center (NSIDC; https://nsidc.org/data/g02135/versions/3). The brightness temperature measurements are converted into SIC, and the original grid is available in polar stereographic projection with a grid cell size of 25 × 25 km (Comiso, 2017; Fetterer et al., 2017; DiGirolamo et al., 2022).

The following CMIP5 models were used in this work: Geophysical Fluid Dynamics Laboratory-Climate Model, Version 3 (GFDL-CM3) (Griffies et al., 2011), Australian Community Climate and Earth System Simulator (ACCESS1.0) (Collier & Uhe, 2012), Max Planck Institute-Earth System Model (MPI-ESM-LR) (Notz et al., 2013), Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM) (Komuro et al., 2012; Giorgetta et al., 2013), and Brazilian Earth System Model, Version 2.5 (BESM-OA2.5) (Nobre et al., 2013; Giarolla et al., 2015; Veiga et al., 2019). The sea ice components of these models range in complexity and include differences in both dynamics and thermodynamics.

To investigate the CMIP5 model's performance to represent the Antarctic SIC, we use spatially standard statistical metrics: Root Mean Square Error (RMSE), Skill, and bias, considering the NSIDC Satellite data as a reference for the period of 1980 to 2005.

$$\text{Skill} = 1 - \frac{\sum \left| X_{\text{mod}} - X_{\text{sat}} \right|^2}{\sum \left(\left| X_{\text{mod}} - \bar{X}_{\text{sat}} \right| + \left| X_{\text{sat}} - \bar{X}_{\text{sat}} \right| \right)^2} \tag{1}$$

The skill is represented by Equation (1) and described in detail by Willmott (1981) and Haidvogel et al. (2008). The skill gave us a measure of the correlation between the simulated (CMIP5 models) and observed (satellite). Skills values close to 1 represent the perfect agreement between the model (X_{mod}) and observations (X_{sat}), whereas skills values close to zero represent disagreement and the inability of the model to correctly represent the observed values. The skill values were estimated two-dimensionally in all grids.

2.2. Brazilian Earth System Model

The BESM-OA is a coupled ocean-atmosphere model that simulates the climate system (Nobre et al., 2013; Veiga et al., 2019). The BESM-OA2.5 atmospheric component used in this work is the Brazilian Global Atmospheric Model (BAM), developed at the Earth System Numerical Modeling Division (DIMNT/INPE) and described in Figueroa et al. (2016). The BAM is a primitive equation model discretized following a spectral transform with horizontal resolution truncated at triangular wavenumber 62 (approximately an equivalent grid size of 1.875˚) with 28 vertical sigma levels with the top level at around 2.73 hPa (if the surface pressure were considered as 1000 hPa). The land surface processes are given by dynamical vegetation, and the bulk transfer coefficients are determined using the Monin-Obukhov theory (Figueroa et al., 2016; Capistrano et al., 2020; Veiga et al., 2019).

The BESM-OA2.5 oceanic component is the Modular Ocean Model version 4.1 (MOM4p1; Griffies et al., 2009; Griffies, 2012) developed at the Geophysical Fluid Dynamics Laboratory (GFDL), which includes the Sea Ice Simulator (SIS) built-in ice model (Winton, 2000). MOM4p1 is an Arakawa B-grid hydrostatic nonBoussinesq ocean model, with a Boussinesq option. Key physical parameterizations include a K-Profile Parameterization (KPP) surface boundary layer scheme of Large et al. (1994), which computes vertical diffusivity, vertical viscosity, and nonlocal transport as a function of the flow and surface forcing. The horizontal grid resolution is set to 1˚ in the longitudinal direction, and in the latitudinal direction, the grid spacing is 1/4˚ in the tropical region (10˚S - 10˚N), decreasing uniformly to 1˚ at 45˚ and to 2˚ at 90˚ in both hemispheres. In the vertical, 50 levels are adopted with a 10 m resolution in the upper 220 m, increasing gradually to about 370 m of grid spacing in deeper layers (Nobre et al., 2013; Giarolla et al., 2015; Veiga et al., 2019; Capistrano et al., 2020). More details about MOM4p1 are described in Griffies et al. (2009).

The SIS component in BESM-OA2.5 is a dynamical/thermodynamical model with three vertical layers (one snow and two ices) and five ice categories of sea ice thicknesses (Winton, 2000; Delworth et al., 2006). The rheology is given by the Elastic-Viscous-Plastic (EVP) technique (Hunke & Dukowicz, 1997), used to calculate the internal stress in sea ice. EVP uses an elastic mechanism in regions of rigid sea ice to increase computational efficiency. SIS calculates the concentration, thickness, temperature, brine content, and snow cover of an arbitrary number of sea ice thickness categories (including open water), as well as the motion of the complete pack (Semtner Jr., 1976). BESM-OA2.5 uses a Flexible Modeling System (FMS) to couple the ocean and atmospheric models (Nobre et al., 2013; Balaji, 2012; Griffies et al., 2009). FMS is a software framework for supporting the efficient development, construction, execution, and scientific interpretation of atmospheric, oceanic, and climate system models (Balaji, 2012).

The Sea Ice Extent (SIE) is the sum of the areas of all grid cells covered by ice, where each pixel must have at least 15% ice. We estimated the SIE using only satellite-derived data to provide an approximation of the sea ice area covered by ice in millions of kilometers. To avoid compensation errors, we decided not to include the SIE from the climate model in this work. As previously discussed by Casagrande et al. (2023), CMIP sea ice simulations with the same sea ice area could have a significant and distinct distribution of sea ice in the Southern Ocean, which can lead to substantial compensation errors. Similar results were found by Notz (2014).

3. Results

3.1. SIC Seasonal Cycle Assessment

The cycle of sea ice growth and melt in the Southern Ocean is the environmental phenomenon with the largest annual variation in area known on Earth's surface (Roach et al., 2020). The seasonal cycle is a crucial characteristic of the Southern Ocean, which is closely linked to air-sea temperatures and plays a significant role in climate change. The SIC variability is driven by a combination of variables such as solar radiation, wind, clouds, and ocean currents (Hobbs et al., 2016).

The average of the observed Antarctic SIC varies from a summer minimum in February to a winter maximum in September for the period of 1980-2005 (**Figure 1**). During the austral winter, the sea ice expands and reaches its maximum extent, covering an area of approximately 18.5×10^6 km^2. As the Austral summer approaches, the sea ice begins to melt and retreats to its minimum extent, covering an area of approximately 2.8×10^6 km^2 (i.e. the difference between the SIC maximum and minimum is more than 15×10^6 km^2).

Figure 1 shows the Antarctic SIC climatology for the annual maximum and minimum from climate models and observations, as well as the biases between each model and the satellite. The Antarctic SIC seasonal cycle for all of the CMIP5 models is consistent with observations, indicating an accurate minimum (maximum) period in February (September) associated with the melting (growing)

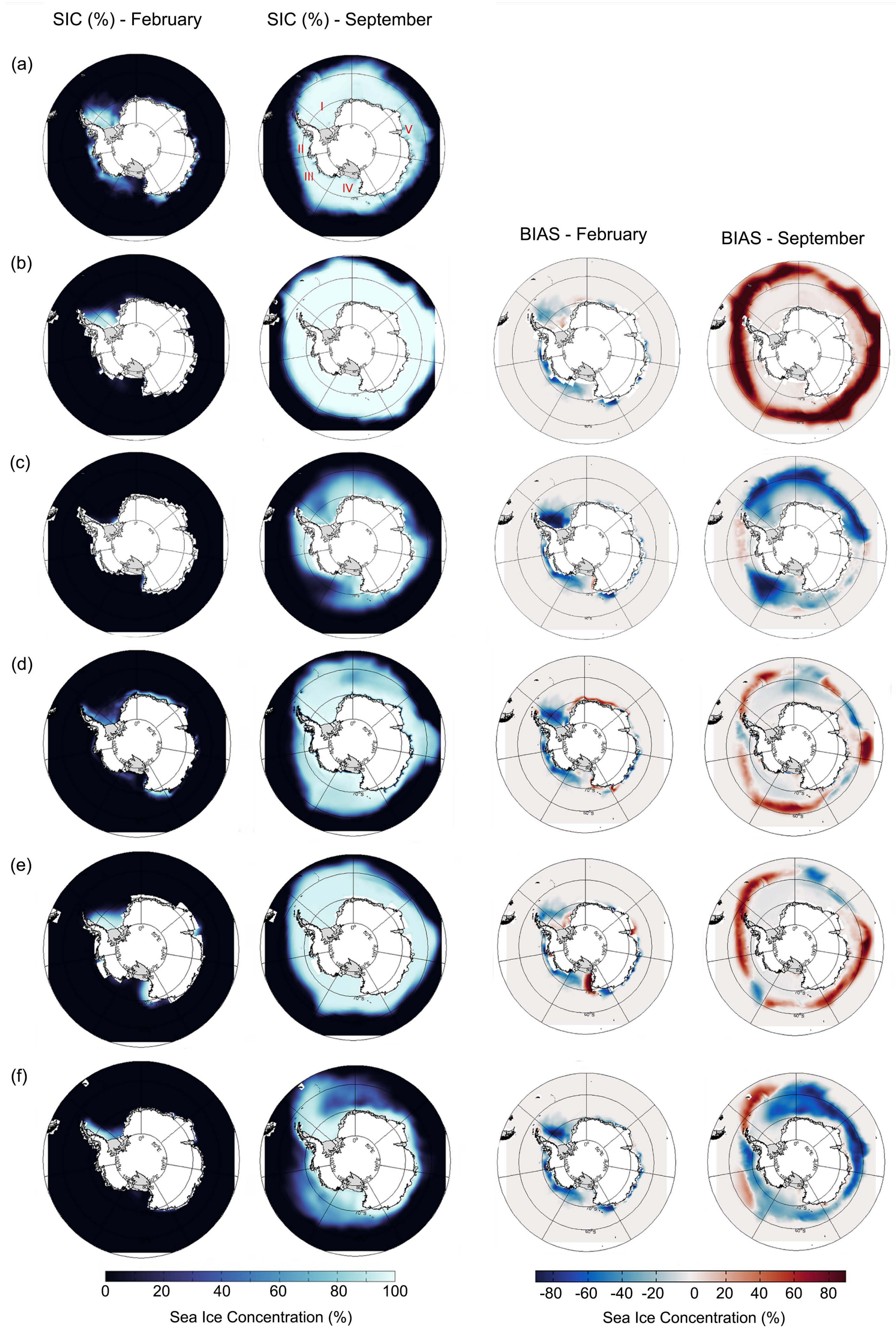

Figure 1. Climatology of Antarctica SIC (%) (1980-2005) in February and September from (a) satellite data, (b) BESM-OA2.5, (c) GFDL-CM3, (d) ACCESS1.0, (e) MIROC-ESM, and (f) MPI-ESM-LR. Antarctic study area: (I) Weddell Sea; (II) Bellingshausen Sea; (III) Amundsen Sea; (IV) Ross Sea; (V) Indian Ocean.

peak amounts. Nevertheless, the spatial pattern exhibits a large spread among the models and observed data (satellite), notably pronounced in the period of maximum sea ice growth in September. SIC values range from 100% near coastal areas to zero in ice-free conditions (open ocean). During the Austral summer, the sea ice melts and disappears in most areas surrounding Antarctica, with only a small sea ice percentage remaining in the Weddell Sea and sectors of the Amundsen-Ross Sea (**Figure 1**). In the Indian sector, the sea ice practically disappears during the Austral summer and begins to grow towards its maximum in September, reaching values close to 100%.

BESM-OA2.5 showed good spatial agreement compared to the satellite and other four CMIP5 models in February (SIC minimum); however, in September (SIC maximum), the model tends to overestimate the Antarctic SIC at the ice edge, particularly close to the Antarctic Circumpolar Current (ACC), which flows clockwise from west to east around Antarctica (**Figure 1(b)**). The ACC is considered one of Earth's most important ocean currents, significantly impacting global climate and ocean circulation (Böning et al., 2008). Improving the sea ice simulation in this region is considered an important issue in climate modeling (Meredith et al., 2019; Oppenheimer et al., 2019).

All five models exhibited a systematic error (underestimation) close to the west Antarctic coast (Atlantic and Pacific Sectors of the Southern Ocean) in February in the following areas: the Weddell Sea, the Amundsen-Bellingshausen Seas, and some regions of the Ross Sea. Considering these areas, the largest difference between the satellite and simulated minimum SIC occurs in the Weddell Sea, recognized as an important region for forming the Antarctic Bottom Water (AABW), which plays a critical role in global ocean circulation. Additionally, the Weddell Sea is a unique region that contains the largest amount of Antarctic multiyear sea ice, influencing both ocean-atmosphere patterns and biological processes (Zemmelink et al., 2008; Ohshima et al., 2013; Turner et al., 2017; Meyer et al., 2017). Comparatively, the BESM-OA2.5 output has the best fit in this area and period, and the GFDL-CM3 is the worst. The results are consistent with Roach et al. (2020), Shu et al. (2015), and Turner et al. (2013).

In some areas along the continental ice shelf of the Ross and Weddell Seas, the MIROC-ESM tends to overestimate the SIC values in February (**Figure 1(e)**). MPI-ESM-LR and GFDL-CM3 models show only a small fraction of ice coverage compared to satellite, which can lead to uncertainty in the robustness of climate simulations and an underestimation of the Antarctic Polar Amplification (APA) phenomenon, as proposed by Casagrande et al. (2020, 2021). The authors suggested that the Antarctic Peninsula and Weddell Sea region have warmed at more than twice the rate of the globe as a whole, and the APA is closely related to changes in sea ice and climate feedback processes. Turner et al. (2013) suggest that the large spread among CMIP5 models in simulating Antarctic sea ice in February may be related to the amplified sea ice albedo feedback mechanism in ice-covered regions, associated with the large amount of shortwave radiation that is still available in this period.

The model's performance in September was distinct for all five models evaluated here, especially close to the ice edge. Most models (except MPI-ESM-LR) showed good agreement near coastal Antarctic areas. BESM-OA2.5 (GFDL-CM3) revealed significant SIC overestimation (underestimation) and an unrealistic spatial representation of Antarctic SIC near the ACC (Weddell Sea and Amundsen-Ross Sea). In this case, it is important to note that BESM-OA2.5 and GFDL-CM3 use the same ocean model (MOM from GFDL) and the same sea ice component (SIS from GFDL), so the expressive differences between the models are most likely due to differences in the atmospheric component and parametrizations of each model. ACCESS1.0 and MIROC-ESM (MPI-ESM-LR) tend to overestimate (underestimate) the SIC in most areas. As expected, the spread among models is reduced in February compared to September due to the small sea ice coverage in this period (**Figure 1**).

According to Roach et al. (2018), the underestimation (overestimation) in summer (winter) is consistent across the population of 40 CMIP5 models. The authors separated models with and without explicit lateral melt terms, and they found that the inclusion of lateral melt may account for the overestimation of low-concentration cover, i.e. the thermodynamic scheme contributes to the uncertainties in the simulations.

3.2. Climate Model Skill Assessments

To assess whether the discrepancy between observed and simulated Antarctic SIC, the Skill and RMSE were used with the NSIDC satellite dataset as a reference, over the 1980-2005 period (**Figure 2**).

Figure 2 shows spatially the model's skill and RMSE for the minimum and maximum SIC periods as simulated by the five CMIP5 models related to satellite data. The model's performance (Skill) improves as the value reaches near 1. The opposite occurs in the RMSE result, i.e. the model's performance improves with decreasing RMSE values (0 - 1).

In February, BESM-OA2.5 simulations exhibited skill (RMSE) values above (below) 0.8 (0.3), indicating good agreement between model and satellite data (**Figure 2(a)**). Compared with the other four CMIP5 models, the BESM-OA2.5 provides the most realistic SIC results in this period. In the Weddell Sea and near coastal areas, most CMIP5 models show low (high) skill (RMSE) values (**Figure 2(a)** and **Figure 2(e)**). GFDL-CM3 showed the lowest (highest) skill (RMSE) values in the Weddell Sea region, demonstrating the inability to represent SIC in this period and region. The skill (RMSE) showed similar results for ACCESS1, MIROC-ESM and MPI-ESM-LR with persistent and systematic high (low) values in near coastal areas in both the Atlantic and Pacific sectors of the Southern Ocean. The results are consistent with Roach et al. (2018, 2020), Shu et al. (2015), and Casagrande et al. (2023).

In September, low skill (and high RMSE), reaching close to zero (1) in the ice edge towards the north in the ACC region, indicated the inability of BESM-OA2.5 to accurately represent the Antarctic SIC (**Figure 2(a)**). Nevertheless, in near

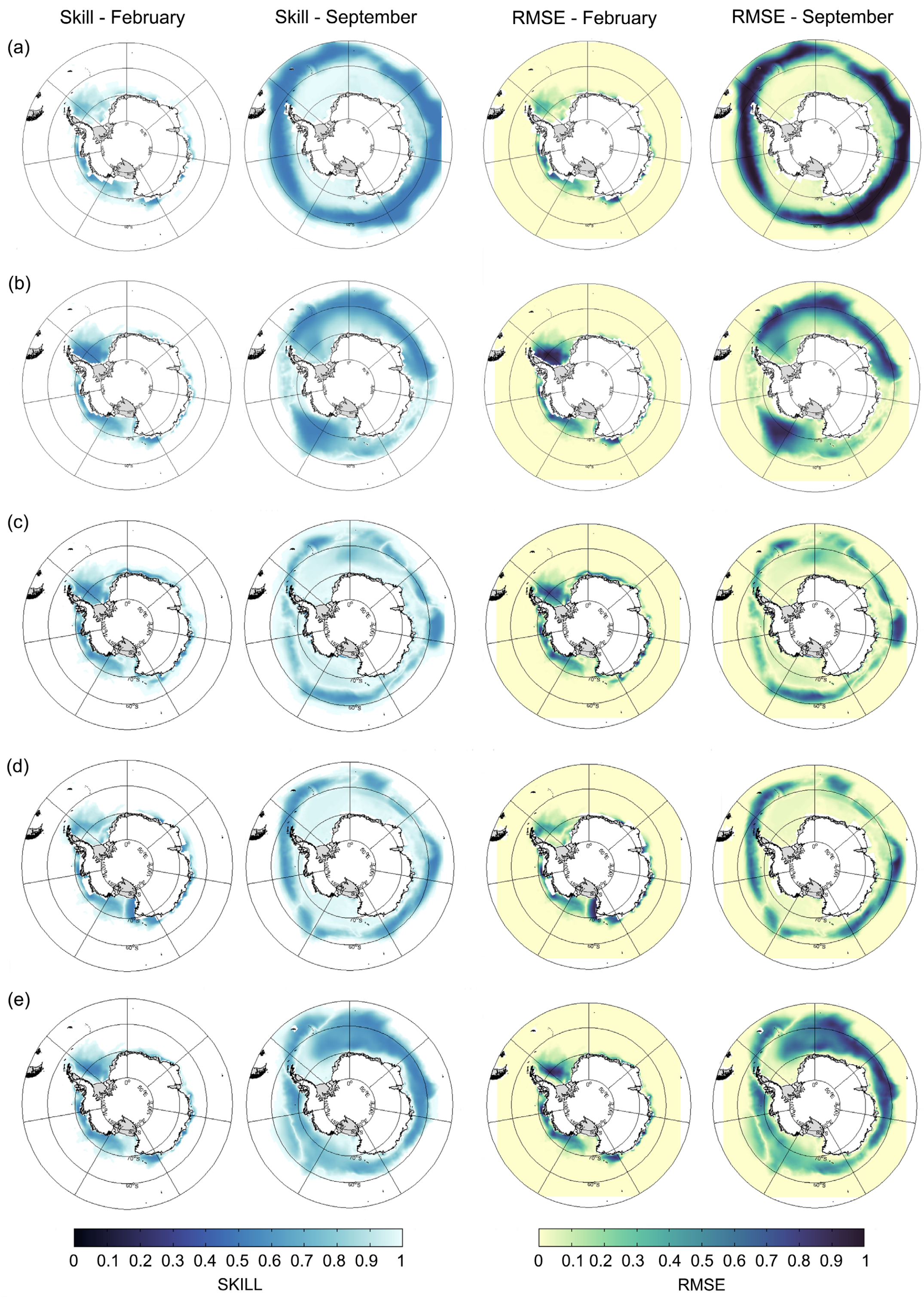

Figure 2. Antarctica SIC skill and RMSE among CMIP5 models and satellite in February and September (a) BESM-OA2.5, (b) GFDL-CM3, (c) ACCESS1.0, (d) MIROC-ESM, and (e) MPI-ESM-LR.

coastal regions, the high skill values (and low RMSE), above 0.8, indicated a good model's performance of the BESM-OA2.5 in simulating the Antarctic SIC (**Figure 2(a)**). As expected, GFDL-CM3 exhibits low skill values (and high

RMSE), particularly close to the Amundsen-Ross Sea and in the Weddell ice edge (**Figure 2(b)**). When compared to CMIP5 models, GFDL-CM3 performs well and shows good agreement with satellite data in the Bellingshausen Sea; the simulated skill (RMSE) values are near to 1 (zero). The skill as simulated by ACCESS1 and MIROC-ESM presents the highest values near coastal areas, decreasing towards the north close to the ACC region (**Figure 2(c)** and **Figure 2(d)**). According to Shu et al. (2015), contrary to the majority of CMIP5 models, the ACCESS1.0 model represents Antarctic sea ice better than the Arctic.

Several studies have investigated the CMIP bias in climate models regarding Antarctic sea ice parameters such as area, extent, concentration, and volume. Hyder et al. (2018) found that the Southern Ocean upper ocean temperature representation in CMIP5 exhibits a large bias as a result of the unrealistic representation of clouds, cloud properties, and shortwave radiation, thus affecting the sea ice formation rate through changes in air-sea heat fluxes. Mahlstein et al. (2013), using CMIP5 simulations, found that models with higher wind speeds usually overestimate the sea ice area, whereas models with more clouds usually underestimate the sea ice area during the cold season. Bintanja et al. (2013, 2015) investigated the effect of increasing fresh water from Antarctic ice shelf melt and the role of ocean warming in the Antarctic sea ice changes. As the basal ice shelf melts, driven by ocean warming, freshening the upper water and thus leads to changes in sea ice. The lack of coupled ice sheet interactions in CGCMs and ESMs simulations produces an unrealistic representation of ice shelves, which contributes to uncertainties in the robustness of sea ice simulations, even in the latest CMIP6 simulations (Pauling et al., 2017; Golledge et al., 2019; Casagrande et al., 2023). Additionally, the uncertain sources may be related to cloud effects (Kay et al., 2016) and spatial resolution that does not permit eddies, recognized as important for the Austral Ocean's dynamic and thermodynamic processes (Hallberg & Gnanadesikan, 2006; Poulsen et al., 2018).

Sea ice modeling in Antarctica faces several limitations and challenges that may affect the reliability and accuracy of the models. Another significant constraint is the scarcity of observational data, particularly in remote sea-ice-covered locations (Blockley et al., 2020). The scarcity of observed data affects the model's initialization and validation, leading to uncertainties in the representation of important thermodynamic and dynamic processes. Blockley et al. (2020) discuss the current state of sea ice modeling, challenges, advances, and limitations that need to be addressed to improve the accuracy and reliability of these models. The need for advances in sea ice modeling includes more accurate physical processes, more realistic ocean circulation representation, including mesoscale eddies, and the development of higher-resolution models (Hofmann & Maqueda, 2011; Langlais et al., 2015; Smith et al., 2022; Rackow et al., 2022). Many uncertainties in sea ice modeling are related to parameterizations, the representation of sub-grid-scale processes, and the sparse and short historical observational data (Michaelis et al., 2020; Liu et al., 2022; Meredith et al., 2019; Casagrande et al., 2023).

Luo et al. (2023) used a new multivariate balanced atmospheric ensemble forcing that was able to suppress model errors of SIC and produce improvements in the accuracy of simulation and better estimates of simulation uncertainties. Eyring et al. (2016) suggested that the greatest challenge in the CMIP6 simulations is understanding the role of the clouds in the general atmospheric circulation, the origins and consequences of systematic model biases, and the cryosphere's sensitivity as a response to CO_2 forcing.

In the near future, more studies using BESM-OA2.5 are needed to better understand sea ice processes, for instance, evaluating sea ice thickness and volume and sea ice changes as a response to CO_2 forcing.

4. Conclusion

In this work, we evaluated the Antarctic SIC historical simulation (1980-2005) from BESM-OA2.5 models for the first time and compared it to four CMIP5 model simulations. Our results were validated by using satellite data from the NSIDC for the same period. The performance of the Antarctic SIC model was evaluated using standard statistical metrics such as Root Mean Square Error (RMSE), Skill, and bias, with the satellite dataset serving as a reference. The observed average of the Antarctic Sea Ice Extent (SIE) ranges from a minimum of around 2.8×10^6 km^2 in February to a maximum of 18.5×10^6 km^2 in September (i.e. the annual amplitude is more than 15×10^6 km^2).

The Antarctic SIC seasonal cycle for all of the CMIP5 models investigated in this work is consistent with observations, indicating the correct minimum (maximum) period in February (September) associated with the melting (growing) peak. However, the correct spatial ice coverage showed a large spread among both the models and satellite dataset, notably greater in September. BESM-OA2.5 simulations were able to correctly represent the spatial ice coverage in February (SIC minimum); nevertheless, in September (SIC maximum), the model tends to overestimate the Antarctic SIC at the ice edge, nearby the Southern Ocean's northern limit in the Polar Front. In February, when the sea ice reaches its annual minimum SIC, most of the models exhibited a systematic error (and large negative biases) in the following areas: the Weddell Sea, the Amundsen-Bellingshausen Seas, and some regions of the Ross Sea. The BESM-OA2.5 model, compared to others examined here, demonstrated the best fit in this area and period. In September, when sea ice reaches its maximum annual SIC, most models showed a large bias close to the ACC flow region. The recent Antarctic sea ice decline has triggered increased interest in the ability of climate models to predict Antarctic sea ice changes and their large-scale effects on both oceanic and atmospheric circulation. Thus, we argue that identifying and understanding the biases in the Antarctic sea ice simulation is an important step toward resolving some potential problems in both CGCMs and ESMs, reducing the uncertainties and leading to more accurate predictions.

Acknowledgements

This research was funded in Brazil by the following projects: National Institute for Science and Technology of the Cryosphere (CNPq 465680/2014-3 and FAPERGS 17/2551-0000518-0) and Multiscale Study of the Coupled Ocean-Atmosphere-Cryosphere System (CNPq 406663/2022-0). We also are thankful to the Earth System Grid Federation (ESGF) and the National Snow and Ice Data Centre (NSIDC) for making the data used here available.

Conflicts of Interest

The authors have declared no conflicts of interest in this article.

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