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Comparative Analysis and Assessment of Artic Sea Ice: Predictions from CMIP6 Models Amid Global Climate Change

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Abstract: Amid global climate change urgency, accurate model predictions are paramount for informed interventions. However, the disparity among prediction models highlights a pressing research gap requiring a deeper and more comprehensive comparison of the differences and consistency of the different models in climate change prediction. This research undertook a comprehensive analysis of 18 CMIP-6 models, aiming to provide a comprehensive comparison and cohesive prediction of ice mass and ice area from 1960 to 2050. The models consistently forecast a substantial decline in Arctic ice coverage and volume. Without marked reductions in carbon emissions, Arctic glaciers are projected to vanish entirely by the close of the century. Furthermore, the correlation analysis results indicate that there is a significant interdependence between sea ice area and sea ice mass was observed, with Pearson R^2 approximately 0.908. Notably, models varied regarding the precise year of the Arctic's complete ice loss, spotlighting the inherent uncertainties of current predictions and the pressing need for mitigation measures. The study illuminates the pressing urgency for a globally coordinated response to carbon emissions and serves as a clarion call for enhanced research into the intricacies of climate change and glacier melting processes to refine future predictions.

Keywords: CMIP-6 models; Climate modeling; Carbon emissions; Nature-based solutions.

1. Introduction

In light of the urgent call for sustainable development and climate action by global frameworks such as the Sustainable Development Goals (SDGs), understanding and addressing climate change is now more crucial than ever [1]. The Earth's climate has varied naturally throughout history due to numerous physical mechanisms. Since the 1800s, however, human activities have become the main factor that led to major changes in weather and temperature patterns, known as climate change. In the changing climate, it is noticeable that the earth's surface temperature is increasing [2]. This rise is attributed to the escalating combustion of fossil fuels, which produces greenhouse gases responsible for trapping the sun's heat. In specific, since the pre-industrial period (between 1850 and 1900), Earth's global average temperature has increased by approximately 1 degree Celsius in total and 0.2 degree Celsius per decade currently [3]. The warming temperature has a great impact on the polar regions. In these regions, ice sheets and glaciers are melting caused to the increasing temperature associated with climate change, which leads to multiple problems, including the Arctic glaciers' mass reduction, the Arctic Ocean's acidification, variation in the ecosystem of calcium carbonate shell-producing species, impact on ecosystems from climate-induced changes, expansion in the range of certain marine species and following impacts in ecosystems, disappearance of permafrost, etc [4]. These changes are profoundly affecting the polar regions, leading to the melting of ice sheets and glaciers and triggering a cascade of environmental challenges all over the world. These potential consequences highlight the need for further capabilities to monitor, understand, and predict the behavior of land ice and its interactions with the atmosphere and the oceans.

In the last decade, new remote sensing technologies and missions, such as NASA's Ice, Cloud, and Land Elevation Satellite (IceSAT), the Gravity Recovery and Climate Experiment (GRACE), Grand Challenges in Cryospheric Sciences, and Operation IceBridge have revolutionized our ability to monitor the state and changes of land ice masses, in particular of the two huge ice sheets in Greenland and Antarctica, and glaciers in remote polar regions [5]. Based on advanced technology, scientists could make efforts to predict the rate of glacial melting and the date that the glacial will disappear entirely, which provides a scientific basis for creating effective policies to mitigate the impacts of climate change. However, in all prediction works, significant speed occurs among different models. Some of this spread is an inevitable consequence of the internal variability of the climate system, and the uncertainty in future forcing. For example, Jahn et al. (2016) find that internal variability causes an uncertainty of 21 years in predicting the year in which the Arctic first becomes seasonally ice-free using a large (40-member) ensemble of model runs, with an additional uncertainty of 5 years due to scenario uncertainty [6]. A similar degree of spread also occurs due to differences between the model's representation of the sea ice and other components of the climate system [7]. Spread may also arise from differences in initial conditions [8]. While advancements in remote sensing have enabled improved monitoring of land ice changes, limited attention has been given to comparing the disparities in outcomes among different models. The variability observed in model outputs underscores the need for rigorous comparative studies to understand their underlying causes and implications.

For previous model inter-comparisons (CMIP3 and CMIP5), primarily only changes in ice extent, volume (or mass), and ice motion have been considered, as these quantities are readily available as model output that can be compared directly to one another and observational or reanalysis references [9]. However, there is an emerging consensus that to understand the reasons for differences in projections of the ice state, we need to be able to look "behind the scenes" to understand the balance of different processes that drive the evolving ice state and how these change as the ice declines. For the CMIP3 models, Holland et al. (2010) calculated the changes in ice mass due to melting, growth, and divergence using monthly mean model values of ice thickness and velocity [10]. They found an appreciable variation in the size and relative importance of changes in these budget components between the models as the sea ice declines. For individual models, diagnostics may be available that allow a more comprehensive decomposition of the model budget. For example, Keen and Blockley (2018) studied changes in the volume budget of the Arctic sea ice in a CMIP5 model under a range of forcing scenarios, considering both annual and seasonal changes in the individual processes causing ice growth and loss [11]. For the latest generation of sea ice models (the CMIP6 models), a Sea-Ice Model Intercomparison Project (SIMIP) has been established, which has defined a comprehensive set of diagnostics allowing for the intercomparison of the mass, energy, and freshwater budgets of the sea ice [12]. To truly comprehend the projections and predictions of these models, it's essential to delve into the intricate processes that influence ice states. This deeper exploration promises a more holistic understanding and can guide more effective interventions in response to climate change.

To address the research gap, this study uses these new diagnostics to present a first intercomparison of the mass budget of the sea ice for 18 CMIP6 models. Note that this is a subset of the CMIP6 models, just including those for which the required outputs were available. We first look at the mean mass budget for a reference period to determine the similarities and differences between the model budgets during a period with relatively little change in the ice state. We then consider how the budgets change as the ice declines during the 21st century and how changes in the budget components relate to changes in the ice state. In Sect. 2 we describe the models and forcing scenarios used, and in Sect. 3 we intercompare the modelled ice area and mass. Considering the mean mass budgets during a reference period, we investigate how the budget evolves during the 21st century. In Sect. 4 and 5 we summarize and discuss our results. Beyond traditional metrics like ice extent and volume, our focus on the sea ice mass budget emphasizes understanding the processes behind climate change. This depth of approach sets a new standard for climate research methodology. Our findings equip policymakers with accurate insights, fostering informed decisions on climate change mitigation and adaptation strategies. In real-world terms, this research lays the groundwork for smarter, evidence-based environmental and infrastructural policies.

2. Materials and Methods

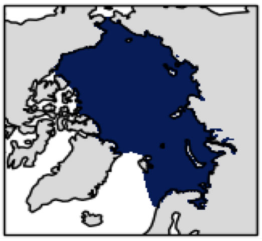


Figure 1. Study area

This research focuses on the Arctic Ocean basin, specifically encompassing the Central Arctic and its adjoining seas: Beaufort, Chukchi, East Siberian, Laptev, Kara, and the Barents Sea (Fig 1). The Arctic region was selected for this study due to its significant susceptibility to climate variations and its paramount importance in global climate systems. By examining this region, we aim to offer valuable insights into the broader implications of sea ice changes on the global climate.

The essence of a climate model lies in its ability to transcribe observed patterns into code using physical equations, forecasting potential future climate shifts. These predictions serve as invaluable tools for policymakers to devise strategies to counter climate change impacts. The climate system is complex, with various factors such as vegetation, human activities, geology, oceans, and volcanic eruptions potentially influencing climate change. Due to this complexity, different scientists create different climate models. It is difficult for policymakers to determine which climate model to trust. Although climate models can be evaluated using indicators, no model has an absolute advantage, so policymakers should not rely on a single model but should use the average to predict climate change.

In this study, we analyze data from 15 CMIP6 models, originating from nine different modeling centers, and data from 3 configurations of the NEMO-CICE ocean sea ice model, which has a similar formulation to one of the CMIP6 models used in this study (HadGEM3-GC3.1-LL) [13]. All these models, and the data provided from each, are listed in Table 1. For each model, the ice area and mass and the area-weighted monthly mean ice mass budget terms were calculated over the domain shown in Fig. 1a, covering the Arctic Ocean basin and the Barents Sea.

Multi-model means are calculated by first averaging all the realizations for each model and then averaging the resulting ensemble means. The mass budget terms are summarized as follows:

-basal growth, ice growth at the base of existing ice;

-frazil ice formation, ice formation in supercooled open water;

-top melt, melting at the top surface of the ice;

-basal melt, melting at the base of the ice;

-lateral melt, melting at the sides of the ice;

-snow ice, ice formation due to the transformation of snow to sea ice due to surface flooding;

-evapsubl, the change in ice mass due to evaporation and sublimation;

-advection, the change in ice mass due to ice being advected into or out of the analysis domain.

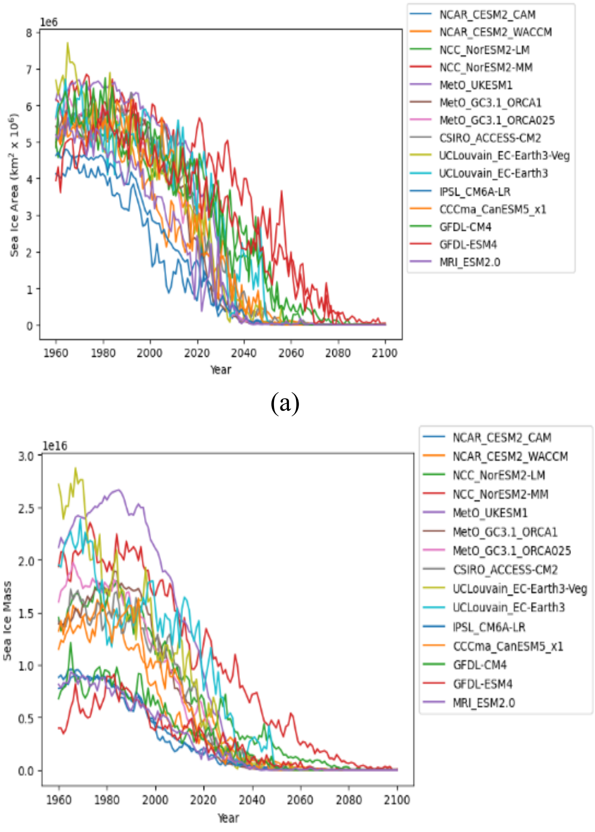
The monthly mean data were calculated for the period 1960-2100 from model integrations using the CMIP6 Hist forcing scenario for the period 1960-2014 and SSP5-8.5 thereafter [14]. The SSP5-8.5 scenario was primarily chosen because, for the majority of participating modeling centers, this was the first scenario to be run, but it also has the advantage of being the scenario with the highest warming signal. This means that we saw relatively large changes in the ice state and the budget terms during the 21st century, and differences between the model budget terms are likely to be more pronounced.

Table 1. List of models and corresponding modeling centers in this study

Model name	Modeling center	No. of integrations Hist	No. of integrations SSP585.5	Notes
HadGEM3-GC31-LL	Met Office	4	4	
HadGEM3-GC31-MM	Met Office	4	4	
UKESM1-0-LL	Met Office	12	5	
EC-Earth3L	UCLouvain/AEMET	1	1	No explicit lateral melt
EC-Earth3-Veg	UCLouvain/SMHI	1	1	There is no explicit lateral melt, and the dynamics term is missing
MRI-ESM2	MRI	5	1	No explicit lateral melt or frazil ice formation
CESM2-CAM	NCAR	11	2	
CESM2-WACCM	NCAR	3	2	
GFDL-CM4	GFDL	1	1	No explicit lateral melt
GFDL-ESM4	GFDL	1	1	No explicit lateral melt
CSIRO_ARCCSS_ACCESS-CM2	CSIRO	1	1	
NorESM2-LM	Met Norway	3	1	
NorESM2-MM	Met Norway	32	1	
CanESM5	ECC	3	3	Missing terms: frazil, lateral melt, evapsubl, dynamics
IPSL_CM6A-LR_default	IPSL	32	2	No explicit lateral melt
NEOMOICE_CORE_default	CPOM	1	1	Forced ocean-ice model (no scenario data)
NEOMICE_CORE_CPOM-CICE	CPOM	1	1	
NEOMICE_DFS5.2_CPOM-CICE	CPOM	1	1	

Note: Where two modeling centers are shown, the first analyzed the model outputs and the second performed the model integrations.

3. Results



(a)

(b)

Figure 2. (a)Image of the predicted variations in sea ice area from 1960 to 2100; (b)Image of the predicted variations in sea ice mass from 1960 to 2100

It is discernible that there are different predictions according to various climate models about the trajectory of the Arctic glacier recession (Fig.2(a) and Fig.2(b)). Such heterogeneity accentuates the multifaceted nuances and inherent contingencies encapsulated within the epistemological framework of each model. It is uncertain when Arctic glaciers will completely melt. There are significant differences in the predicted melting rates among different climate models, with the projected melting time ranging from 2040 to 2100, a difference of 60 years. Such a substantial range not only highlights the nascent nature of our contemporary predictive models but also emphasizes the critical window available for proactive interventions. This indicates that there is a lot of uncertainty in the predictions of current climate models, reflecting the immaturity of these models, which need further improvement. This uncertainty also means that there is still time for action and to find effective solutions to mitigate the impact of Arctic glacier melting. It emphasizes the need for scientists to continue efforts to improve climate models to enhance prediction accuracy and reliability.

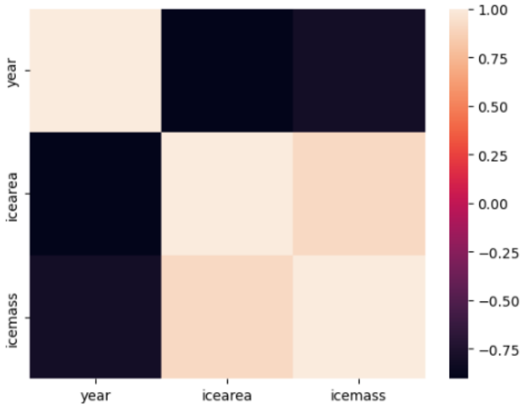
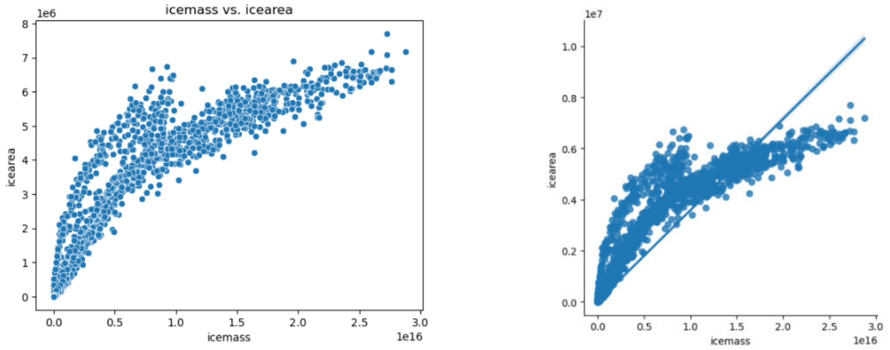


Figure 3. Correlation heatmap plot of sea ice area and sea ice mass.

Nevertheless, amidst this diversity of predictions, all the models have consistent results that there would be a marked reduction in the Arctic's ice coverage and volume, especially in the absence of substantive mitigation of carbon emissions. Analyzing the representations in Fig.2(a) and Fig.2(b), it becomes salient that, notwithstanding the distinct characteristics of each model, there exists a convergent consensus regarding the precipitous declination of ice metrics. Such consensus, despite the inherent model-specific discrepancies, underscores the gravity of the looming ecological perturbations. Furthermore, the heatmap presented in Fig.3 provides a nuanced depiction of this trend. The gradational variation in chromaticity, particularly when juxtaposing 'year' with 'ice area' and 'ice mass', delineates a robust inverse relationship between the temporal continuum and the associated cryospheric parameters. This comprehensive visualization not only reaffirms the aforementioned analytical inferences but also amplifies the imperative for rigorous scientific exploration and sagacious interventions to preempt the prospective deleterious outcomes. It behooves policymakers to delineate and promulgate prescriptive measures commensurate with this urgency.



(a) (b)

Figure 4. (a) Scatterplot of sea ice area and sea ice mass for the given data frame. (b) Scatterplot of sea ice area and sea ice mass for the given data frame, with a regression line. Pearson R Result (statistic=0.908, p value=0.000)

The results indicate that there is an interdependent relationship between sea ice area and sea ice mass. There is a significant correlation evident by the clustering of data points according to the scatterplots illustrated in Fig.4(a) and Fig.4(b). The accompanying regression line in Fig.2(b) also reiterates this observation, with a Pearson R statistic of approximately 0.908, indicating a robust correlation. This robust correlation is crucial for understanding the dynamics of sea ice, as it implies that variations in the area covered by sea ice are not happening in isolation, but are closely tied to changes in the mass of the sea ice. This relationship is significant for climatologists and researchers studying polar regions, as it can provide insights into how changes in one aspect of the sea ice could potentially affect another, aiding in the creation of more accurate models and predictions for future sea ice behavior under different climate scenarios.

4. Discussion

4.1. Factors causing different predictions of glacier melting by different models

Different climate models, while exhibiting consensus in some areas, portray variability in their projections concerning the rate of glacier melting. Such heterogeneities may stem from the models' varying emphases on factors beyond temperature that potentially contribute to glacier melting. A study conducted by Krishnan et al. (2019) elucidated that some climate models foregrounding accelerated glacier melting typically project a more pronounced increase in temperature [15]. Conversely, those anticipating a more gradual rate of glacier melt tend to correlate with modest temperature rises. This posits that the magnitude of temperature augmentation may have a direct bearing on the anticipated rate of glacier recession. Su et al. (2022) delved into the intricate nexus between glacier melting and extraneous determinants beyond temperature [16]. They posited that a correlation coefficient approaching unity would signify the exclusivity of temperature as the predominant influence on glacier melting. In contrast, a substantially diminished correlation coefficient would intimate the potential interplay of alternative factors influencing glacier dynamics. Their findings revealed a coefficient of 0.78, suggesting that while temperature remains a cardinal determinant, other physical and atmospheric parameters also contribute substantively to glacier melting dynamics.

To interrogate the potential oversights leading to these disparities, a hypothetical scenario can be envisaged in the future study wherein two models project equivalent temperature rises. If these models, despite the analogous temperature predictions, diverge in their glacier melt projections, it would bolster the hypothesis that variables beyond temperature play an instrumental role in influencing glacier dynamics. Such an outcome would be corroborative of the postulation that glacier melting is contingent not merely on thermal variables but is modulated by an array of physical processes.

4.2. Environmental Policies for Climate Change

Glacier melting is a climate phenomenon that has attracted attention. It is generally believed that glacier melting is primarily caused by greenhouse gas emissions leading to global warming. The atmospheric concentration of carbon dioxide and other greenhouse gases produced by industry, transport, deforestation, and burning fossil fuels, among other human activities, warm the planet. Oceans absorb 90% of the Earth's warmth, and this affects the melting of marine glaciers. In the wake of mounting evidence pointing towards the imminent threats posed by glacier melting, environmental policy formulation and implementation become paramount. Research has consistently underscored the significant role of anthropogenic activities, primarily greenhouse gas emissions, in exacerbating this global challenge [17]. As iterated in section 4.1, while the correlation between temperature rising and glacial melt is undeniably strong, other factors may also come into play, emphasizing the need for a comprehensive policy response.

Firstly, addressing the root causes of glacier melting necessitates a reevaluation of the world's reliance on fossil fuels. Policies aiming to reduce carbon emissions, such as the imposition of carbon taxes, subsidy reallocations from fossil fuels to renewable energy sources, and stricter emissions standards for industries, are vital [18]. Such policies not only mitigate the direct impacts on glaciers but also address broader climate change implications.

Secondly, environmental policies should also encompass adaptive strategies. Recognizing that some degree of glacier melting is now inevitable, strategies must be formulated to adapt to the changing landscapes, rising sea levels, and associated ecological and socio-economic repercussions [19]. This entails infrastructural developments in vulnerable areas, conservation efforts for affected ecosystems, and social safety nets for communities at risk.

Furthermore, international cooperation is indispensable. Glacier melting is a transboundary issue, and its implications, from rising sea levels to changing weather patterns, are felt globally. Collaborative research, shared technology, and coordinated policy measures, as exemplified by the Paris Agreement, are necessary to address the multifaceted challenges posed by this phenomenon [20].

5. Conclusion

This study focuses on analyzing 18 CMIP-6 models to form a prediction of ice mass and ice area between 1960-2050, which helps to compare and conclude of Arctic melting rate and the year that sea ice will entirely melt down. This study offers an enhanced comprehension of the Arctic ice trajectory by rigorously analyzing and contrasting various climate models, thereby addressing the extant knowledge gaps in predictive tools. Practically, the findings underscore the urgency for coordinated global action to reduce carbon emissions, emphasizing the imminent ecological shifts and challenges. The results indicate that all the models have consistent results that there would be a marked reduction in the Arctic's ice coverage and volume. However, different climate models have different predictions for the rate of glacier melting, which may be related to the predicted magnitude of temperature increase and the influence of other physical processes. Further research on climate change and the physical processes related to glacier melting is needed to more accurately predict the speed of glacier melting.

While this study offers valuable perspectives, it presents certain limitations. One limitation is the lack of thorough examination of the factors contributing to the discrepancies among the different models. Future research could delve deeper into these foundational elements to provide a more holistic grasp of model discrepancies and the ensuing ramifications.

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