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Key Points:

- Future Arctic climate change in winter strongly depends on the strength of the increase in poleward ocean heat transport (OHT)
- Arctic climate change in the NEMO-family climate models is much more pronounced
- NEMO-family climate models have larger increases in poleward OHT

Supporting Information:

Supporting Information may be found in the online version of this article.

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Future Arctic Climate Change in CMIP6 Strikingly Intensified by NEMO-Family Climate Models

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Abstract Climate change in the Arctic has substantial impacts on human life and ecosystems both within and beyond the Arctic. Our analysis of CMIP6 simulations shows that some climate models project much larger Arctic climate change than other models, including changes in sea ice, ocean mixed layer, air-sea heat flux, and surface air temperature in wintertime. In particular, dramatic enhancement of Arctic Ocean convection down to a few hundred meters is projected in these models but not in others. Interestingly, these models employ the same ocean model family (NEMO) while the choice of models for the atmosphere and sea ice varies. The magnitude of Arctic climate change is proportional to the strength of the increase in poleward ocean heat transport, which is considerably higher in this group of models. Establishing the plausibility of this group of models with high Arctic climate sensitivity to anthropogenic forcing is imperative given the implied ramifications.

Plain Language Summary Arctic climate is projected to change dramatically in the future based on the latest climate models. However, there is a large discrepancy between these climate models. We find that simulated Arctic climate change tends to be much larger in models using the community ocean model "NEMO" as their ocean component. Future Arctic climate change in winter strongly depends on the strength of the increase in poleward ocean heat transport, which is considerably higher in the NEMO-family climate models. There are some indications that this group of models can better reproduce the observed winter sea ice decline and mixed layer depth in the Barents Sea in their historical simulations. We suggest that investigating the model physics in the NEMO-family climate models in comparison with other models may ultimately help to reduce the overall uncertainty in climate change projections.

1. Introduction

The Arctic is very susceptible to global climate change. Its surface air temperature (SAT) is warming at a rate 2–4 times higher than the global average starting from the 1970s (Bekryaev et al., 2010; Holland & Bitz, 2003; Rantanen et al., 2022; Serreze & Barry, 2011). The phenomenon of Arctic amplification has been found not only in historical observations and climate model projection simulations, but also in proxy reconstructions of paleo climate changes (Pithan & Mauritsen, 2014; Renssen et al., 2009). Warming amplification has also been detected in the ocean component of the Arctic based on analysis of climate models (Shu et al., 2022). The sea ice decay associated with Arctic warming is a crucial indicator of both Arctic and global climate changes (Notz & Stroeve, 2016; Polyakov et al., 2010; Shu et al., 2022). Arctic sea ice extent (SIE) in September has halved since the late 1970s (Perovich et al., 2017) and the location of the winter sea ice edge has also considerably retreated, potentially affecting weather and climate across the Northern Hemisphere (Cohen et al., 2014; Coumou et al., 2018; Overland et al., 2016; Screen et al., 2018).

Atmosphere-ocean-sea ice interactions play an important role in Arctic climate change. The presence of Arctic sea ice limits the vertical mixing in the upper ocean and maintains a cold halocline (Fer, 2009; Polyakov et al., 2017), which is an insulating barrier between the underlying warm Atlantic Water layer and the mixed layer and sea ice above. However, with the rapid increase in Arctic temperatures and the melting of sea ice, the Arctic Ocean stratification is changing. The reduction in sea ice cover has promoted stronger vertical mixing in the upper ocean (Rainville & Woodgate, 2009; Tsamados et al., 2014) and weakened the halocline stratification in the Arctic Eurasian Basin (Polyakov, Rippeth, et al., 2020; Wang & Danilov, 2022). These ocean changes could contribute to the ventilation of the Atlantic Water layer and enhance sea ice basal melting (Polyakov et al., 2017; Polyakov, Alkire, et al., 2020). A positive trend in the poleward ocean heat transport (OHT) to the Arctic Ocean by Atlantic inflows over the past decades has been found, and it has greatly influenced the Arctic climate (Årthun et al., 2012; Barton et al., 2018; Tsubouchi et al., 2021; Wang et al., 2020). Arctic Atlantification was observed in the Barents Sea and the eastern Eurasian Basin (Ingvaldsen et al., 2021; Polyakov et al., 2017). Climate model simulations indicate that persistent increases in Atlantic Water heat inflow to the Arctic Ocean in a warming climate will sustain the Arctic Ocean amplification (Shu et al., 2022) and feed the Arctic atmospheric amplification as well (Beer et al., 2020; Shu et al., 2022; van der Linden et al., 2019). However, in a future warming climate, the Barents Sea will lose cooling efficiency due to stronger atmospheric warming in this region, and the remaining ocean heat will become an important source of ocean warming in the Arctic deep basin, with strong impacts on ocean stratification, winter sea ice cover and atmosphere warming in the Arctic interior (Shu et al., 2021, 2022).

Climate models are key tools for understanding future climate changes (Jahn, 2018; Landrum & Holland, 2020; Screen et al., 2018), although they are often subject to large uncertainties in the Arctic, such as for the simulated Arctic warming (Latonin et al., 2021; Pithan & Mauritsen, 2014; Smith et al., 2019), sea ice decline (Docquier et al., 2019; Li et al., 2017; Notz & Community, 2020), and Arctic Ocean hydrography and stratification (Heuzé et al., 2023; Khosravi et al., 2022; Muilwijk et al., 2022; Shu et al., 2019). Future changes in the Arctic climate will have significant impacts on human life and marine ecosystems (Chambault et al., 2022; Ingvaldsen et al., 2021). Therefore, it is required to improve the understanding of the extent and influencing factors of the Arctic climate sensitivity in state-of-the-art climate models.

Here, based on the simulations of the Coupled Model Intercomparison Project Phase 6 (CMIP6), we investigate the processes of Arctic atmosphere-ocean-sea ice interactions in a warming climate. We find that the winter ocean surface mixed layer depth (MLD), sea ice cover, sea surface heat flux (SSHF), and SAT in the Arctic are projected to change dramatically in the future, but their changes have great discrepancies across CMIP6 models, especially in the Eurasian Basin. The discrepancies are significantly correlated between these climate variables, and can be largely explained by the difference in the simulated poleward OHT from the North Atlantic, which interestingly has a strong dependence on the ocean model component used in the climate models. Specifically, we find that the large group of climate models with NEMO (Nucleus for European Modelling of the Ocean) as their ocean model component tend to simulate higher poleward OHT and thus much more rapid Arctic climate change compared to other climate models.

2. Materials and Methods

The first realizations of 23 CMIP6 coupled models listed in Table S1 in Supporting Information S1 are used. These are the models that provided all the required variables. The simulations for the period from 1950 to 2014 are from their historical experiments. The future projections are driven by external forcing based on the Shared Socioeconomic Pathway 585 (SSP5-8.5) scenario, which represents the high end of the range of future pathways with an effective radiative forcing of 8.5 W m^{-2} in 2100 (O'Neill et al., 2016; Riahi et al., 2017).

To assess the simulations of sea ice in CMIP6 climate models in the historical period, we use satellite observations of SIE from the National Snow and Ice Data Center (NSIDC; Meier et al., 2021). We compare the simulated OHT in CMIP6 historical simulations with the estimate from the Ocean ReAnalysis System 5 (ORAS5; Zuo et al., 2019). The fifth generation ECMWF reanalysis (EAR5; Hersbach et al., 2020) and Polar science center Hydrographic Climatology (PHC; Steele et al., 2001) are also used in this study to evaluate the simulations of Arctic surface air warming and the climatology of ocean surface MLD, respectively.

In this study, the ocean surface MLD is defined as the depth where the potential density is larger than the surface potential density by 0.1 $\mathrm{kg/m^3}$ (Peralta-Ferriz & Woodgate, 2015). The SIE is calculated as the sum of grid cell areas where sea ice concentration (SIC) is larger than 15%. The OHT through each Arctic Ocean gateway is calculated using monthly seawater potential temperature and ocean velocity following Shu et al. (2022) as:

$$\mathrm{OHT}(v,T) = \rho_0 c_p \int_{-H(\lambda)}^{0} \int_{\lambda_1(z)}^{\lambda_2(z)} v(T - T_{\mathrm{ref}})\, d\lambda\, dz \tag{1}$$

where ρ_0 is the density of sea water, c_p is the specific heat capacity of sea water, v is ocean velocity locally perpendicular to the section of each gateway, T is potential temperature in the section, T_{ref} is reference temperature set

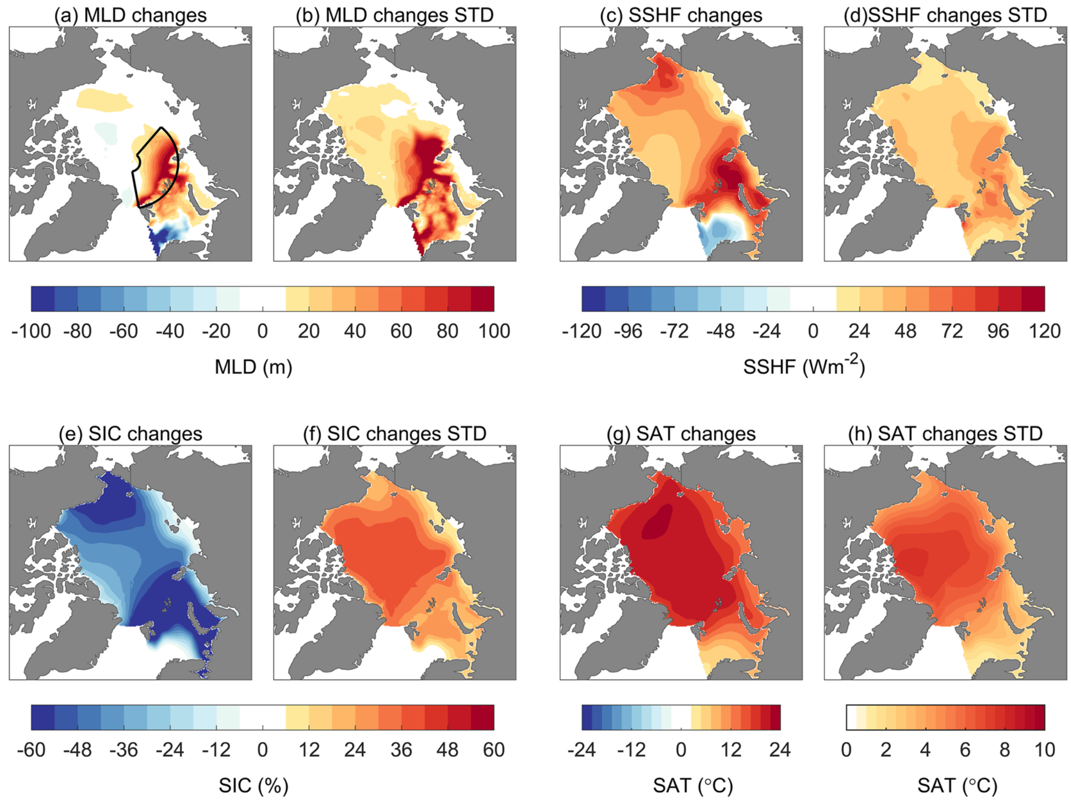

Figure 1. Arctic future climate changes. The changes of winter (January to March) average (a) ocean mixed layer depth (MLD), (c) sea surface heat flux (SSHF), (e) sea ice concentration (SIC), and (g) surface air temperature (SAT) for the period of 2081–2100 relative to the period of 1979–2020 based on CMIP6 multimodel mean results. Their intermodel spreads (one standard deviation) are shown in (b), (d), (f), and (h), respectively. The black box in (a) represents the Eurasian Basin used in Figures 2 and 4. Positive SSHF changes in (c) indicate enhanced ocean surface heat loss.

to 0°C in this study, H is water depth, and λ is the distance along the gateway transect. OHT is calculated along the zigzag grid lines on the native model grids to largely guarantee heat conservation and avoid ambiguities associated with a regridded land/sea mask.

3. Results

3.1. Arctic Future Climate Change in CMIP6

Under the SSP5-8.5 scenario, dramatic future changes in Arctic climate are projected by CMIP6 models (Figure 1). The depth of the ocean surface mixed layer of the Arctic Ocean has important impacts on the heat transfer between the ocean, sea ice, and atmosphere (Sirevaag et al., 2011; Steele et al., 2011). CMIP6 multimodel mean (MMM) results show that winter MLD in the eastern Eurasian Basin will deepen markedly in the future. Relative to the period of 1979–2020, the winter MLD averaged over the whole Eurasian Basin is projected to be deeper by >50 m in the period of 2081–2100 (the long-term future period considered in this study), while regionally the increase in the MMM MLD along the Eurasian continental slope can reach >100 m (Figure 1a). The deepening of the MLD is related to stronger winter convection represented by more sea surface heat release (Figure 1c). The largest increase in winter SSHF is located along the inflow pathways of Atlantic and Pacific waters. In the Atlantic sector, the strong increase in the MLD of >100 m is colocated with the dramatic increase in the SSHF of >80 W m^{-2} in the northern Kara Sea and along the continental slope of the Eurasian Basin (Figures 1a and 1c). The regional decrease in MLD and SSHF in the southwestern Barents Sea reflects the reduction in the ocean cooling efficiency in this region in a warming climate (Shu et al., 2021; Skagseth et al., 2020).

The increase in ocean surface heat release is associated with the reduction in the sea ice cover in a warming climate, as indicated by the spatial correlation between the changes in SSHF and SIC (compare Figures 1c

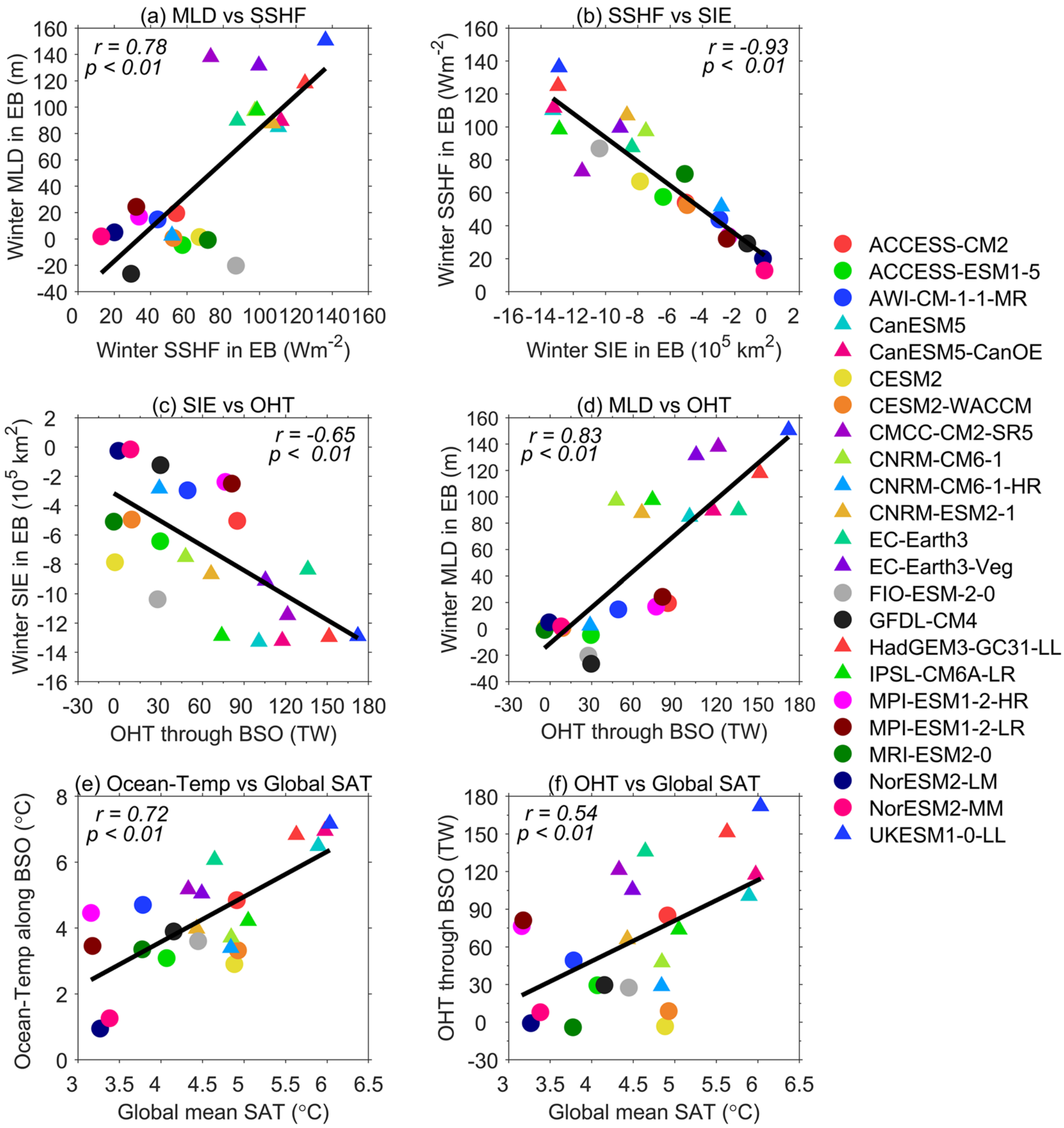

Figure 2. The relationship between the future changes of main climate variables in CMIP6 models. Scatter plots of future changes: (a) winter mixed layer depth (MLD) versus winter sea surface heat flux (SSHF), (b) winter SSHF versus winter sea ice extent (SIE), (c) winter SIE versus annual mean ocean heat transport (OHT) through the Barents Sea Opening (BSO), (d) winter MLD versus annual mean OHT through the BSO, (e) ocean temperature along the BSO versus global mean surface air temperature (SAT), and (f) OHT through the BSO versus global mean SAT. The MLD, SSHF, and SIE are calculated over the Eurasian Basin indicated by the black box in Figure 1. The black lines show the linear fit. The changes are the differences between the periods of 2081–2100 and 1979–2020. CMIP6 models with NEMO as their ocean component are marked by triangles, and other models are marked by circles.

and 1e). For the period of 2081–2100, the winter SIC decreases by >30% in the Arctic Ocean, with the greatest reduction of >60% in the Eurasian Basin, Chukchi Sea, northern Barents Sea, and Kara Sea (Figure 1e). Winter sea ice decline weakens the insulating effect of sea ice in air-sea heat exchange. The winter SAT in the Arctic will rise dramatically (Figure 1g), which partially can be attributed to the increase in ocean heat release to the atmosphere. The winter SAT averaged over the Arctic will rise by >14°C at the end of the 21st century. The SAT increase in the midterm future (2041–2060) clearly demonstrates the direct effect of the ocean surface heat release along the Atlantic Water inflow in warming the atmosphere, as the SAT increase is intensified over the Kara Sea and Eurasian Basin (Figure S1 in Supporting Information S1). The spatial pattern of the SAT change becomes more uniform in the Arctic at the end of the 21st century (Figure 1g), which is linked to the fact that the winter sea ice decline and SSHF increase in the central Arctic are more apparent in the long-term future (Figures 1c, 1e, and Figures S1c, S1e in Supporting Information S1).

The spatial patterns of the future wintertime climate change in the Arctic indicate that the ocean, sea ice, and atmosphere in the Arctic strongly interact with each other, and the ocean heat convergence to the Arctic Ocean from lower latitudes is a key player in driving Arctic climate change. The latter implies that the representation of the ocean processes in the CMIP6 models can strongly influence the simulated Arctic climate change, which will be addressed below by analyzing individual models.

3.2. Different Arctic Climate Sensitivity

The changes in MLD, SSHF, SIC, and SAT in CMIP6 models have a large intermodel spread (one standard deviation) (Figure 1 and Figure S1 in Supporting Information S1), which indicates that CMIP6 models have a great difference in Arctic climate sensitivity. For example, winter MLD in 10 models (CanESM5, CanESM5-CanOE, CMCC-CM2-SR5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, EC-Earth3-Veg, HadGEM3-GC31-LL, IPSL-CM6A-LR, and UKESM1-0-LL) will deepen markedly in the Eurasian Basin (Figure S2 in Supporting Information S1). In these models, the winter MLD increases by >200–300 m in the eastern Eurasian Basin, while MLD increase is nearly absent in this region in other models.

We find that the climate change signals of winter MLD, SSHF, and SIE in the Eurasian Basin are significantly correlated among the models (Figure 2). The correlation coefficients of the SSHF changes with the MLD and SIE changes are 0.78 and −0.93 (Figures 2a and 2b), respectively, and both exceed the 99% confidence level. In winter, lower SIE with larger open water areas allows stronger surface cooling as indicated by larger sea surface heat release, which causes stronger winter convection and deeper MLD. Meanwhile, deeper MLD tends to bring more oceanic heat upwards to enhance sea ice basal melting. Therefore, the physical process of atmosphere-ocean-sea ice interaction can explain the significant correlations between the model spreads of the simulated MLD, SSHF, and SIE.

As mentioned above, the largest changes in MLD, SSHF, and SIC in the Atlantic sector follow the pathways of Atlantic Water inflow (Figure 1 and Figure S1 in Supporting Information S1). This indicates that future Arctic climate changes are closely related to the increased OHT into the Arctic Ocean, which can cause ocean warming, sea ice decline, and increase in SSHF and MLD in previously ice-covered areas (Årthun et al., 2017; Docquier & Koenigk, 2021; Shu et al., 2021, 2022). Therefore, significant correlations can be found between the future changes of the winter SIE and MLD in the Eurasian Basin and the future changes of the annual mean OHT through the Barents Sea Opening (BSO; Figures 2c and 2d). The future increase in net OHT through the BSO is much more prominent than that through the Fram Strait (Figure S3 in Supporting Information S1). The future changes in OHT through the BSO in the CMIP6 models have a great discrepancy with a range from about 0 to 170 TW (Figures 2c and 2d), so the future changes in Arctic climate are very different between the models.

3.3. Arctic Climate Sensitivity Linked to Ocean Component Models

The magnitudes of simulated climate changes can be influenced by many factors, such as natural internal variability, model numerics, parameterizations, model resolutions. Here, we find that the future Arctic climate projections are closely linked to the ocean models used in different climate models. Among the 23 climate models analyzed in this study, 11 models employ the NEMO ocean model or modified versions based on it (Table S1 in Supporting Information S1). It is obvious that the NEMO-family climate models tend to simulate larger climate changes with more pronounced increase in MLD and SSHF and larger reduction in SIE in the Eurasian Basin in accordance with stronger increase in BSO heat inflow (Figures 2a–2d, where NEMO-family climate models are marked with triangles). The aforementioned 10 models with regional MLD increase of >200 m in the eastern Eurasian Basin all belong to the NEMO family (Figure S2 and Table S1 in Supporting Information S1). Other model components of the climate models and detailed model configurations can also influence the simulated Arctic climate changes as shown by the different results within the climate models of the NEMO family, but our analysis suggests that it is highly possible that the choice of ocean models have the largest impact on the Arctic climate change projections.

The striking impact of the ocean models on the simulated Arctic climate changes is illustrated by comparing the changes in winter MLD, SSHF, SIC, SIE, and SAT between the NEMO-family climate models and the non-NEMO models in Figures 3 and 4. There is a strong contrast in the winter MLD changes between the two model groups (Figures 3a and 3b). The NEMO-family climate models simulate a pronounced mixed layer deepening of >200 m

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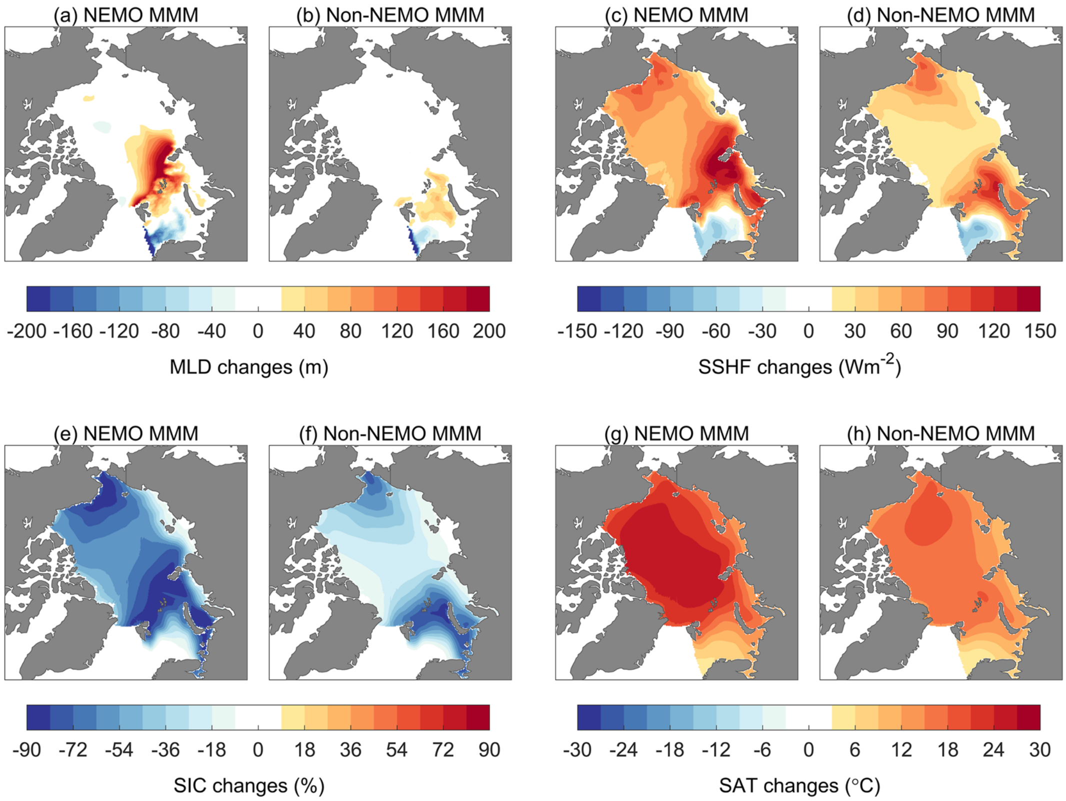

Figure 3. Arctic future climate changes in two groups of CMIP6 models. The changes of winter (January to March) (a, b) ocean mixed layer depth (MLD), (c, d) sea surface heat flux (SSHF), (e, f) sea ice concentration (SIC), and (g, h) surface air temperature (SAT) for the period of 2081–2100 relative to the period of 1979–2020. (a), (c), (e), and (g) are multimodel mean (MMM) results of the climate models employing NEMO. (b), (d), (f), and (h) are MMM results of other climate models.

in the eastern Eurasian Basin (Figure 3a), while the non-NEMO models only obtain MLD increases of a few tens of meters in the northern Barents and Kara Seas (Figure 3b). The MMM MLD increase in the Eurasian Basin in CMIP6 projections can be mainly attributed to the NEMO-family climate models (Figure 4a). The increase in the SSHF in the eastern Eurasian Basin can reach >150 W m^{-2} averaged over the NEMO-family climate models, about twice the magnitude of the non-NEMO models (Figures 3c and 3d).

The projections of Arctic sea ice also differ dramatically between these two groups of models for SIC (Figures 3e and 3f) and SIE (Figure 4b). In the NEMO-family climate models, the strong reduction of SIC in the southern Eurasian Basin and Chukchi Sea implies that these areas will be nearly ice-free in winter at the end of the 21st century, while in the non-NEMO models the SIC reduction is only about 50% in these areas (Figures 3e and 3f). In these two groups of models, the winter SIE in the Eurasian Basin is 2.5×10^5 km^2 (80% reduction) and 6.5×10^5 km^2 (50% reduction) at the end of this century, respectively (Figure 4b).

A large discrepancy in SAT projections between these two model groups is also clear. In 2081–2100, the winter SAT will increase by >24°C in the central Arctic in the NEMO-family climate models, but <18°C in the non-NEMO models (Figures 3g and 3h). Averaged across the Arctic, the increase in the winter SAT at the end of the 21st century is about 5°C higher in the NEMO-family climate models (Figure 4c).

The intriguing difference in the simulated Arctic climate changes between the two model groups is associated with their great discrepancy in the OHT through the BSO (Figure 4d). On average, both model groups simulate positive trends in the OHT through the BSO in a warming climate, but the OHT in the NEMO-family climate models is nearly twice as much as in the non-NEMO models at the end of the 21st century (Figure 4d). For the Fram Strait, the simulation discrepancy in the future change of the net OHT between the two model groups is relatively small compared with the BSO (Figure S3 in Supporting Information S1). The discrepancy in the OHT through the Bering Strait between the two model groups (Figure S3 in Supporting Information S1) is consistent

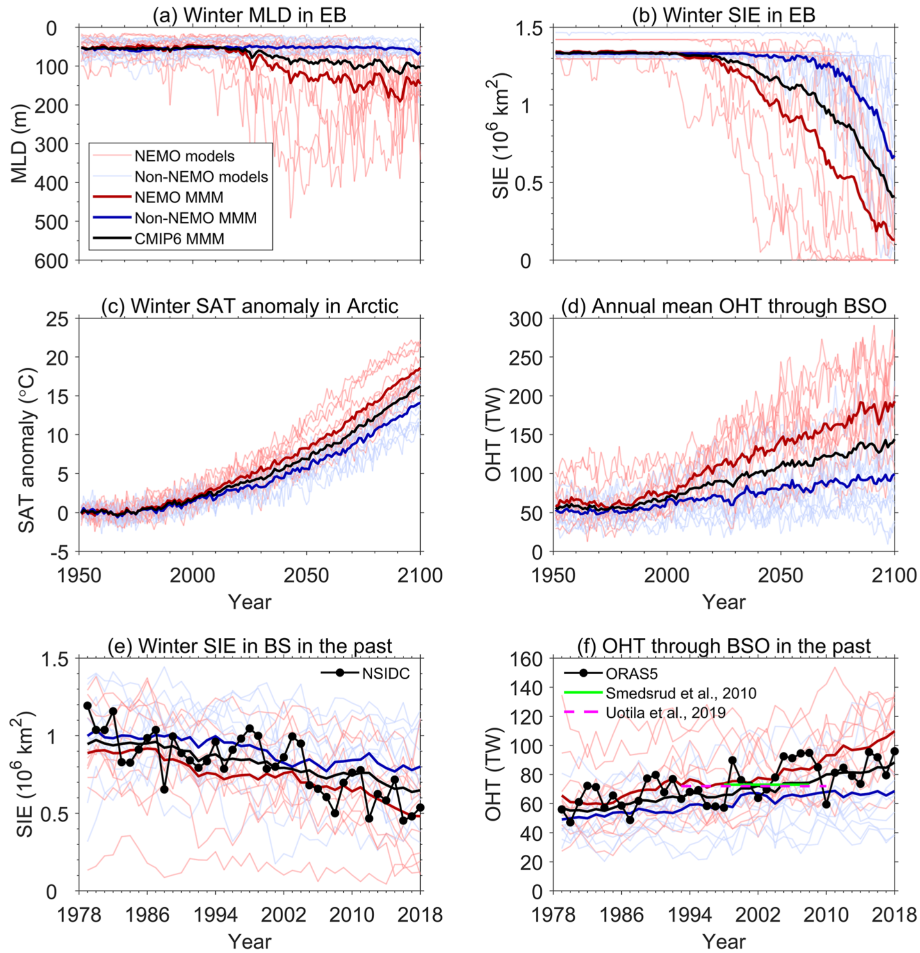

Figure 4. Time series of Arctic climate variables and ocean heat transport (OHT). (a) Winter (January to March) ocean mixed layer depth (MLD) and (b) winter sea ice extent (SIE) in the Eurasian Basin (EB). (c) Winter surface air temperature (SAT) anomaly in the Arctic relative to the period of 1951–1970. (d) Annual mean net OHT through the Barents Sea Opening (BSO). (e) Winter SIE in the Barents Sea (BS) in the historical simulations and observations. (f) Annual mean OHT through the BSO during 1979–2018. The green line in (f) is the estimated OHT through the BSO in the period of 1997–2008 from Smedsrud et al. (2010). The magenta dashed line in (f) is the estimated OHT through the BSO in the period of 1993–2010 based on the average of 10 different reanalysis data sets from Uotila et al. (2019).

with their difference in winter sea ice decline in the Pacific sector of the Arctic Ocean (Figures 3e and 3f). The larger increases in OHT through the BSO and Bering Strait cause more rapid Arctic Ocean warming in the NEMO-family climate models. The Arctic Ocean Amplification factor, the ratio of the warming rate of the Arctic Ocean to that of the global ocean (considering the whole ocean depth; Shu et al., 2022) is 3.7 and 2.1 in the NEMO and non-NEMO family of climate models, respectively.

The positive trend in OHT through the BSO is mainly caused by the increases in ocean temperature at the BSO in a warming climate (Shu et al., 2022), which is the case for both the model groups (Figures S4 and S5 in Supporting Information S1). Significant correlations are found between the future changes of ocean temperature and OHT at the BSO and the future change of the global mean SAT (Figures 2e and 2f). Despite the fact that all models are driven by the same anthropogenic forcing, the NEMO-family climate models tend to simulate much stronger global warming, which is associated with larger poleward OHT. Two non-NEMO climate models CESM2 and CESM2-WACCM also have high global climate sensitivity to anthropogenic forcing (Zelinka et al., 2020) and thus relatively large increase in global mean SAT in a warming climate, but they have weak increases in poleward OHT (Figure 2f), thus weak sea ice decline and small changes in MLD (Figures 2c and 2d).

4. Discussion

CMIP6 MMM results indicate that the Arctic will experience rapid climate changes in the future under the SSP5-8.5 scenario, especially in the Eurasian Basin, where winter atmosphere-ocean-sea ice interaction will become stronger in a warming climate. However, CMIP6 models show great discrepancy in the magnitude of the projected Arctic climate change. Our study reveals that the magnitudes of the Arctic climate changes in winter, including sea ice cover, ocean surface mixed layer, sea surface heat loss, and air temperature, are significantly correlated with future changes in poleward ocean heat convergence. We also find that the climate models with NEMO as their ocean component tend to project larger increase in OHT into the Arctic Ocean, which further leads to greater Arctic climate changes in winter. So, a large part of the intermodel spread in Arctic climate sensitivity stems from the choice of ocean component in coupled climate models. The reasons for this ocean model dependence need further investigation, and warrant a concerted effort in the model development community. For example, the role of vertical mixing schemes employed in coupled climate models should be better understood. NEMO employs the TKE turbulent closure scheme (Madec et al., 1998), while the K-Profile Parameterization vertical mixing scheme (Large et al., 1994) is often used in other ocean models.

Over the past several decades, increased OHT through the BSO induced rapid sea ice decline in the Barents Sea in winter, which is one of the most prominent signals of climate change in the Arctic. The comparison between observations and the two groups of CMIP6 climate models for the winter SIE in the Barents Sea (Figure 4e) indicates that the non-NEMO models slightly overestimate the SIE mean state and underestimate the SIE trend, while the NEMO-family climate models are closer to observations. We also use the OHT through the BSO in the ORAS5 reanalysis and the estimate from a set of reanalysis data sets (Uotila et al., 2019) to evaluate CMIP6 climate models. The results suggest that non-NEMO models might slightly underestimate the mean OHT and its upward trend in the historical simulations, while NEMO-family climate models might have slight overestimations (Figure 4f). We note that these reanalysis data sets are also based on simulations and might be subject to uncertainties. The difference of Arctic surface warming trends during 1979–2021 between the two model groups is consistent with the difference in OHT, with the NEMO-family climate models overestimating the air temperature trend in the Barents Sea and non-NEMO climate models underestimating the trend (Figure S6 in Supporting Information S1). MLDs from these two model groups are also compared with that derived from PHC3.0 (Figure S7 in Supporting Information S1), indicating that the NEMO-family climate models are slightly better in simulating winter MLD. The above comparisons of sea ice and MLD simulations indicate that the NEMO-family climate models may better project future Arctic climate change, while this is somehow inconclusive considering the model performance in the representation of OHT and air warming in the historical period.

Studies using previous-generation climate models indicate that deep convection is likely to emerge in the Arctic Ocean in a warming climate (Lique & Thomas, 2018; Lique et al., 2018). Here, we show that in CMIP6 models deep convection of a few hundred meters may emerge within this century under the scenario of SSP5-8.5 only in NEMO-family climate models. Considering the surprisingly large differences in simulated Arctic climate change between the NEMO-family climate models and non-NEMO climate models, even when using multiple models from CMIP6 to assess future Arctic climate, the MMM results can be strongly influenced by the availability of required model data from different groups of models (i.e., how many models from each group are used in calculating the MMM). In an extreme case, if a single climate model is used to assess the Arctic climate change in the future, the findings, including the future change in Arctic Ocean surface mixed layer and sea ice cover, will be radically different depending on which model family is used. Effort to reduce the large intrinsic model uncertainties in simulating Arctic climate is therefore needed. Our findings about the strong dependence of Arctic climate changes on ocean models imply a possibility to identify and reduce a considerable part of climate model intrinsic uncertainties.

Data Availability Statement

The CMIP6 models used in this study are listed in Table S1 in Supporting Information S1. The CMIP6 data sets can be downloaded from https://esgf-node.llnl.gov/search/cmip6/. Satellite-observed SIC data set are from NSIDC at https://doi.org/10.7265/efmz-2t65. The ocean reanalysis data (ORAS5) are from https://doi.org/10.24381/cds.67e8eeb7. The ERA5 is from https://doi.org/10.24381/cds.f17050d7. The PHC3.0 is from http://psc.apl.washington.edu/nonwp_projects/PHC/Data3.html.

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