Recent upper Arctic Ocean warming expedited by summertime atmospheric processes

Zhe Li, Qinghua Ding, Michael Steele & Axel Schweiger

The observed upper (0–50 m) Arctic Ocean warming since 1979 has been primarily attributed to anthropogenically driven changes in the high latitudes. Here, using both observational and modeling analyses, we demonstrate that a multiyear trend in the summertime large-scale atmospheric circulation, which we ascribe to internal variability, has played an important role in upper ocean warming in summer and fall over the past four decades due to sea ice-albedo effect induced by atmospheric dynamics. Nudging experiments in which the wind fields are constrained toward the observed state support this mechanism and suggest that the internal variability contribution to recent upper Arctic Ocean warming accounts for up to one quarter of warming over the past four decades and up to 60% of warming from 2000 to 2018. This suggests that climate models need to replicate this important internal process in order to realistically simulate Arctic Ocean temperature variability and trends.
Recent global warming fueled by increasing anthropogenic greenhouse gases is most prominent in the Arctic with significant atmospheric and oceanic warming and pronounced sea ice and land ice melting. Warming of the upper ocean in the Arctic is contributing to sea ice loss and changes of ocean circulation. However, our understanding of Arctic upper ocean temperature variability in the past decades and its main drivers remains limited, with previous studies mainly focusing on two processes. The primary one is due to recent sea ice reduction, which allows the ocean to gain more heat, especially during the fall season over the upper 150 m feature a tilted downward intrusion starting from June to August at the surface and propagating downward toward 50 m by fall (i.e., from September–October–November, or SON; Fig. 1f). This downward heat transfer suggests that recent fall upper ocean warming (Fig. 1a) originates from more absorption of heat at the surface in summer (i.e., JJA) because the sea ice-albedo effect which is more efficient in summer allows stronger oceanic uptake of solar radiation during ice melting seasons. This connection operates well on interannual time scales, with the causal direction examined by a lead–lag relationship between JJA Pan-Arctic tropospheric (surface to 300 hPa average) air temperature and ocean temperature in each month and depth (Fig. 1g, h). It is clear that JJA atmospheric warming significantly precedes upper ocean warming from early summer to the following fall and even winter since it takes time to melt sea ice and then warm the ocean due to the larger heat capacities of ocean and sea ice. This calculation suggests that atmospheric forcing drives ocean warming rather than the reverse in summer.

This subsurface fall warming is primarily confined to the Beaufort, Chukchi, and East Siberian Seas (hereafter collectively referred to the “Pacific Peripheral Seas Sector”, or PPSS) and the Laptev, Kara, Barents, Norwegian, and Greenland Seas (hereafter referred to as the “Atlantic Peripheral Seas Sector”, or APSS; Fig. 1c). The former is the area where the most pronounced sea ice decline in the melting season has been observed since 1979 (Fig. 1c). Concomitant with the trends in upper ocean warming is a trend in the atmospheric upper tropospheric circulation: for example, geopotential height at the tropopause at 300 hPa (Z300): its variability is a measure of temperature variations of the entire air column below 300 hPa; a higher Z300 also means that the circulation changes toward a pattern with stronger anticyclonic movement in the Northern Hemisphere) has been rising over northeastern Canada and Greenland (Fig. 1d). The calculation using the Arctic Ocean domain average variables suggests that the SON upper ocean warming (0–50 m average) ocean temperature (using reanalysis data; see Methods) has a close association with summertime (i.e., JJA) values of both Z300 and tropospheric air temperature (Table 1). A similar but slightly weaker relationship is observed between the domain average JJA upper ocean temperature with the simultaneous domain average Z300 and tropospheric air temperature (Table 1). SON oceanic warming may reflect an accumulation of changes over JJA due to the larger heat capacities of ocean and sea ice. Thus, the JJA atmosphere—SON ocean connection becomes more significant than the simultaneous connection and the dynamics of this lag relationship will be the focus of this study.

To illustrate the lag process that links the JJA atmospheric circulation pattern to SON upper ocean temperature change, we correlate the domain average SON upper ocean temperature with the spatial fields of JJA Z300 and tropospheric air temperature in the Arctic respectively (Supplementary Fig. 1a, b). An Arctic summer with higher-than-average Z300 and warmer tropospheric air temperature centered over Greenland and the Arctic Ocean appears to consistently precede a warmer-than-average upper ocean in the Arctic in SON (Supplementary Fig. 1a, b). Importantly, the pattern derived from the detrended variables exhibits a very similar structure to the one obtained using raw data, suggesting that the impacts of the JJA atmospheric circulation on the SON upper ocean temperature change also exist on interannual and longer time scales. This domain average SON upper ocean temperature related circulation pattern shows a
strong similarity with the linear trend of JJA Z300 field in the past 40 years and therefore upper ocean warming appears to be driven by the atmospheric circulation trend in JJA. Figure 1g, h also indicate that atmospheric warming in JJA influences the ocean surface at zero lag, and influences deeper layers later i.e., in SON. A more rigorous examination of the JJA atmosphere—SON ocean coupling is performed through maximum covariance analysis (MCA) between the JJA atmospheric circulation and SON upper ocean temperature in the Arctic to investigate whether the links between atmosphere and ocean are tied to fundamental modes of variability with a spatially coherent structure (Supplementary Fig. 2). These collectively suggest that a portion of the SON upper ocean warming trend in the past decades results from JJA atmospheric circulation variability on an interdecadal time scale.

**Table 1 Correlations between the summer large-scale atmospheric circulation and upper ocean temperature in fall and summer.**

|                  | JJA Z300 | JJA tropospheric air temp |
|------------------|----------|--------------------------|
| SON upper ocean temp |          |                          |
| Corr (with trend)         | 0.56     | 0.74                     |
| Corr (without trend)       | 0.48     | 0.66                     |
| JJA upper ocean temp       |          |                          |
| Corr (with trend)          | 0.53     | 0.69                     |
| Corr (without trend)       | 0.45     | 0.57                     |

Correlations of JJA/SON Arctic Ocean domain-average upper (0–50 m average) ocean temperature with JJA domain-average Z300 and tropospheric (surface to 300 hPa average) air temperature with trends and without trends respectively.
warming to SON upper ocean warming beneath? Ding et al. showed that a JJA high pressure anomaly can melt summer sea ice through increased downwelling longwave radiation (DLR) at the surface. To investigate how a similar mechanism affects upper ocean temperature, we examine the surface energy transfer between the atmosphere and the ocean. Arctic domain averages of SON upper ocean temperature, September sea ice area (SIA), and JJA tropospheric air temperature are highly correlated with JJA net downward heat flux ($Q_{\text{net}}$), all of which exhibit a patch of significant correlations over the Arctic Ocean (Fig. 2a–c, positive for temperature (Fig. 2a, c) and negative for SIA (Fig. 2b)). Domain averages of ocean temperature, SIA, and air temperature co-vary with $Q_{\text{net}}$ with detrended correlations ranging from 0.73 to 0.88 (Fig. 2d). This co-variability suggests that atmospheric warming during JJA first melts sea ice, and then warms the resulting open water in the following months.

Next, we examine the trends and correlations between domain average of JJA $Q_{\text{net}}$ with the individual component fluxes (see Methods; Eq. 1) over the past 40 years. The increasing trend in $Q_{\text{net}}$ is mostly due to reduced upwelling shortwave radiation (USR), and secondarily to increased fluxes in DLR at the surface (Fig. 2e). Further, DLR and USR are two major contributors in determining $Q_{\text{net}}$ at the surface on both interannual and interdecadal time scales (Fig. 2d, e). As the surface albedo decreases with sea ice melt, more solar radiation is absorbed by the darker ocean. Downwelling shortwave radiation (DSR) decreases substantially over the 40 years, but this is a secondary effect resulting from the reduction of multiple reflections between a shrinking sea ice coverage and clouds. Thus, DLR and USR serve as the key fluxes to link JJA air temperature and SON upper ocean temperature in the Arctic.

Wind-nudging experiments using CESM. To provide additional evidence that changes in atmospheric circulation are driving the rise of upper ocean temperature through an adiabatic warming process, we conduct a set of nudging experiments to quantify the effect of the atmospheric circulation on upper ocean temperature in the Arctic. In this experiment we nudge the winds of the Community Climate System Model (CESM) to reanalysis while anthropogenic forcing is fixed at the level of year 2000 ($CO_2 = 367$ ppm), which is very close to the observed mean $CO_2$ concentration over the past 40 years ($CO_2 = 369$ ppm; see Methods). The goal of this experiment is to assess the contribution of wind forcing on sea ice melting and upper ocean warming by comparing the nudging experiment with the historical simulations of the same model and the observational evidence. Since the same model is used in both the...
historical and nudging experiments, the comparison of the two sets of experiments (CESM Large Ensemble (CESM-LEN) Project vs. nudging experiments) sheds light on the respective role of winds and anthropogenic forcing in recent changes of upper ocean temperature. First, we examine the response of CESM1 to anthropogenic forcing by examining the 40-member ensemble mean of the historical simulation. The 40-member ensemble is considered sufficient to largely remove the effect of internal variability and thereby only reflects the external forcing. We examine upper tropospheric (300 hPa) winds as an indicator of the larger scale circulation. Unlike the observed upper tropospheric wind trend in ERA5, the wind trend due to anthropogenic forcing is very weak and only accounts for a small part of observed trends (Supplementary Fig. 3). This suggests that the observed upper air wind trend in the past four decades is primarily due to internal variability of the climate system. The nudging experiment consists of five 40-yr historical runs from 1979 to 2018, in which simulated winds within the Arctic (north of 60°N) are nudged to the corresponding 6-hourly ERA5 winds (see Methods). The five members are initiated with different atmospheric, sea ice and oceanic conditions on 1979/1/1 (see Methods) and the ensemble mean of the five realizations is analyzed hereafter to remove impacts of initial conditions in the simulations. The climatology of sea ice concentration, ocean temperature, and salinity in the Arctic in the ensemble mean of these 40-yr nudging runs exhibits roughly similar patterns and magnitude as the ORAS5 reanalysis (Supplementary Figs. 4, 5; See Methods), which gives us confidence that the model has sufficient skill to simulate the mean state in the Arctic Ocean.

The simulated spatial pattern of upper ocean temperature trend is similar to that in ORAS5 in the PPSS from 1979 to 2018 and the pattern in the PPSS and APSS for the 2000–2018 period although the temperature increases are slightly weaker (Fig. 3c–f). It is particularly noted that the warming in the Barents Sea in the nudging simulations bears strong resemblance to ORAS5 for the 2000–2018 period (Fig. 3c, f), with the spatial correlation coefficient between these two trend patterns (Fig. 3c, f) within the Arctic (north of 70°N) reaching 0.77. The simulated domain average SON upper ocean temperature shows a highly correlated temporal variation with ORAS5 (for the period 1979–2018: \( r = 0.63 \) with trend, \( r = 0.67 \) without trend; for the period 2000–2018: \( r = 0.91 \) with trend, \( r = 0.80 \) without trend) on both interannual and interdecadal time scales (Fig. 3a). This suggests that the wind-driven circulation change indeed plays an important role in upper ocean warming in the Arctic. The mean trend in the simulated upper ocean temperature in the five nudging runs is 0.04 °C per decade, while that in the ensemble mean of the 40 CESM-LEN members is 0.09 °C per decade. The combined upper ocean temperature trend due to the two forcings is 0.13 °C per decade, which is slightly lower than the trend of 0.17 °C per decade in ORAS5 over the last 40 years, suggesting that the sum of these two forcings can explain most of SON upper ocean warming. Based on their contributions to the warming in ORAS5 (0.04/0.17 and 0.09/0.17), we estimate that the internal, wind-driven variability accounts for 24% of upper ocean warming while anthropogenic forcing accounts for 53% of upper ocean warming over the past 40 years. While the wind-driven ocean warming is largely confined to the Chukchi, East Siberian, and Laptev Seas over the 40-year period, substantial warming in the Atlantic sector shows little connection with wind-driven processes. This changes when we perform a similar calculation for the period 2000–2018, when reanalysis wind and ocean data in the Arctic are available. The spatial and temporal lead-lag relationship of \( Q_{\text{net}} \) and \( Q_{\text{short_bl}} \) is what is expected if changes in \( Q_{\text{net}} \) first drive sea ice loss and subsequent upper ocean warming. This provides the physical mechanism that ties large-scale wind variability and its effect on \( Q_{\text{net}} \) to upper ocean warming via the ice-albedo effect and the deepening of the MLD.

### Poleward ocean heat transport contribution

Although the nudging runs well-replicate the upper ocean temperature rise in
the Arctic, especially over the PPSS, model vs. reanalysis (ORAS5) differences remain (e.g., Fig. 3c, d). This indicates that some additional factors not directly captured by atmospheric wind forcing may play a role in driving changes in the Arctic, especially over the APSS. Poleward ocean heat transport (POHT) is in part driven by winds but are also affected by large-scale ocean dynamics that are not directly tied to winds (or at least not at the time scales considered here). We consider POHT in the upper 50 m through two separate gates into the Arctic Ocean, a Pacific Gate measuring heat in flow through the Bering Strait and an Atlantic Gate measuring net heat inflow from the Nordic Seas (Fig. 4a). In this section, we explore the role of POHT on upper ocean warming, although we do not provide a quantitative “variance explained” analysis as in previous sections. This is because an exercise that would involve ocean state nudging is beyond the scope of this study.

SON upper 50 m POHT through the Atlantic Gate derived from ORAS5 shows an upward trend since 2000 (Fig. 4a), especially via the branch of that through the Barents Sea (Supplementary Fig. 9b), and is strongly correlated with SON upper ocean temperature on both interannual and interdecadal time scales for the period 1979–2018 ($r = 0.80$ with trend; $r = 0.58$ without trend). Correlating the POHT time series with upper ocean temperature field shows that the variability of POHT through the Atlantic Gate in SON strongly affects the Barents and Kara Seas (Fig. 4b). The cause of the high correlations in the parts of the central Arctic Ocean is puzzling. One possible reason is that an air-sea heat flux exchange is able to quickly take the warm signal from the Barents and Kara Seas to the central Arctic Ocean via the atmosphere. This simultaneous connection may also result from some influences in preceding seasons that can regulate upper ocean temperature in both the central Arctic Ocean and the Barents and Kara Seas. In contrast, POHT through the Pacific Gate has an increasing trend as well (Fig. 4a) but only affects the Chukchi Sea (Fig. 4c).

The variability of simulated SON upper 50 m POHT through the Pacific Gate in the wind-nudging runs very successfully capture the counterpart in ORAS5 (Fig. 4e; $r = 0.9$ with trends,
r = 0.89 without trends), but this is not the case for the Atlantic Gate (Fig. 4d and Supplementary Fig. 9). This suggests that winds play an important role in driving POHT through the Bering Strait52,53. Nevertheless, wind-driven POHT through the Bering Strait only has a weak correlation with upper ocean temperature in the interior of the basin and appears to have little impact on Pan-Arctic Ocean warming. We also compare SON upper 50 m POHT via the Atlantic Gate in the nudging runs with that in the 40-member ensemble means of the historical simulation in CESM (Fig. 4d, e). None of these capture the increasing trend of POHT through the Atlantic Gate as seen in ORAS5, suggesting that SON upper 50 m POHT changes through the Atlantic Gate are likely determined by more complex factors that are not directly driven by winds and anthropogenic forcing in our model, such as the initial ocean condition, deeper layer oceanic variability, internal oceanic thermohaline variability in the Arctic and heat transport from the lower latitudes where observed winds are not specified19,54–56. The role of anthropogenic forcing in contributing to increasing POHT via the Atlantic sector remains an open question since this attribution appears to be sensitive to approaches used to detect this feature19,57. Importantly, the fact that our nudging simulations did not capture an upward trend in POHT through the Atlantic Gate further supports our main finding: namely, the role of our identified mechanism in expediting Arctic Ocean warming via summertime atmospheric processes.

**Discussion**

Our study suggests that a portion of upper Arctic Ocean warming over the past few decades can be explained by low-frequency atmospheric variability characterized by a trend toward anomalous anticyclonic circulation over the Arctic Ocean and Greenland. This process produces subsidence and adiabatic warming which acts to warm the atmosphere, melt sea ice, and deepen the ocean mixed layer. The resulting open water warms via shortwave radiation absorption and enhanced vertical mixing. Our nudging experiments confirm that adiabatic dynamical forcing associated with winds in the Arctic is able to explain up to 24% of SON upper ocean warming from 1979 to 2018, which is mostly confined to the Chukchi, East Siberian, and Laptev Seas, and up to ~60% of the Pan-Arctic upper ocean warming for the period 2000–2018.

We have previously suggested that internal atmospheric forcing is in part forced by sea surface temperature variability in the tropics via a Rossby wave train58. The capability to replicate both local air-ice-ocean coupling as well as an accurate tropical—
Arctic Ocean connection is thus a key model skill. However, simple evaluations conducted in previous studies indicate that some models have trouble replicating both the full strength of the local coupling on interannual time scales and also tropical—Arctic Ocean connections. An efficient and well-developed metric, emphasizing a lead-lag connection between JJA atmospheric temperature with SON ocean temperature as we show in Fig. 1f, g, is thus needed to better evaluate the performance of models in representing this Arctic atmosphere-sea ice-ocean coupling and its possible linkage with remote forcing.

In this study, we primarily focus on the surface layer of the Arctic Ocean and local ocean—air coupling through thermodynamical processes. However, the surface heat balance is also influenced by ocean mixing, the deep ocean circulation and heat transport from sub-Arctic Oceans. In particular, the surface heat balance is also needed to better evaluate the performance of models in representing this Arctic atmosphere-sea ice-ocean coupling and its possible linkage with remote forcing.

The barotropic feature of the POHT through the Atlantic Gate (see Methods) requires an integrated view of heat transport throughout the whole depth. Other factors, such as water mass exchanges between the Arctic and Atlantic/Pacific Oceans, and freshwater storage changes, will become more important when we shift our focus to ocean lateral heat flux convergence and the deeper layers of the Arctic Ocean. Moreover, the ocean mixing is not only sensitive to surface winds, Ekman convergence and pumping in the surface layer around the central Beaufort Gyre, but also regulated by brine rejection. Recently, the “Atlantification” process has been suggested to be associated with weakened stratification and increased vertical mixing, which enhances upward heat fluxes to the surface. This process may influence upper ocean warming and sea ice melt and may not be well-replicated in our simulations. Further studies are needed to better understand the relationship and interaction between the Arctic Ocean and the internal large-scale atmospheric process described here.

Methods

Reanalysis and observation data. In situ observations of the upper ocean temperature are very limited and sparse in the Arctic Ocean compared to the North Atlantic, which inhibits our ability to study the multi-decadal large-scale variability of climate diagnostics, such as heat and salinity budgets. However, observational constraints on future anthropogenic warming critically depend on accurate estimates of past ocean temperature change. Reanalyses are another tool that provide multi-variate dynamical consistency in both spatial and temporal dimensions. We primarily use the Ocean Reanalysis System 5 (ORASS) in this study to investigate the changes in upper ocean temperature and heat transport and their relationship with atmospheric variability over the past four decades. The ORASS dataset (the horizontal resolution is about 0.25° ×0.25°) is constructed by the ECMWF global operational ensemble reanalysis system containing an eddy-permitting ocean and sea-ice system and the OCEANS system. Reprocessed surface temperature from HadISST2 and OSTIA operational, sea-ice concentration from OSTIA and OSTIA operation, in situ temperature/salinity profiles from EN4 with XBT/MBT correction and GIS operational, and satellite sea level anomaly from AVISO DT2014 with revised MDT are assimilated in this system via NEMOVAR using a 5 day assimilation window with a model time step of 1200 s. Global mean sea-level changes are constrained using AVISO DT2015 L4 SMLA and NRT. The atmospheric forcing of ORASS is derived from ERA-40 (before 1979), ERA-Interim (1979–2015), and ECMWF NWP (2015–present). ORASS includes five ensemble members and covers the period from 1979 onwards. In this study, the ensemble mean of the five members is analyzed. Although various in situ observations are assimilated in ORASS, there are only a limited number of temperature/salinity profiles in the EN4 product in the central Arctic Ocean, which may potentially degrade the accuracy of ORASS in reflecting real observations over the region.

To evaluate the ORASS, we compare its upper (0–50 m average) ocean temperature changes in the Arctic Ocean over the period 1979–2018 with other widely used reanalysis products (SODA3.4.2 and GECCO3) and observation (WOA18). All ocean temperature in the reanalyses are potential temperatures, and we convert in situ temperature from WOA18 to potential temperature to be consistent with other reanalyses. The trends of upper ocean temperature time series in ORASS and SODA3.4.2 are similar with 0.165 °C per decade for ORASS and 0.187 °C per decade for SODA3.4.2 (note the shorter time period from 1980 to 2016), both of which are smaller than that of GECCO3 (0.279 °C per decade). However, more important for this study, the variabilities of temperature time series and spatial patterns of upper ocean temperature trends in the three reanalyses are consistent (Fig. 1a and Supplementary Fig. 10). Comparisons with ‘observation’ only dataset is complicated by the fact that WOA18 only provides decadal monthly means of temperature for three decades (1985–1994, 1995–2004, 2005–2017), but the decadal average of upper ocean temperature time series derived from ORASS over two decadal periods (1985–1994 and 1995–2004) are close to that in WOA18, while it is slightly larger than WOA18 over the period 2005–2017 (Fig. 1a). Spatial patterns of long-term trends of upper ocean temperature are derived from these reanalyses are about the same in patterns and correlation coefficients of 0.74 for ORASS, 0.65 for SODA3.4.2 and 0.64 for GECCO3 (and ORASS has the highest correlation), although GECCO3 exhibits stronger warming than WOA18 over the whole basin (Supplementary Fig. 11). In addition, observational data from the UpTempO Buoy Project was used to compare with reanalyses and we find that they will well replicate UpTempO upper ocean temperature variability from 2000 to 2017 (Fig. 1a). Based on these evaluations, we believe that ORASS is a reliable data source for this study.

We also use monthly circulation, air temperature, and radiation fields from 1979 to 2018 from ERA5 reanalysis data. Monthly sea ice concentration is obtained from Nimbus-7 SSMR and DMSP SSM/I-SSMIS passive microwave data version-1 provided by the National Snow and Ice Data Center (NSIDC).

Maximum covariance analysis (MCA). MCA is used to determine the dominant covarying patterns of high-latitude atmospheric circulation and upper ocean warming in the Arctic. MCA analysis is applied by using singular value decomposition (SVD) covariance matrix between latitude above 60°N (2300 and SON upper (0–50 m average) ocean temperature over the period 70–90°N). Simply put, MCA analysis can isolate the most coherent pairs of the spatial patterns and identify a linear relationship between two different fields that are most closely coupled. The leading modes show the spatial patterns and time series of the two fields that are optimally coupled. The corresponding singular value represents the squared covariance fraction, which indicates the relative importance of that pair of vectors in relationship to the total covariance in the two fields.

Radiation fluxes. Qshort is calculated as the following, with units of Wm−2:

\[ Q_{\text{short}} = \text{DLR} - \text{ULR} + \text{DSR} - \text{USR} + \text{SHF} + \text{LHF} \]

where DLR and ULR are downward and upwelling longwave radiations, respectively; DSR and USR are downward and upwelling shortwave radiations, respectively; SHF is sensible heat flux; LHF is latent heat flux. All radiative flux variables are positive downward and represent heat transferred from the atmosphere to the surface.

Wind-nudging experiments using CESM1. As we are interested in the contribution of wind forcing to upper ocean warming in the Arctic in our model simulations, we use 6-hourly ERA5 wind fields for nudging. The experiments consist of five 40-year historical runs from 1979 to 2018 using the CESM1 fully-coupled model. In these runs, Arctic (north of 60°N) atmospheric winds from the surface to the top of the atmosphere in the model are fully nudged to the corresponding 6-hourly ERA5 winds (the relaxation timescale of the nudging is about 6 h) with various different sea ice initial conditions derived from a long (150 year) spin-up simulation, and there is no nudging effect everywhere else. Anthropogenic forcing is held constant in the nudging experiments and spin-up run at the level of year 2000 (i.e. CO2 at 367 ppm) so that greenhouse gas concentrations throughout the integration is very close to the observed 40-yr averaged values (i.e. CO2 at 369 ppm). To address the issue of “assimilation shock”, the tendency of models to equilibrate to imposed winds, we first run a 150-year perpetual simulation with the model continuously nudged to winds in year 1979 in the Arctic (from the surface to the top of atmosphere) and forced by constant anthropogenic forcing from year 2000. In this spin-up, the model takes almost 100 years for the Arctic mean upper ocean temperature to adapt to wind fields and then varies stably around a constant level afterwards (Supplementary Fig. 12). The model states on Jan. 1 of the last 5 years of this spin up are then separately used as initial conditions to reinitialize a set of new five members of 40-yr nudging simulations in which imposed winds in the Arctic are allowed to vary from 1979 to 2018. In this study, we focus on the ensemble mean of these five members to understand wind forcing on ocean temperature and other fields in the Arctic. In addition, one advantage of this set of simulations is that the POP2 of the CESM1 can simulate Qshort, which is calculated by the KPP vertical mixing scheme and not available in ORASS. This variable will tell us how much of incoming shortwave flux at the surface can be absorbed by the whole depth of the ocean surface boundary layer in each oceanic grid based on the fraction of solar shortwave flux penetrating to the bottom of this layer.

The mean sea ice and oceanic states simulated by wind-nudging experiments. Although we are interested in the anomalous response to imposed winds, an examination of the simulated sea ice and oceanic mean states is necessary to ensure that our physical model is able to respond to imposed forcing. We examine the long-term (1979–2018) mean March and September sea ice extent in observations (Supplementary Fig. 4a, b).
Received: 9 May 2021; Accepted: 22 December 2021; 
Published online: 18 January 2022

References

1. Cohen, J. et al. Recent Arctic amplification and extreme mid-latitude weather. Nat. Geosci. 7, 627–637 (2014).
2. Frye, J. C. et al. One hundred years of Arctic surface temperature variation due to anthropogenic influence. Sci. Rep. 3, 2645 (2013).
3. Landrum, L. & Holland, M. M. Extremes become routine in an emerging new Arctic. Nat. Clim. Change 10, 1108–1115 (2020).
4. Perlwitz, J., Hoerling, M. & Dole, R. Arctic tropospheric warming: causes and linkages to lower latitudes. J. Clim. 28, 2154–2167 (2015).
5. Serreze, M. C. & Francis, J. A. Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability. Nat. Clim. Change 6, 856–860 (2016).
6. Beer, E., Eisenman, I. & Wagner, T. J. W. Polar amplification due to enhanced heat flux across the halocline. Geophys. Res. Lett. 47, e2019GL086706 (2020).
7. Carmack, E. et al. Toward quantifying the increasing role of oceanic heat in sea ice loss in the new Arctic. Bull. Am.eteorol. Soc. 96, 2079–2105 (2015).
8. Polyakov, I. L. et al. Observational program tracks Arctic Ocean transition to a warmer state. Eos, Transac. Am. Geophys. Union 88, 398–399 (2007).
9. Skagseth, O. et al. Reduced efficiency of the Barents Sea cooling machine. Nat. Clim. Change 10, 661–666 (2020).
10. Steele, M., Ermold, W. & Zhang, J. Arctic Ocean surface warming trends over the past 100 years. Geophys. Res. Lett. 35, L19715 (2008).
11. Timmermanns, M.-L., Tooloo, J., & Kriifshiif, R. Warming of the interior Arctic Ocean linked to sea ice losses at the basin margins. Sci. Adv. 4, eaat6773 (2018).
12. Zhang, J. Warming of the arctic ice-ocean system is faster than the global average since the 1960s. Geophys. Res. Lett. 32, L10602 (2005).
13. Shu, Q., Wang, Q., Song, Z. & Qiao, F. The polar enhanced Arctic Ocean cooling machine in a warming climate. Nat. Commun. 12, 2966 (2021).
14. Notz, D. & Stroeve, J. Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. Science 354, 747–750 (2016).
15. Polyakov, I. V., Walsh, J. E. & Kwok, R. Recent Changes of Arctic Multyear Sea Ice Coverage and the Likely Causes. Bull. Am. Meteorol. Soc. 93, 145–151 (2012).
16. Stroeve, J. C., Markus, T., Boisvert, L., Miller, J. & Barrett, A. Changes in Arctic melt season and implications for sea ice loss. Geophys. Res. Lett. 41, 1216–1225 (2014).
17. Shiller, C., & Notz, D. Changing state of Arctic sea ice across all seasons. Environ. Res. Lett. 13, 103001 (2018).
18. Zhang, R. Mechanisms for low-frequency variability of summer Arctic sea ice extent. PNAS 112, 4570–4575 (2015).
19. Arhun, M., Eldevik, T. & Smedsrud, L. H. The Role of Atlantic Heat Transport in Future Arctic Winter Sea Ice Loss. J. Clim. 32, 3327–3341 (2019).
20. Polyakov, I. V. et al. Arctic Ocean Warming Contributes to Reduced Polar Ice Cap. J. Phys. Oceanograph. 40, 2743–2756 (2010).
21. Ricker, R. et al. Evidence for an increasing role of ocean heat in Arctic winter sea ice growth. J. Clim. 1. 1–42 (2021).
22. Iqube, C., Arctic sea ice heatied from below. Nat. Geosci. 8, 172–173 (2015).
23. Lozier, M. S. et al. A sea change in our view of overturning in the subpolar North Atlantic. Science 363, 516–521 (2019).
24. Mayer, M., Haimberger, L., Pietschnig, M. & Storto, A. Facets of Arctic energy accumulation based on observations and reanalyses 2000–2015. Geophys. Res. Lett. 43, 10,420–10,429 (2016).
25. Steele, M., Zhang, J. & Ermold, W. Mechanisms of summertime upper Arctic Ocean warming and the effect on sea ice melt. J. Geophys. Res. 115, C11004 (2010).
26. Oldenburg, D., Armour, K. C., Thompson, L. & Bitz, C. M. Distinct Mechanisms of Ocean Heat Transport Into the Arctic Under Internal Variability and Climate Change. Geophys. Res. Lett. 45, 7692–7700 (2018).
27. Polyakov, I. V. et al. Weakening of Cold Halocline Layer Exposes Sea Ice to Oceanic Heat in the Eastern Arctic Ocean. J. Clim. 33, 8107–8123 (2020).
28. Serreze, M. C. et al. The large-scale energy budget of the Arctic. J. Geophys. Res. 112, D11122 (2007).
29. Tushubochi, T. et al. Increased ocean heat transport into the Nordic Seas and Arctic Ocean over the period 1993–2016. Nat. Clim. Change 11, 21–26 (2021).
30. Lindsay, R. W. & Zhang, J. The Thinning of Arctic Sea ice, 1988–2003: Have We Passed a Tipping Point? J. Clim. 18, 4879–4904 (2005).
31. Proshutinsky, A., Dukhovskoy, D., Timmermanns, M.-L., Krishfield, R. & Bamber, J. L. Arctic circulation regimes. Philos. Trans. R. Soc. 373, 20140160 (2015).
32. Timmermans, M.-L. & Marshall, J. Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate. J. Geophys. Res. 125, e2019JC015758 (2020).

32. Timmermans, M.-L. & Marshall, J. Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate. J. Geophys. Res. 125, e2019JC015758 (2020).

33. Krish.

34. Baxter, I. et al. How Tropical Pacific Surface Cooling Contributed to Accelerated Sea Ice Melt from 2007 to 2012 as Ice Is Thinned by Anthropogenic Forcing. J. Clim. 32, 8583–8602 (2019).

35. Huang, Y., Ding, Q., Dong, X., Xi, B. & Baxter, I. Summertime low clouds to projected Arctic and Antarctic sea-ice loss. Nat. Geosci. 13, 275–281 (2020).

60. Jahn, A. & Laiho, R. Forced Changes in the Arctic freshwater Budget Emerge in the Early 21st Century. Geophys. Res. Lett. 47, e2020GL088854 (2020).

61. Salie, J.-B. et al. Summertime increases in upper-ocean stratification and mixed-layer depth. Nature 591, 592–598 (2021).

62. Steele, M., Ermold, W. & Zhang, J. Modeling the formation and fate of the near-surface temperature maximum in the Canadian Basin of the Arctic Ocean. J. Geophys. Res. 116, C11015 (2011).

63. Lind, S., Ingvaldsen, P. B. & Furevik, T. Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. Nat. Clim. Change 8, 634–639 (2018).

64. Polyakov, I. V. et al. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science 356, 285–291 (2017).

65. Uotila, P. et al. An assessment of ten ocean reanalyses in the polar regions. Clim. Dyn. 52, 1613–1650 (2019).

66. Storto, A. et al. Ocean Reanalyses: Recent Advances and Unsolved Challenges. Front. Mar. Sci. 6, 418 (2019).

67. Zuo, H., Balmaseda, M. A., Tietse, S., Mogensen, K. & Mayer, M. The ECWMF operational ensemble reanalysis–analysis system for ocean and sea ice: a description of the system and assessment. Ocean Sci. 15, 779–808 (2019).

68. Mogensen, K. & Balmaseda, M. W. The NEMOVAR ocean data assimilation system as implemented in the ECWMF ocean analysis system for 4. 59 (2012) https://doi.org/10.21957/5xy9r7im.

69. Carton, J. A., Chepurin, G. A. & Chen, L. SODA3: A New Ocean Climate Reanalysis. J. Clim. 31, 6967–6983 (2018).

70. Köhl, A. Evaluating the GECCO 1948–2018 ocean synthesis – a configuration for initializing the MPI-ESM climate model. Quarterly J. R. Meteorol. Soc. 146, 2250–2273 (2020).

71. Boyer, T. P. et al. World Ocean Atlas 2018. NOAA National Centers for Environmental Information. Dataset. https://accessor.nodc.noaa.gov/NCI/NOA (2018).

72. Bebouz, V., Smith, T. M., Steele, M., Huang, B. & Zhang, H.-M. Improved Estimation of Proxy Sea Surface Temperature in the Arctic. J. Atmospheric Oceanic Technology 37, 341–349 (2020).

73. Hersch, H. et al. The ERAS global reanalysis. Quarterly J. R. Meteorol. Soc. 146, 199–2049 (2020).

74. Cavaliere, Donald, Parkinson, Claire, Gloersen, Per & Zwally, H. Jay. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1. (1996) https://doi.org/10.5067/8GQ8LZQVL0VL.

75. Bretherton, C. S., Smith, C. & Wallace, J. M. An Intercomparison of Methods on satellite scatterometer observations. J. Marine. Sys. 168, 38–56 (2017).

76. Ilcak, M. et al. An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part III: Hydrography and fluxes. Ocean Model. 100, 141–161 (2016).

77. Perovich, D. K. et al. Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback. Geophys. Res. Lett. 34, L19505 (2007).

78. Zhang, J., Rothrock, D. A. & Steele, M. Warming of the Arctic Ocean by a strengthened Atlantic Inflow: Model results. Geophys. Res. Lett. 25, 1745–1748 (1998).

79. Danielson, S. L. et al. Coupled wind-forced controls of the Bering–Chukchi shelf circulation and the Bering Strait throughflow: Ekman transport, continental shelf waves, and variations of the Pacific–Arctic sea surface height gradient. Prog. Oceanograph. 125, 40–61 (2014).

80. Zhang, W., Wang, Q., Wang, X. & Daniilov, S. Mechanisms Driving the Interannual Variability of the Bering Strait Throughflow. J. Geophys. Res. 125, e2019JC015308 (2020).

81. Muilwijk, M. et al. Arctic Ocean Response to Greenland Sea Winter Anomalies in a Suite of Model Simulations. J. Geophys. Res. Ocean. 124, 6286–6232 (2019).

82. Wang, Q. et al. Ocean Heat Transport Into the Barents Sea: Distinct Controls on the Upward Trend and Interannual Variability. Geophys. Res. Lett. 46, 13180–13190 (2019).

83. Wang, Q. et al. Intensification of the Atlantic Water supply to the Arctic Ocean through Fram Strait induced by Arctic sea ice decline. Earth Space Sci. Open. Arch. https://doi.org/10.1002/essoar.10501439.1 (2019).

84. Muilwijk, M., Smedsrud, L. H., Ilicak, M. & Drange, H. Atlantic Ocean Heat Transport Variability in the 20th Century Arctic Ocean From a Global Ocean Model and Observations. J. Geophys. Res. 123, 8159–8179 (2018).

85. Bonan, D. B. & Blanchard-Wrigglesworth, E. Nonstationary Teleconnection Between the Pacific Ocean and Arctic Sea Ice. Geophys. Res. Lett. 47, e2019GL085666 (2020).

86. England, M. R., Polvani, L. M., Sun, L. & Deser, C. Tropical climate responses to projected Arctic and Antarctic sea-ice loss. Nat. Geosci. 13, 275–281 (2020).
results, with assistance from Q.D, M.S., and A.S. M.S. provided particular guidance on ocean observations and ocean model analysis. A.S. provided insight on climate model analysis. All authors equally contributed to the writing and the revision of this article.

**Competing interests**
The authors declare no competing interests.

**Additional information**
*Supplementary information* The online version contains supplementary material available at [https://doi.org/10.1038/s41467-022-28047-8](https://doi.org/10.1038/s41467-022-28047-8).

**Correspondence** and requests for materials should be addressed to Qinghua Ding.

**Peer review information** *Nature Communications* thanks the anonymous reviewers for their contribution to the peer review of this work. Peer reviewer reports are available.

**Reprints and permission information** is available at [http://www.nature.com/reprints](http://www.nature.com/reprints)

**Publisher’s note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.