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Simulated Twentieth-Century Ocean Warming in the Amundsen Sea, West Antarctica

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Key Points:

- An ensemble of ice-ocean simulations is used to study conditions in the Amundsen Sea over the twentieth century
- The simulations show a long-term ocean warming trend on the continental shelf, which is not yet clear in the shorter observational record
- The trends are partly driven by anthropogenic forcing, suggesting the ocean and ice shelves may also be sensitive to future climate policy

Supporting Information:

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

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Abstract

Rapid ice loss is occurring in the Amundsen Sea sector of the West Antarctic Ice Sheet. This ice loss is assumed to be a long-term response to oceanographic forcing, but ocean conditions in the Amundsen Sea are unknown prior to 1994. Here we present a modeling study of Amundsen Sea conditions from 1920 to 2013, using an ensemble of ice-ocean simulations forced by climate model experiments. We find that during the early twentieth century, the Amundsen Sea likely experienced more sustained cool periods than at present. Warm periods become more dominant over the simulations (mean trend 0.33°C/century) causing an increase in ice shelf melting. The warming is likely driven by an eastward wind trend over the continental shelf break that is partly anthropogenically forced. Our simulations suggest that the Amundsen Sea responded to historical greenhouse gas forcing, and that future changes in emissions are also likely to affect the region.

Plain Language Summary

Ice loss from the West Antarctic Ice Sheet is one of the fastest growing contributions to sea level rise. The pattern of melting suggests that the ocean has been warming in the Amundsen Sea, but we don't know what the ocean was like in this region before observations started in 1994. In this study, we model the ocean conditions over the last century, using a set of 20 ice-ocean simulations fed with the output of larger climate models. Our simulations suggest that the Amundsen Sea used to be cooler than it is today. Over the last century, ocean temperatures have increased, but this is hard to detect in observations because the trend is obscured by frequent swings between cold and warm conditions. The main cause of the warming in our simulations is changes in the winds near the edge of the Amundsen Sea that pump more warm water from the deep ocean onto the shallower continental shelf. These wind trends are partly caused by greenhouse gas emissions from the burning of fossil fuels. Whether the Amundsen Sea continues to warm, or whether temperatures stabilize, will likely hinge on the success of future climate policies to reduce emissions.

1. Introduction

The West Antarctic Ice Sheet (WAIS) is a region of particular concern for global sea level rise. Ice loss from the WAIS is mainly controlled by the ocean, which melts the floating ice shelves fringing the ice sheet. Thinning of these ice shelves causes a loss of buttressing and acceleration of the upstream glaciers, which then unpin from the bedrock and cause grounding line retreat. The geometry of the WAIS makes it more susceptible to destabilization: It is largely grounded below sea level (Fretwell et al., 2013) with many inland-sloping regions known as retrograde beds. Depending on the level of ice shelf buttressing (Gudmundsson et al., 2012), retrograde beds could lead to an unstable regime, in which grounding line retreat would continue even without further warming of the ocean (Schoof, 2007).

It is clear from observations that ice loss has already begun. Satellite estimates of mass loss from the Antarctic Ice Sheet show that the WAIS is the main contributor, losing ≈160 Gt of ice per year (Shepherd et al., 2018). This ice loss is focused in the Amundsen and Bellingshausen Seas (Paolo et al., 2015), suggesting ocean-driven melting is the cause. Rapid grounding line retreat has also been observed in the Amundsen Sea, and in many regions the grounding lines have crossed into retrograde beds (Rignot et al., 2014). There is evidence that this period of ice loss dates back to at least the 1970s (Jenkins et al., 2010), and perhaps as early as the 1940s (Smith et al., 2017).

Given the strong evidence of increased ocean-driven melting in the Amundsen Sea, it may seem surprising that there is no clear warming signal in ocean temperatures on the continental shelf. Rather, the water at middepth, which can most easily access the ice shelf cavities, oscillates between cold Winter Water (WW, ≈−1°C) and warm Circumpolar Deep Water (CDW, 0–1°C). This oscillation occurs on a roughly decadal cycle (Dutrieux

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et al., 2014; Jenkins et al., 2018) as the thermocline, which separates the two water masses, rises and falls. As a result, observations are so dominated by decadal variability that trends based on the short records available cannot be relied upon (Schmidtko et al., 2014). It is possible that ice loss from the WAIS is driven by geometric feedbacks (such as self-sustained grounding line retreat on a retrograde bed), triggered by a decadal anomaly earlier in the twentieth century and largely unaffected by recent temperatures (Jenkins et al., 2016). Alternatively, variability in subsurface temperatures could be obscuring a longer-term signal by which warm periods become more dominant.

A major driver of Amundsen Sea variability is the winds over the nearby continental shelf break (Jenkins et al., 2016; Thoma et al., 2008). Eastward wind anomalies favor the onshore transport of warm CDW, which raises the thermocline and warms the shelf at middepth. Conversely, westward wind anomalies reduce onshore transport, leading to a deeper thermocline with cold WW at middepth. Winds at the shelf break are strongly influenced by Pacific variability, with eastward anomalies associated with positive phases of El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). However, climate model simulations suggest these cycles are superimposed on a long-term eastward trend in winds over the shelf break (P. R. Holland et al., 2019). This trend results partly from the ongoing strengthening and poleward shift of the Southern Hemisphere westerly winds, a feature of anthropogenic greenhouse gas forcing (Swart et al., 2015). It would be expected to cause long-term warming of the Amundsen Sea, manifested as an increased presence of decadal warm anomalies.

While the link between eastward wind anomalies and increased ice shelf melting offers a credible explanation for WAIS ice loss, it cannot be thoroughly tested based on observations alone. In-situ oceanographic measurements in the Amundsen Sea have only existed since 1994 (S. S. Jacobs & Hellmer, 1996), and their spatial and temporal coverage is still sparse. As such, we have partially observed only two cycles of the continental shelf's response to decadal wind forcing, which is insufficient to resolve centennial trends. It is therefore unclear whether the relationship between winds and melting holds on timescales longer than decadal. Negative feedbacks on the shelf, related to changes in baroclinic ocean circulation or surface fluxes, could plausibly counteract a centennial trend in wind forcing. It is therefore unknown what conditions the Amundsen Sea experienced earlier in the twentieth century, and whether warm periods have indeed become more common as a result of human activity.

In this study we use an ice-ocean model of the Amundsen Sea, forced by climate model reconstructions beginning in 1920, to fill these gaps in our knowledge. By running an ensemble of centennial simulations, we can detect long-term trends in ocean conditions on the continental shelf. In particular, we evaluate whether the ocean responds to changes in atmospheric forcing over the last century. This result will determine, by extension, whether the Amundsen Sea is also likely to respond to future changes in greenhouse gas emissions.

2. Methodology

Our modeling approach is to perform a hypothesis test regarding the role of historical atmospheric forcing on the Amundsen Sea, rather than to create a complete reconstruction or hindcast. We do not consider changes in non-atmospheric boundary conditions, including ice shelf geometry, iceberg calving, and the lateral ocean boundaries. These variables, often poorly constrained by observations at present, are almost completely unconstrained in the past. While the Amundsen Sea sector is known to have experienced grounding line retreat (Jenkins et al., 2010) and changes in calving (MacGregor et al., 2012) over the past decades, it is not clear how these changes could best be prescribed. Furthermore, global climate models are not designed to simulate water masses accurately on the Antarctic continental shelf (Asay-Davis et al., 2017), so their historical ocean simulations cannot be relied upon in this region. We therefore keep all boundary conditions, apart from atmospheric forcing, fixed at the present day. This design means we do not consider the effects of remote ocean processes (Spence et al., 2017), ice shelf geometric feedbacks (Donat-Magnin et al., 2017), or changes in the origin and properties of CDW (Nakayama et al., 2018; Sallée et al., 2013).

Our simulations are performed using the Massachusetts Institute of Technology general circulation model (MITgcm) (Losch, 2008; Marshall et al., 1997) including components for the ocean, sea ice, and ice shelf thermodynamics. Here we build on the Amundsen Sea configuration of Assmann et al. (2013), Kimura et al. (2017), and Bett et al. (2020), which has been updated and re-tuned to provide best agreement with observations when forced with the latest ERA5 atmospheric reanalysis (Copernicus Climate Change Service, 2017). A detailed model description is given in Text S1 in the Supporting Information S1.

When forced with ERA5, the model generally agrees with observations, in terms of mean conditions as well as interannual variability (Text S2 in the Supporting Information S1). Its main bias is a predisposition to occasional convection on the continental shelf, which temporarily cools and freshens the deep waters. Such an event occurs once during the ERA5-forced simulation, although it was not observed during this time. The potential impact of this bias on our results is discussed later.

In this study, we present twentieth-century simulations forced with the atmospheric output of the Pacific Pacemaker Ensemble (PACE) of climate model simulations (Schneider & Deser, 2018). PACE consists of 20 realizations of the global Community Earth System Model (CESM), running from 1920 to 2013 with historical forcing including changes in greenhouse gases. The simulations are also constrained to follow observed sea surface temperature anomalies in the tropical Pacific. This constraint is useful for studying the last century in the Amundsen Sea, as Pacific variability has a strong influence on this region, and has contributed to centennial trends (P. R. Holland et al., 2019). These simulations preserve the observed record of Pacific variability, including ENSO and the IPO, while sampling the range of other modes of variability at all timescales. Since PACE has a cold and dry bias over Antarctica, we apply spatially varying bias corrections to some variables (Text S3 in the Supporting Information S1), but not to winds over the shelf break. Each MITgcm simulation is preceded by a 30-year spin-up, consisting of the forcing period 1920–1949 repeated once. Drift occurs in approximately the first 10 years of spinup and not thereafter.

3. Results

3.1. Simulated Trends Over the Last Century

It has previously been shown (P. R. Holland et al., 2019) that the PACE ensemble exhibits a significant eastward trend in zonal wind over the Amundsen Sea shelf break (Figure 1a). Our ice-ocean simulations show, for the first time, that these wind trends correspond with oceanographic changes on the Amundsen Sea continental shelf. We find a significant warming trend at middepth (Figure 1b) of 0.33°C/century in the ensemble mean. We also find a significant increase in ice shelf melting (Figure 1c) of 47%/century, although this trend may be less reliable as we do not consider ice shelf geometric feedbacks. In both cases, these trends represent an increase of 1–2 standard deviations over the simulation. Middepth salinity on the continental shelf also has a significant positive trend of 0.021 psu/century, consistent with greater influx of CDW across the shelf break. (The significance of ensemble mean trends in this study is determined using a 2-sided *t*-test for the 20 individual trends, against the null hypothesis that the mean is zero.)

The ensemble mean trend represents the response of the system to both radiative forcing and centennial-scale Pacific variability (Schneider & Deser, 2018). The detrended ensemble mean variability (variations in the dark blue line relative to the black trend line in Figure 1) represents shorter-term Pacific variability. The timing of decadal variations in the ensemble mean is largely consistent with the glaciological record. We simulate a warm period around 1970, with reduced ensemble spread indicating high confidence. This warm period aligns with the final ungrounding of Pine Island Glacier from a submarine ridge, as estimated from sediment records (Smith et al., 2017) and remote sensing (Jenkins et al., 2010; shaded region 2 in Figure 1c). We also simulate warm periods in the early 1990s and early 2000s, corresponding with the onset of recent thinning of the Pine Island and Thwaites Glaciers respectively (Konrad et al., 2017; shaded regions 3 and 4 in Figure 1c). However, our simulations do not show an obvious warm period in the 1940s, which is estimated as the initial ungrounding of Pine Island Glacier (Smith et al., 2017; shaded region 1 in Figure 1c). While the strong El Niño of the early 1940s (Schneider & Steig, 2008; Steig et al., 2013) is apparent in the zonal winds, it is less obvious in the temperature and melting.

The spread of the ensemble indicates internal non-Pacific variability, including Atlantic and Indian Ocean modes of variability, and local feedbacks on the continental shelf. This ensemble spread is substantial, demonstrating that tropical Pacific variability is far from the only determinant of conditions on the continental shelf. The ERA5-forced simulation is shown in Figure 1 for comparison, and is equivalent to an individual ensemble member. It generally falls within the ensemble spread, suggesting our PACE bias corrections are successful. Hovmöller

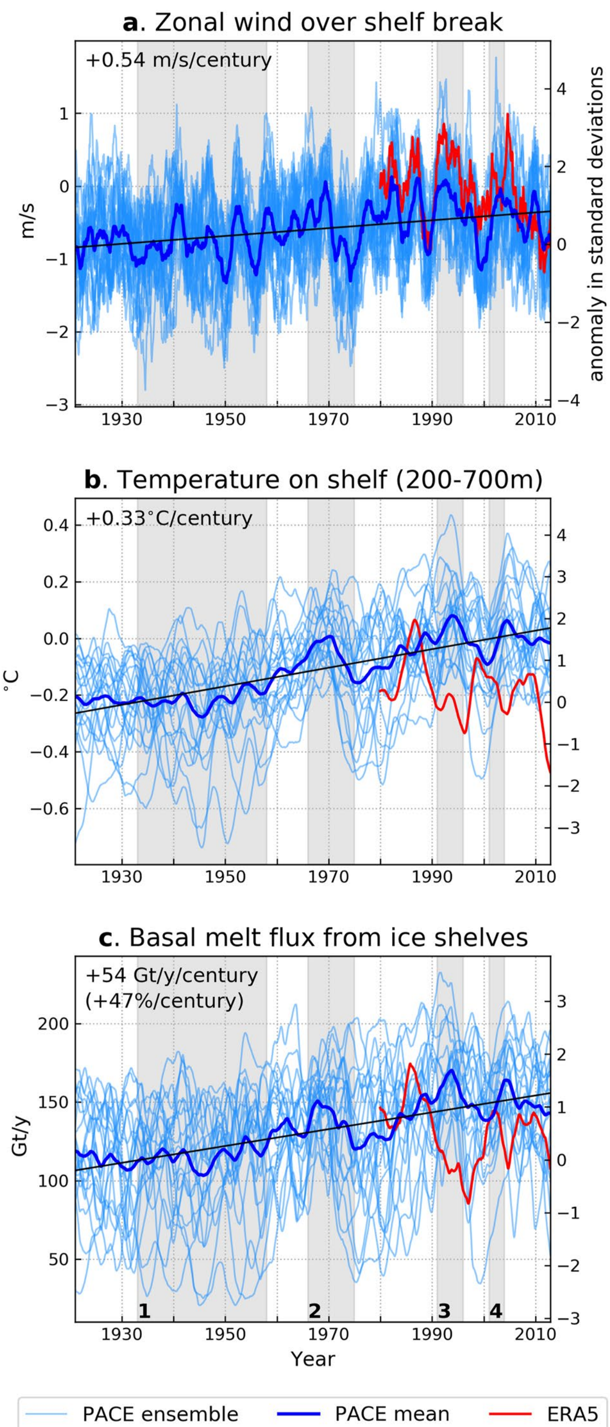

Figure 1. Timeseries of conditions in the Pacific Pacemaker Ensemble (PACE) simulations (blue) and the ERA5 simulation (red). Thinner blue lines show the 20 PACE ensemble members, while the thicker blue line is the ensemble mean. (a) Zonal wind (m/s) averaged over the shelf break. (b) Temperature (°C) averaged over the Amundsen Sea continental shelf between 200 and 700 m. (c) Basal melt flux (Gt/y) for ice shelves between Dotson and Cosgrove inclusive (see Figure 2). The regions used for (a and b) are defined in Figure S1 in the Supporting Information S1. All timeseries are 2-year running means. Also shown are the ensemble mean trends (black lines and printed values), all of which are significant at the 99% level. For (c), the trend is also expressed as a percentage of the ensemble mean over the first 30 years. The second *y*-axis on the right of each panel scales the results to show the anomaly, in standard deviations, from the first 30 years. Shaded time periods show the estimated dates of major glaciological events, labeled in (c): (1, 2) the initial and final ungrounding of Pine Island Glacier from a submarine ridge (Smith et al., 2017); (3, 4) the onset of recent thinning of Pine Island and Thwaites Glaciers, respectively (Konrad et al., 2017).

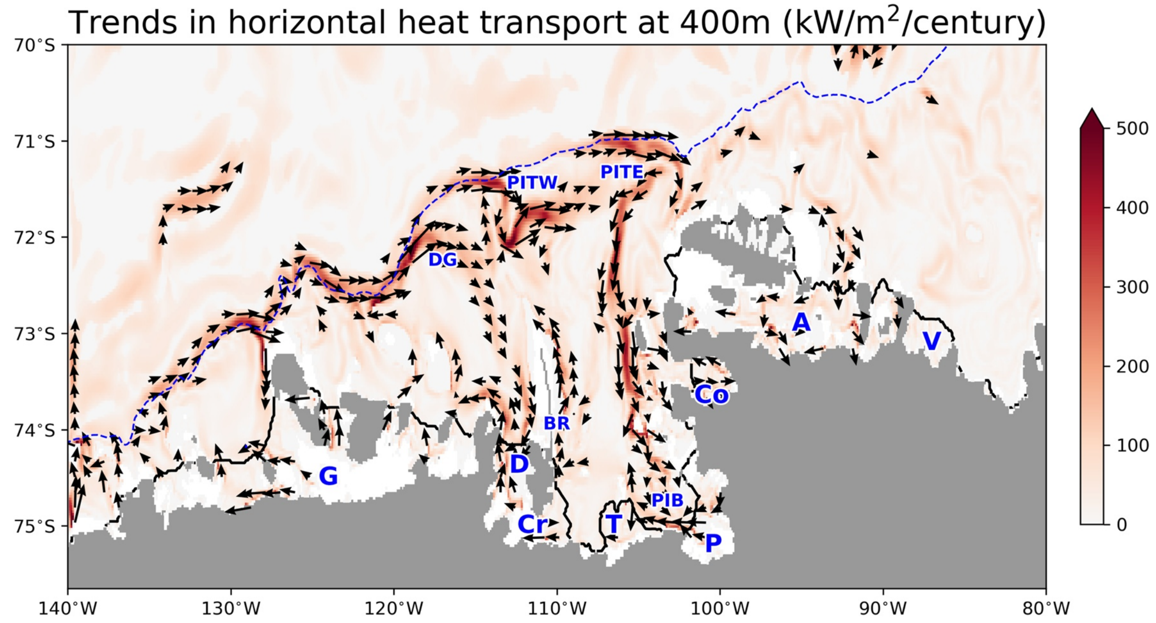

Figure 2. Ensemble mean trends in horizontal advection of heat, relative to the surface freezing point. The *x* and *y* components of the trend are calculated separately using annual means, and their magnitude is shaded in red. Vectors are plotted where the magnitude exceeds 125 kW/m^2/century. Trends which are not significant at the 95% level are set to zero; this applies to the *x* and *y* components individually. The dotted blue line shows the 1000 m depth contour on the shelf break. Blue labels indicate the ice shelves (G = Getz, D = Dotson, Cr = Crosson, T = Thwaites, P = Pine Island, Co = Cosgrove, A = Abbot, V = Venable) and other topographic features (DG = Dotson-Getz Trough, PITW = Pine Island-Thwaites West Trough, PITE = Pine Island-Thwaites East Trough, BR = Bear Ridge, PIB = Pine Island Bay).

temperature plots (Figure S8 in the Supporting Information S1) confirm that the PACE simulations resemble ERA5, although the phasing of the variability is heterogeneous.

3.2. Mechanism of Warming

Coincident trends in winds and middepth temperature are not proof of causation. However, a closer analysis of the warming reveals behavior consistent with the changes in winds. Trends in horizontal heat transport near the base of the thermocline (Figure 2) show a strengthening of existing pathways of onshore CDW flux. Increased eastward heat transport along the shelf break at 400 m depth indicates a strengthening of the undercurrent (Walker et al., 2013), just as would be expected from eastward wind anomalies (Thoma et al., 2008). The undercurrent then turns onshore through three main bathymetric troughs and flows toward the cavities. Note that strengthened heat transport could also be influenced by the ice shelf meltwater feedback (Donat-Magnin et al., 2017; Jourdain et al., 2017), which enhances circulation of CDW on the shelf.

Analysis of the heat budget on the continental shelf (Figure 3a) shows that changes in advection are mostly responsible for the warming below 200 m. There is a large ensemble spread, ranging from approximately −20 to +700 EJ by the end of the simulation, but the ensemble mean trend is significantly positive at the 99% level. There is a small contribution from vertical diffusion and KPP transport, of ≈9% of the magnitude of the advective trend. Penetration of heat from shortwave radiation has a negligible impact.

A closer look at a representative transect through 106°W (Figure 3b) reveals that advective warming is strongest at middepth (200–500 m), indicating a raised thermocline and stronger onshore flow of CDW (see also Figure S10 in the Supporting Information S1). This is consistent with a wind-driven mechanism, but could also be amplified by the ice shelf meltwater feedback strengthening circulation on the shelf. Vertical diffusion and KPP transport (Figure 3c) partially offsets the changes in advection, and reflects the displacement of the seasonal mixing depth as the thermocline rises. Diffusion and KPP slightly contribute to warming below 500 m, likely related to a reduction in cold convective events that deepen the KPP mixing (Text S4 in the Supporting Information S1). Shortwave penetration (Figure 3d) only affects the near-surface, but a positive trend in this region reflects the loss of sea ice cover, as discussed later.

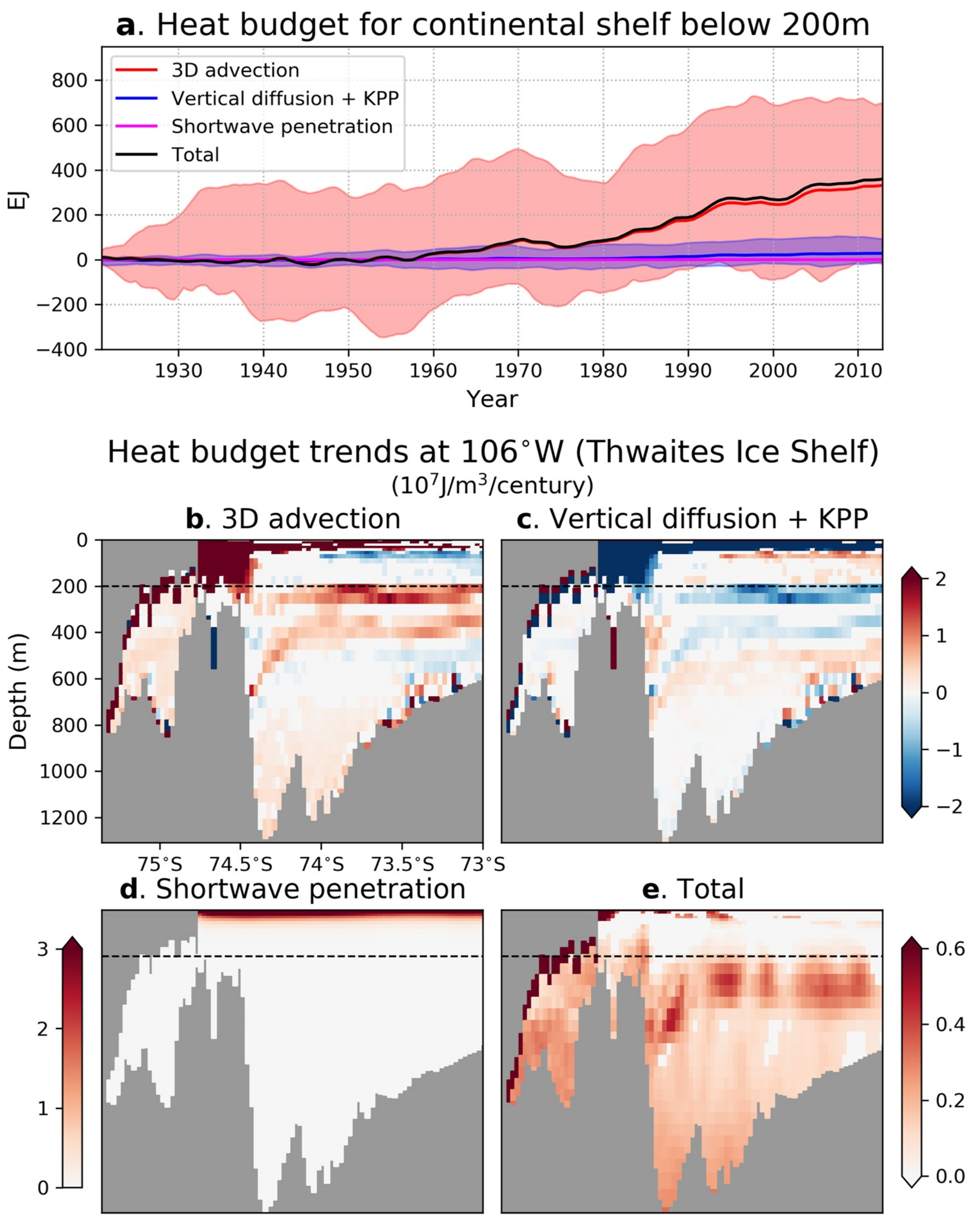

Figure 3. Analysis of heat budget terms in the interior ocean: convergence of heat from 3D advection, the sum of vertical diffusion and KPP transport of heat (note there is no explicit horizontal diffusion in this configuration), and penetration of heat from shortwave radiation. Each term is expressed as a time-integrated anomaly from the ensemble mean over the first 30 years, thus representing the accumulation of heat relative to this baseline period. (a) Timeseries (2-year running means) of each term integrated over the Amundsen Sea continental shelf (Figure S1 in the Supporting Information S1) below 200 m, excluding ice shelf cavities. Solid lines show the ensemble mean, while shaded regions show the ensemble spread for each term. "Total" is the sum of the other terms. EJ = 10^{18} J. (b–e) Ensemble mean trends for each term on the transect through 106°W (Figure S1 in the Supporting Information S1), including Thwaites Ice Shelf. Trends are calculated at each point from annually averaged values, and set to zero where they are not significant at the 95% level. (b and c) share the same color scale. The black dashed line shows the 200 m cutoff. Panel (e) shows the trend in the sum of the displayed terms (b–d), and does not include heat fluxes at the sea surface or the ice shelf base.

The sum of these terms closes the heat budget in the interior ocean (Figure 3e). Total warming is strongest at middepth, which confirms that advective warming resulting in a raised thermocline is the dominant mechanism. There is also advective warming of the deep water below 500 m, which could indicate a stronger onshore flux of CDW below the thermocline. However, it could also be influenced by a reduction in cold convective events, as quantified in Text S4 in the Supporting Information S1. We find that reduced convection locally amplifies the warming trend close to the coastline, particularly at depth. When convection is accounted for, the underlying warming is pervasive across the shelf, with a similar magnitude in all regions.

3.3. Changes at the Sea Surface

While the warming in our simulations appears to be wind-driven, we cannot determine this unambiguously. Wind stress is not the only forcing which changes during our simulations, and in fact the PACE ensemble exhibits significant trends in multiple atmospheric variables over the last century. Here we examine simulated changes at the sea surface and in sea ice, and discuss their potential relevance to the cavities.

Warming of the near-surface atmosphere ranges from ≈1.2–2°C/century over the domain (Figure 4a). Surface humidity and precipitation also exhibit positive trends (not shown). These thermodynamic trends can be expected to strengthen in the future as climate change continues. There is also a weakening of the southerly coastal winds (Figure 4b) which drive sea ice export and formation. This trend affects the regions in front of the Abbot, Dotson, and Getz Ice Shelves. There is a similar weakening of the easterly winds in front of Cosgrove Ice Shelf and the westward-facing Abbot ice front (not shown), but no significant trends in Pine Island Bay.

Sea ice freezing weakens (Figure 4c), which is caused by a combination of factors: weakened coastal winds, warmer and moister air, and entrainment of warmer deep water. As less sea ice is exported northward and along the coastal current, sea ice melting also weakens (Figure 4d), particularly near the Getz Ice Shelf. The remaining sea ice is thinner (Figure 4e), especially in regions where ice converges, such as east of Bear Ridge. Sea ice concentration declines almost uniformly, at a rate of ≈10% fractional area per century (not shown). The net surface freshwater trend into the ocean is generally positive (Figure 4f).

Ultimately, the response of the surface ocean is that of warming (Figure 4g) and coastal freshening in Pine Island Bay (Figure 4h), which is mainly driven by the advection of ice shelf meltwater. Warming and freshening of the surface both stratify the water column, which likely contributes to a reduction in convective events. We find that reduced convection can explain some of the warming in our simulations, but is not the main cause (Text S4 in the Supporting Information S1). While our simulations are consistent with a primarily wind-driven explanation, we conclude that a separate study applying idealized forcing changes would be required to determine this unambiguously.

3.4. Discussion and Conclusions

We have presented an ensemble of ice-ocean simulations testing the response of the Amundsen Sea to changes in atmospheric forcing over the last century. We find that prior to the advent of in-situ observations, the Amundsen Sea was likely dominated by cool conditions, with less pronounced warm periods than in recent decades. Our simulations show a clear long-term trend of subsurface warming and increased ice shelf melting, which coincides with glaciological observations of increased ice loss from the WAIS.

The pattern of warming in our simulations, with an increased flux of CDW along established flow pathways onto the continental shelf, is consistent with the expected response to eastward wind trends over the shelf break (Thoma et al., 2008). The link between winds and melting has been examined in decadal observations (Dutrieux et al., 2014; Jenkins et al., 2018), and our simulations confirm this relationship also holds on longer timescales.

It remains a possibility that other mechanisms are contributing to the simulated warming trend. In particular, changes in surface fluxes stratify the water column, which reduces the occurrence of cold convective events. These events have not been observed in a widespread manner in the Amundsen Sea, but it is possible they were commonplace earlier in the century, as our simulations suggest. Further research is needed to clearly separate the roles of westerly winds and surface stratification on Amundsen Sea warming, particularly since the latter mechanism has been found to be important in some future projections of ice shelf melting (Naughten et al., 2018; Timmermann & Hellmer, 2013).

Perhaps most importantly for the wider community, our results build a link between human activity and Amundsen Sea ocean conditions. The influence of Pacific variability, combined with limited oceanographic observations,

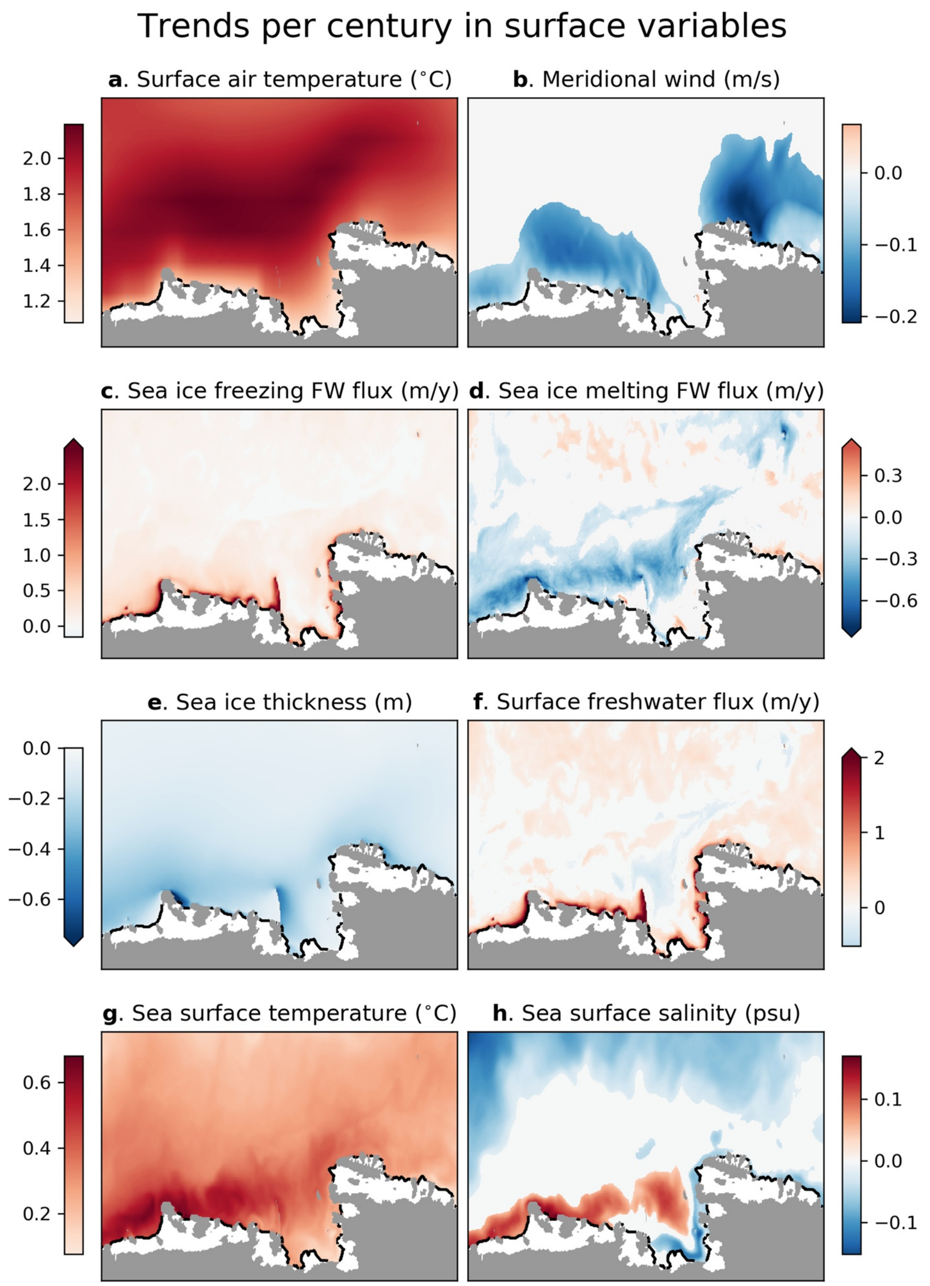

Figure 4. Ensemble mean trends in surface variables, shown in units per century and calculated using annual means. Trends which are not significant at the 95% level are set to zero, and ice shelves are masked. Sea ice freezing and melting in (c and d) are shown in m/y of freshwater flux into the ocean (positive means freshening; note different color scales), while sea ice thickness in (e) is shown in m of sea ice.

has long obscured the detection of a robust warming trend on the continental shelf. Our simulations provide the missing link connecting long-term wind trends and ice loss from the WAIS. These wind trends are driven by anthropogenic changes in greenhouse gases combined with centennial changes in tropical Pacific variability (P. R. Holland et al., 2019), and are expected to continue in a warming climate (Goyal et al., 2021).

Given that the Amundsen Sea appears to respond to anthropogenic forcing over the last century, it follows that the region should also respond to future anthropogenic forcing. If rising greenhouse gas emissions cause wind trends to continue or accelerate, we can expect the continental shelf to become even more dominated by warm conditions and increased ice shelf melting. Conversely, if emissions are sufficiently reduced and the winds stabilize, further warming of the shelf could be prevented. The future of the Amundsen Sea, therefore, is still to be decided.

Data Availability Statement

The model source code and configuration files are publicly accessible (Naughten, 2021b); here we use the PAS_PACE configuration. The pre- and post-processing code has also been publicly archived (Naughten, 2021a). The model output has been archived by the UK Polar Data Centre and is publicly accessible (Naughten, 2022).

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