Regional controls on the sea ice-mixed layer depth relationship in the West Antarctic Peninsula (WAP)

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August 4, 2023

Abstract

In the West Antarctic Peninsula (WAP), complex interactions between the cryosphere, ocean and atmosphere produce an environment with large geographical, seasonal and interannual variability which is highly vulnerable to climate change. The seasonal sea ice cycle and its interactions with upper-ocean mixing play an important role in structuring this environment. Here we show that the relationship between sea ice and mixed layer depth (MLD) varies regionally between the WAP shelf and off-shelf regions. Using an MITgcm regional model of the WAP and Bellingshausen Sea for 1989-2018, we find that on the WAP shelf, high winter sea ice coverage is related to shallow spring mixed layers, whereas in a region offshore of the shelf, high winter sea ice coverage is related to deep spring mixed layers. The exact boundary between positive and negative correlations between winter sea ice concentration (SIC) and spring MLD varies decadally. Our results can be explained by a nonlinear relationship between SIC and momentum flux into the ocean, with a minor additional role for the timing of seasonal processes. Transport of sea ice across the model domain dampens this mechanism except in regions of very large sea ice export such as polynyas. With sea ice conditions projected to undergo large changes over the course of the century, understanding the relationship between sea ice and upper-ocean mixing in this unique and vulnerable location is crucial for understanding the wider impacts of climate change on biological productivity in the polar oceans.
Regional controls on the sea ice - mixed layer depth relationship in the West Antarctic Peninsula (WAP)

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Key Points:
• High winter sea ice concentrations (SIC) drive shallower mixed layers on the WAP shelf in spring, but deeper mixed layers off the shelf.
• This can be explained by a non-linear relationship between SIC and air-sea momentum transfer, as well as the timing of seasonal events.
• The transport of sea ice across the region is a minor dampener of this mechanism, except in regions of large sea ice export.

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Abstract
In the West Antarctic Peninsula (WAP), complex interactions between the cryosphere, ocean and atmosphere produce an environment with large geographical, seasonal and interannual variability which is highly vulnerable to climate change. The seasonal sea ice cycle and its interactions with upper-ocean mixing play an important role in structuring this environment. Here we show that the relationship between sea ice and mixed layer depth (MLD) varies regionally between the WAP shelf and off-shelf regions. Using an MITgcm regional model of the WAP and Bellingshausen Sea for 1989-2018, we find that on the WAP shelf, high winter sea ice coverage is related to shallow spring mixed layers, whereas in a region offshore of the shelf, high winter sea ice coverage is related to deep spring mixed layers. The exact boundary between positive and negative correlations between winter sea ice concentration (SIC) and spring MLD varies decadally. Our results can be explained by a nonlinear relationship between SIC and momentum flux into the ocean, with a minor additional role for the timing of seasonal processes. Transport of sea ice across the model domain dampens this mechanism except in regions of very large sea ice export such as polynyas. With sea ice conditions projected to undergo large changes over the course of the century, understanding the relationship between sea ice and upper-ocean mixing in this unique and vulnerable location is crucial for understanding the wider impacts of climate change on biological productivity in the polar oceans.

Plain Language Summary
The West Antarctic Peninsula (WAP) is a unique place that is undergoing many changes because of climate change. Sea ice forms on top of the ocean in autumn and winter and can affect the mixing of water in the surface of the ocean. This mixing has important impacts on life in the ocean. In this study, we use a computer model to investigate the relationship between sea ice and mixing in the WAP. We find that there are differences in this relationship across the WAP, such that increased winter sea ice is related to decreased spring mixing in the shallow coastal regions, and to increased spring mixing in the deeper offshore regions. This can be explained by the relationship between sea ice and wind mixing: broken-up sea ice cover can increase wind mixing, whereas full sea ice cover is a barrier to wind mixing. The timing of seasonal processes, such as sea ice formation and melt, also plays a role. It is important to understand the mechanisms shaping the relationship between sea ice and upper-ocean mixing because this can help us understand the wider impacts of climate change on polar environments.

1 Introduction
The upper-ocean mixing regime is a key factor determining biological productivity in the West Antarctic Peninsula (WAP). Its impacts on primary producers are manifold and range from an entrainment of nutrients from deeper waters to a modulation of light limitations (Saba et al., 2014; Venables et al., 2013; Vernet et al., 2008). Sea ice in turn has complex effects on upper-ocean mixing, which can be broadly split into the categories of sea ice formation and melt, and the moderation of wind forcing (Montes-Hugo et al., 2009; Rozema et al., 2017; Venables et al., 2013; Vernet et al., 2008). Sea ice formation in autumn leaves behind high-salinity brine in the ocean’s surface layer which sinks according to its density. This process induces vertical mixing, leading to a deepening of the mixed layer. Spring sea ice melt adds freshwater back into the upper ocean, which forms a shallow, highly buoyant lens that is gradually eroded by turbulent mixing processes (Barthelemy et al., 2015; Moffat & Meredith, 2018; Petty et al., 2014).

Large concentrations of sea ice can act as a barrier that protects the ocean from wind-induced mixing (Montes-Hugo et al., 2009; Venables et al., 2013). However, the strength of upper-ocean mixing may not be linearly related to sea ice concentration (SIC). Martin et al. (2014) found that in the Arctic, momentum transfer into the upper ocean peaks
at a SIC of approximately 80%. Consequently, the effect of sea ice on upper-ocean mixing may change qualitatively depending on season, where the presence of sea ice may increase upper-ocean turbulence during its growth and breakup phases, and inhibit momentum transfer at its maximum coverage.

Various studies confirm a relationship between reduced sea ice cover in winter and deeper mixing in spring (Venables et al., 2013; Venables & Meredith, 2014), with wider physical and biogeochemical implications including a higher ocean heat content in spring, decreased iron availability, more variable light conditions, and decreased primary productivity. Concurrently, an increase in primary productivity following high sea ice winters may be attributed to sea ice insulating the ocean from wind mixing, keeping winter mixed layers shallow (Schrofield et al., 2017). The response of primary productivity to changes in sea ice extent (Montes-Hugo et al., 2009) as well as MLD (Vernet et al., 2008) may however vary regionally along the WAP, and with distance from the coast.

These results point to a relationship between sea ice and the mixed layer that is governed by a combination of increased shelter from wind mixing in winter and an increased input of meltwater in spring, with high winter SICs being related to shallow spring mixed layers. However, the majority of the observations supporting a relationship between winter SIC and spring MLD in the WAP were taken in coastal locations on the central and northern WAP shelf (e.g. Kim et al., 2018; Venables & Meredith, 2014, and with the exceptions of Montes-Hugo et al., 2009 and Vernet et al., 2008). Previous modelling work focusing on the evolution and breakdown of vertical stratification has explicitly excluded lateral transport processes of sea ice (Meredith & King, 2005). Sea ice transport and compaction processes (Massom et al., 2018), lateral gradients in climate variables, as well as spatial variability in oceanographic conditions may however pose further complications to the relationship between SIC and MLD.

The WAP is a region with complex hydrography and large differences between the shelf and offshore environment. The region offshore of the WAP shelf is directly influenced by the waters of the Antarctic Circumpolar Current (ACC), with warm Upper Circumpolar Deep Water (UCDW) located at varying depths below approximately 250 m (Moffat et al., 2008; Moffat & Meredith, 2018). This warm, nutrient-rich water mass is upwelled at the shelf break and can be found in highly modified form (mUCDW) on the continental shelf (Martinson et al., 2008; Martinson & McKee, 2012). Differences in water column structure below the mixed layer may have impacts on MLD evolution throughout the year.

The WAP and Bellingshausen Sea region has been subject to large recent environmental changes. Unlike most other regions in Antarctica, the region has experienced long-term atmospheric warming (Jones et al., 2019; Vaughan et al., 2003), with ocean warming being documented more recently (Meredith & King, 2005; Schmidtke et al., 2014). There has been a decrease in sea ice extent of $54 \times 10^5$ km$^2$ per decade over the period 1979-2013 in the Amundsen and Bellingshausen Sea sector (Turner et al., 2015), with a large decrease in the length of the sea ice season over similar time scales (Massom et al., 2008; Stammerjohn et al., 2012). The currently observed record-low in Antarctic sea ice extent (Meier, Stewart, et al., 2021) further demonstrates the regime shift currently underway in the Antarctic climate system and adds to the urgency of research considering the impacts of sea ice decline on the ocean. While the Antarctic atmospheric warming trend has reversed in recent years (Oliva et al., 2017; Turner et al., 2016), projections indicate a future rise in atmospheric temperatures even under a 1.5°C warming scenario (Hoegh-Guldberg et al., 2018) and a concomitant decrease in SIC (Roach et al., 2020; Siegert et al., 2019). This projected warming in the Antarctic Peninsula is larger than the global average (Hoegh-Guldberg et al., 2018). In light of these projections and the currently observed record-low Antarctic sea ice extent (Meier, Stewart, et al., 2021), it is of high importance to understand regional differences in the intricate relationship between sea ice and upper-ocean mixing in the WAP, which, due to its large present-day
climate variability, can serve as a model system for examining the effects of future cli-
rate warming on polar marine environmental systems further afield.

While the WAP shelf is one of the most studied regions in Antarctica, more ob-
servations are still needed to understand how this system might respond to climate change
(Henley et al., 2019). While long-term research programs are in operation across large
parts of the central and northern WAP, continuous observations are particularly sparse
in the Bellinghausen Sea and the WAP south of Marguerite Bay due to sea ice condi-
tions making the region inaccessible (Henley et al., 2019). Even further north in the WAP,
sea ice often prohibits sampling during the winter season, with many cruises only oper-
ing in the summer months. Numerical modelling can be used to fill this gap in the
availability of observational data. In this paper we use regional coupled ice-ocean mod-
elling to further our mechanistic understanding of the relationship between SIC and MLD
in a variety of settings in the WAP and Bellinghausen Sea region. We give particular
focus to regional variations in the relationship between SIC and MLD during the win-
ter and spring seasons. We assess potential drivers for these regional variations, and ex-
amine decadal shifts in the regional patterns of the relationship between sea ice and upper-
ocean mixing.

The model set-up used in this study is discussed in Section 2 alongside a compar-
ison of various methods used to calculate MLD, and an overview of the analyses performed
using our model output. Section 3 describes our model validation process focusing on
SIC and mixed layer characteristics. Section 4 describes our results. Section 5 discusses
four mechanisms that may be individually or jointly responsible for the regional variabil-
ity in the SIC-MLD relationship, and discusses their implications in light of a changing
WAP. Conclusions can be found in Section 6.

2 Methods

2.1 Model set-up

This study makes use of a Massachusetts Institute of Technology general circula-
tion model (MITgcm) set-up for the WAP (Regan et al., 2018; Schultz et al., 2021) which
will be referred to as MITgcm-WAP in this paper. The MITgcm is a numerical hydro-
dynamic model which is widely used and offers flexibility through its many packages rep-
resenting key components of the Earth system, such as sea ice, ice shelves and the at-
mosphere. Its development is extensively described in the literature (Adcroft et al., 2004;
Adcroft & Campin, 2004; Hill & Marshall, 1996; Marotzke et al., 1999; Marshall et al.,

Our model grid spans the region between 95 and 55°W, and 74.4 to 55°S; this in-
cludes the WAP in the east, the Bellinghausen Sea in the west, and the Antarctic Cir-
cumpolar Current in the north (Figure 1). We use a grid resolution of 0.2°, leading to
a meridional grid spacing of approximately 6km in the southern WAP and approximately
13km in the northern WAP.

Atmospheric boundary forcing is represented by the MITgcm external forcing pack-
age. While the studies of Regan et al. (2018) and Schultz et al. (2021) use ERA-Interim
reanalysis data as atmospheric boundary conditions, we have updated the model to use
the newer ERA5 product at 6-hourly intervals (ERA5 monthly averaged data on pres-
sure levels from 1940 to present [November 2020]; Hersbach et al., 2023). These pro-
vide a higher spatial resolution of 0.28° instead of 0.75°. It is important to note that ERA5
shows a smaller recent (1991-2015) warming trend over the WAP than ERA-Interim (Bozkurt
et al., 2020). ERA5 reanalysis data are used for precipitation, meridional and zonal wind
speed (at 10m above the sea surface), surface (2m) temperature and specific humidity,
downward longwave and shortwave radiation, and the atmospheric pressure field. All ex-
ternal forcing fields have a temporal resolution of 6 hours and were linearly interpolated
onto our model grid. Lateral boundary conditions (ocean temperature, salinity and velocities, and sea ice area, thickness and velocities) are handled by the MITgcm OBCS package using 1990-1999 monthly averages from Holland (2014). Glacial runoff is represented as a constant input of freshwater at the ocean surface which declines exponentially with distance from the coast up to a distance of 100km (Regan et al., 2018). This is consistent with observations of freshwater distribution on the WAP shelf (e.g. (Dierssen et al., 2002)). Due to the small effect of tidal stirring in the region (Brearley et al., 2017), the model does not simulate tides.

The model uses the MITgcm seaice package described in Losch et al. (2010) with an elastic-viscous-plastic rheology following Hunke and Dukowicz (1997). We set the air-ice drag coefficient to $2 \times 10^{-3}$, while the air-ocean and ocean-ice coefficients are kept at default values of $1 \times 10^{-3}$ and $5.5 \times 10^{-3}$, respectively.

Vertical mixing is represented by a non-local K-profile parameterisation (KPP; Large et al., 1994). KPP has separate algorithms describing mixing processes in the ocean’s surface boundary layer and the interior ocean: the surface boundary layer is defined in every grid column by a bulk Richardson number, while mixing in the surface boundary layer is expressed as a gradient-flux term dependent on the vertical gradient in tracers, and a non-local term that enhances mixing in unstable conditions. Mixing in the interior ocean in this implementation is influenced by shear instability and internal wave activity, with double diffusion not represented. KPP is commonly used in ocean models and a validation of KPP against observations can be found in Large et al. (1994).

The model is initialised on January 1, 1979 and run for 40 years. The first ten years of the model run (1979-1988) are treated as spin-up, except for the purpose of MLD validation where we make use of model output from year 7 (1985) onward. A time step of 1200 seconds is used, which facilitates model stability while keeping computational costs relatively low.

2.2 MLD calculations

There are various widely used methods and algorithms for calculating MLD, the usefulness of which depends on local hydrographic conditions. The most common calculations use either an absolute temperature or density threshold, or a temperature or density gradient threshold (Holte & Talley, 2009). An absolute density (temperature) threshold sets the MLD to the first depth below the surface at which the density (temperature) differs from its surface value by a predetermined amount. The density (temperature) gradient method sets the MLD to the first depth at which the density (temperature) gradient reaches a predetermined value. Less common metrics include the location of a property maximum in the subsurface or the use of curve fitting (Holte & Talley, 2009).

Our criterion for determining a useful MLD metric is to find an algorithm that closely follows the subsurface maximum of the squared Brunt-Väisälä frequency $N$

$$N^2 = -\frac{g}{\rho_0} \frac{d\rho_0}{dz}$$

where $g$ is the gravitational acceleration, $\rho_0$ is the potential density, and $z$ is depth. The Brunt-Väisälä (or buoyancy) frequency is the frequency at which a parcel of water will oscillate if vertically displaced in a stable environment (Gill, 1982). It can therefore be used as a measure of stratification, where the MLD is the depth of maximum stratification. This metric has been commonly used in studies of the WAP (Carvalho et al., 2017).

Figure 2 shows MLDs calculated using absolute density and temperature threshold methods as well as density and temperature gradient methods, all using a range of different (gradient) thresholds, for two different locations in our model domain.
We choose the use of an absolute density threshold based on it providing a smooth representation of MLD which follows the maximum $N^2$ when a maximum in stratification is present. This is a more robust metric than using a density gradient threshold, where the MLD defaults to the seafloor during the winter breakdown in stratification (Figure 2). Temperature-based MLD metrics are rejected on the basis of the polar oceans being predominantly stratified by salinity, but are shown in Figure 2 for illustration purposes.

Various possible density thresholds were tested in order to determine their effect on calculated MLDs (Figure 2). Density thresholds of 0.3, 0.4 and 0.5 kg m$^{-3}$ behave qualitatively similarly and differ by less than 30 m in the locations shown. Since a 0.4 kg m$^{-3}$ density threshold corresponds best with the MITgcm default MLD diagnostic ("MXLDEPTH"), we use this metric hereafter.

2.3 Analysis

The model was initiated in 1979 and run until 2018. The first ten years (1979-1988) were treated as spin-up time. Model output diagnostics were generated as monthly averaged two and three dimensional fields which were then further processed to generate the results shown in this paper. Time series are shown averaged over four different regions shown as boxes in Figure 1: ‘Shelf South’, ‘Shelf North’, ‘Off-shelf South’ and ‘Off-shelf North’.

The aim of this paper is to investigate the relationship between winter sea ice conditions and the spring MLD in various subregions across our model domain. Sea ice extent, thickness and volume were investigated as potential measures of winter sea ice conditions but were ultimately rejected in favour of using SIC due to its simplicity, the wide availability of satellite remote sensing SIC data for model validation, and our later focus on the exposure of the surface ocean to wind mixing.

Correlations between winter (June, July, August) SIC and spring (September, October, November) MLD were calculated for each cell in the model grid by treating the data from each grid cell column as an individual time series. Monthly SIC and MLD anomalies were calculated separately for each time series by subtracting the 30-year (1989-2018) monthly grid cell column mean from the time series. Seasonal means were then calculated for each of these time series of anomalies. Linear correlation coefficients between the time series of winter SIC and spring MLD anomalies were calculated for each grid cell column using standard Matlab functions. Linear regression coefficients were calculated to ascertain that strong correlations are not caused by a lack of variability in SIC or MLD. Maps of regression coefficients can be found in the supplementary materials. Correlation and regression calculations were made for the entire 30-year dataset (excluding the spin-up period), as well as separately for each decade (1989-1998, 1999-2008, 2009-2018) to investigate decadal differences in the SIC-MLD relationship.

In addition to SIC we also analyze freshwater flux out of the ocean associated with sea ice formation, and freshwater flux into the ocean associated with sea ice melt. This is calculated by splitting the freshwater flux across the ocean surface that is associated with sea ice into its positive and negative components at every time step (code provided by K. Naughten). Seasonal averages of these fluxes are calculated as described for SIC and MLD above. These freshwater diagnostics provide a measure of how much sea ice has formed and melted in a given region over the winter and spring seasons, whereas SIC is a measure of how much sea ice was present on average, and therefore what proportion of the ocean surface has been directly exposed to the atmosphere. This allows us to differentiate between the effects of sea ice formation and melt on the hydrographic makeup of the water column compared to the effects of wind mixing, as well as to account for the effects of sea ice transport across the model domain.
All time series are shown for the first decade (1989-1998) for better readability. The corresponding figures for 1999-2008 and 2009-2018 can be found in the supplementary information.

3 Model validation

3.1 Data

To assess the performance of our model, we compared modelled SIC and MLD to observational datasets (mixed layer temperature and salinity are shown in the supplementary information). Modelled SIC was compared to the monthly NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 (Meier, Fetterer, et al., 2021). This dataset combines SIC data from the NASA Team algorithm (Cavalieri et al., 1984) and NASA Bootstrap algorithm (Comiso & Sullivan, 1986) and is available on a 25x25km polar stereographic grid. A comparison of various remote sensing sea ice products with ship-based observations demonstrates the dataset's low bias in the Antarctic (Kern et al., 2019). A recent analysis of sea ice extent and area trends from this dataset is provided by Meier et al. (2022).

Monthly sea ice data from the aforementioned dataset was linearly interpolated onto the MITgcm-WAP grid, with land cells being masked out according to the MITgcm-WAP bathymetry. Only data from the inner part of the MITgcm-WAP grid (93.2-63.2°W and 73.8538-61.2253°S; Figure 1) was used for validation purposes; this excludes the model boundaries as well as the western Weddell Sea, which is only included in the model domain to represent water exchange across the Bransfield Strait region in the northern WAP more accurately.

Temperature and salinity model output was compared to World Ocean Atlas 2018 data (WOA; Boyer et al., 2018; Locarnini et al., 2018; Zweng et al., 2019). WOA is a quality controlled, gridded dataset of World Ocean Database data at standard depth levels, with a vertical resolution of down to 5 m in the surface ocean. Data are available as monthly averages over time spans of approximately ten years; Figures are shown comparing model output to WOA data from 1985-1994.

WOA temperature and salinity data were linearly interpolated onto the MITgcm-WAP model grid. Monthly means averaged over the relevant time periods were computed from temperature and salinity model output. As done for sea ice validation, land cells were masked out and both model and observational datasets were reduced to the inner part of the MITgcm-WAP grid to exclude the model boundaries and the Weddell Sea. MLD was calculated for the interpolated WOA data as well as for our model output using an algorithm by Greene et al. (2019, following Holte and Talley, 2009), with a density threshold of 0.4kg m⁻³ in relation to the surface layer (see section 2.2).

3.2 Sea ice

A comparison of modelled SIC data and NSIDC remote sensing data is shown in Figures 3 (1989-1998), S1 (1999-2008) and S2 (2009-2018). There is a good degree of correspondence in the seasonal variability of SIC in our model and the NSIDC data. Winter and spring SICs show a similar geographical distribution in the two datasets, with only some slight underestimations of the extent of the marginal ice zone in our model (Figures 3, S1, S2). These differences may be related to the model's drag terms. While there is a small bias towards low summer SICs during all decades, the model shows strong agreement with the NSIDC data in autumn, with the exception of Marguerite Bay where the model overestimates SIC.

There are some disagreements in SIC between model and NSIDC data in coastal locations (e.g. Marguerite Bay in autumn; Figure 3), indicating a faster re-growth of sea
ice in these locations at the end of summer in our model. Overall however, the seasonal cycle in SIC is captured well by our model, giving us confidence in using it as a tool for this study.

### 3.3 Mixed layer characteristics

Figure 4 shows monthly averaged MLDs for the period of 1985-1994, calculated from our model output as well as WOA data as described in Section 3.1. Figures S3 and S4 show mixed layer temperature and salinity for 1985-1994. The expected seasonal cycle in MLD is well represented in the model, with a clear deepening of the MLD during autumn and winter, and a subsequent shoaling that begins at the coast. There is good agreement between model and WOA data during the winter season, with some modelled MLDs being deeper than the WOA mixed layers in the south of the domain. However, it should be considered that there are very few observations from this region during the winter due to prohibitive sea ice conditions. During all other seasons, our model tends to underestimate MLD throughout much of its domain, and particularly along the coast and on the southern shelf. Figure S4 indicates that the bias towards shallow summer MLDs may be caused by a surplus of freshwater in the mixed layer. This freshwater disperses over the seasons, with winter and spring mixed layer salinity showing a good agreement between the model and WOA data.

One theory for the presence of these large quantities of freshwater on the southern shelf in summer is the representation of runoff in the model. Freshwater is introduced into the uppermost layer of the ocean at rates that are constant in time and decline with distance from the coast (see Section 2.1). While there may be issues with the depth of freshwater input from runoff, the runoff term in this model set-up is a constant term in time without any seasonal variability. Since the bias towards low mixed layer salinity is largest in summer and dissipates over spring, this discrepancy is more likely caused by freshwater input processes which do show seasonal variability, such as sea ice, iceberg, or glacial melt. While we note that there are biases towards shallower MLDs in our model, we are confident in the model’s overall representation of MLD dynamics throughout the seasons.

### 4 Results

#### 4.1 SIC-MLD relationship

Figure 5 shows a regional distribution of correlation coefficients calculated for average winter (June, July, August) SIC anomalies, and the same year’s average spring (September, October, November) MLD anomalies for the 30-year time period of 1989-2018. Average correlation coefficients for each subregion can be found in the first column of Table 1. Correlations are negative over most of the WAP continental shelf, showing that large winter SICs are correlated with shallow spring MLDs. Particularly strong correlations can be found in Marguerite Bay and within a few kilometres of the northern WAP coast. There are also significant negative ($p < 0.05$) correlations between the two anomalies on the southern WAP shelf. There is an area with significant positive correlations off the shelf, with large winter SICs being correlated with deep spring MLDs. This region is found off the shelf between approximately 66° and 71°S and extends northeastwards in a narrow band along the WAP shelf break. In the area off the shelf north of 66°S, correlations are weakly negative.

Figure S5 shows regression coefficients calculated for the same dataset. Despite the strong bands of negative and positive correlations along the northern WAP shelf, regressions in this area are weak. Strong positive regression coefficients are found for the area with positive correlations between 66° and 71°S. Negative regression coefficients are found across most of the southern shelf region, with particularly strong values near the coast.
of the southern shelf between 89 and 82°W. There are also multiple small regions of positive regression across the southern shelf region, corresponding to small scale regions of positive correlation. The overall pattern of regression is similar to that of correlation, suggesting areas of strong correlation also exhibit sufficient interannual variability in SIC and MLD.

Figure 6 splits up the 30-year correlation coefficients shown in Figure 5 into 10 year segments (1989-1998, 1999-2008, 2009-2018), with Table 1 stating average correlation coefficients for each subregion. Linear regression coefficients can be found in Figure S6. Most notably, the first decade (1989-1998) shows very strong, significant ($p < 0.05$) negative correlations and regressions on the southern shelf, and positive correlations and regressions off the continental shelf as well as on the northern shelf. These patterns are very similar to those of the 30-year dataset, but with the first decade (1989-1998) showing stronger correlations and regressions with larger areas of significance than the 30-year dataset.

The pattern of negative correlations on the southern WAP shelf as well as north of approximately 66°S, and positive correlations between 66 and 71°S and along the shelf break of the northern shelf weakens in the second (1999-2008) and third (2009-2018) decades. In 1999-2008, there is still a notable band of positive correlations along the shelf break which is positioned towards the shore to the east of approximately 77°W, and offshore of the shelf break to the west of 77°W. While strong negative correlations are still found on the shelf (especially in Marguerite Bay), regressions are relatively weak throughout the model domain. The patch of strong negative correlation and regression found near the coast of the southern shelf during 1989-1998 decreases in strength and even changes sign to the west of approximately 82°W. The overall pattern of negative and positive correlations for 2009-2018 is similar to that of 1999-2008, with a slight increase in the total area showing positive correlations and an increase in patchiness.

Figures 5 and 6 show correlations between winter SIC and spring MLD with the winter months being June to August, and the spring months being September to November. A qualitatively similar pattern in correlations is obtained when shifting these definitions forward or backward by one month, as shown in Figures S7 and S8 for the full 30-year model run, and Figures S9 and S10 for each decade.

Time series of monthly SIC and MLD averaged over the four regions (Figure 1) are shown in Figure 7 for 1989-1998 (Figures S11 and S12 show the same results for 1999-2008 and 2009-2018), together with monthly mean wind speed and wind speed normalised by the sea ice-free area. SICs are highest on the southern shelf, with periods of multiple months of 100% SIC and an average maximum SIC of 99% across all years (Table 2). The maximum SIC is typically reached before the start of winter and remains stable into the spring months. The interannual variability in average winter SIC is low. On the southern shelf, approximately two thirds of all winters have relatively shallow MLDs of up to around 100m, while there are deeper mixing events (up to 200m) during the remainder of the years. These MLDs are the deepest across the study domain for the study period. Deep winter mixing events sometimes coincide with increased monthly mean wind speeds, but this is not always the case (Figure 7). Mixed layer shoaling tends to occur during the spring months, with minimum depths around 8m typically only being reached in early summer (Table 3). In years with anomalously high winter SICs during which the ocean becomes entirely closed off to wind mixing, spring MLDs tend to be shallower than during years with continuous winter wind mixing (e.g. 1990 compared to 1991; Figure 7).

The southern off-shelf region and the northern shelf show similar SIC and MLD behaviour in that sea ice usually does not stay at 100% concentration for longer than a month, if full cover is reached at all (Figure 7 and Table 2). Maximum SIC is only reached over the course of winter, or even in early spring (e.g. 1992). Average winter SICs are
highest during years where near-maximum SICs are reached in early winter, and remain high throughout the season (e.g. 1991). These years tend to have deep spring mixing. Average maximum monthly MLDs during the winter and spring season reach approximately 91m in the southern off-shelf region, and 66m on the northern shelf. Variability in the depth of the maximum monthly MLD is lower in both of these regions than on the southern shelf (Table 3), with a low sensitivity of MLD to absolute wind speed (as opposed to wind speed scaled by SIC). For example, the absolute wind speed is similarly high in the southern off-shelf in the winters of 1991 and 1992, while the spring MLD is considerably shallower in 1992 (Figure 7). Spring and summer minimum MLDs in the southern off-shelf region and on the northern shelf remain at a slightly deeper depth than on the southern shelf, with respective average minimum depths of 11 and 13m.

SIC in the northern off-shelf region is highly variable, with some years being completely sea-ice-free (e.g. 1989; Figure 7). Maximum SICs of approximately 80% are a rare occurrence (e.g. 1994). At an average of 101m, average maximum MLDs are however only slightly deeper than in the southern off-shelf region (Table 3). There is some variability in the depth of the maximum MLD, with deep maxima showing some correspondence with high sea ice-normalised winter wind speeds (Figure 7).

### 4.2 Freshwater

Figure 8 shows overview maps of the 30-year (1989-2018) average winter freshwater flux out of the ocean from sea ice formation, and the average spring freshwater flux into the ocean from sea ice melt. The majority of freshwater flux from sea ice formation occurs along the southern coast of the Bellingshausen Sea, with further freshwater flux from sea ice formation being spread relatively uniformly across the entire region that is usually ice-covered in winter (up to approximately 66°S in the west of the domain, and 62°S in the east of the domain). While freshwater from spring sea ice melt also enters the ocean across this region, it is more concentrated along the northern extent of the region, i.e. the winter marginal ice zone and the northern WAP coast. There is strong freshwater input into the ocean from sea ice melt in the south of Marguerite Bay.

Figure 9 shows time series of freshwater flux out of and into the ocean for the four subregions for 1989-1998. Figures S13 and S14 show the same results for 1999-2008 and 2009-2018. Table 4 summarises mean yearly integrated freshwater fluxes from freezing and melting, and the average month of maximum freshwater flux from each process. Integrated over the year, freshwater flux from sea ice melting is larger than that from freezing in all regions except the southern shelf. Mean annual freshwater fluxes are largest on the southern shelf, with a mean annual flux of 82.6 kg/m² from freezing and 71.7 kg/m² from melting, peaking on average in April and July, respectively (Table 4). While the freshwater flux from freezing consistently starts building up before the flux from melting, there is considerable overlap between the timings of the fluxes in all regions, with flux into the ocean often occurring during the same months as flux out of the ocean (Figure 9). This is particularly true for the northern off-shelf region where both fluxes are mostly confined to the winter and spring season, with peaks in both fluxes often occurring during the same month. While the increase and decrease in both fluxes over the winter and spring season are symmetrical in the northern off-shelf region, this is not the case in the other regions. The freshwater flux out of the ocean related to sea ice formation increases rapidly and then tapers off more slowly over the course of the season on the southern and northern shelf, and in the southern off-shelf region; meanwhile, on the northern shelf and in the southern off-shelf region, the freshwater flux into the ocean related to sea ice melt increases slowly while the freshwater flux out of the ocean is still tapering off, then decreases rapidly after its peak. Note that while traces of this pattern are found on the southern shelf, the pattern is most pronounced in the southern off-shelf region and on the northern shelf.
4.3 Hydrography

Hovmöller plots showing the evolution of temperature and salinity with time in the upper 500m of the water column are presented in Figures 10 and 11 for each of the four subregions for 1989-1998. Figures S15-18 show temperature and salinity Hovmöller plots for 1999-2008 and 2009-2018. The seasonal variability in temperature in the upper 40m is relatively similar in all four subregions, with an increase in temperature in summer, and a cooling in winter (Figure 10); a slight exception to this is found on the southern shelf where even the surface ocean remains at its winter temperature during many summers. Warm summer surface temperatures last longest and reach deepest in the northern off-shelf region, with temperatures warmer than 2°C commonly reached in the upper 50m during the summer months. The largest differences between the four subregions however are found below the depth of the mixed layer. While temperatures on the southern shelf remain almost at freezing point far below the mixed layer, warm (approximately 2°C) temperatures are found at a shallow depth (<200 m) in the southern off-shelf region. The depth of this warm water mass in the water column seems to vary in tandem with seasonal variations in MLD, however the warmer water mass is not fully entrained into the mixed layer at any point during our study (Figure 10). Similarly to the southern off-shelf region, there is an increase in temperature below the mixed layer in the northern off-shelf region and on the northern shelf; however, the underlying water mass is colder in these locations (approximately 0 to 1°C in the northern off-shelf region, and -0.5 to +0.5°C on the northern shelf). The gradient between cold surface water and the warmer underlying water mass in winter is therefore considerably stronger in the southern off-shelf region.

Figure 11 shows large differences in the salinity profiles of the four subregions, as well as their seasonal evolution. A summer freshening is evident in the upper 30-70m, and is most pronounced on the southern shelf and barely detectable in the northern off-shelf region. This freshening tends to reach below the mixed layer particularly in the beginning of the melt season. This signal is particularly clear on the southern shelf, where distinct plumes of summer meltwater are in stark contrast to the higher salinity (>34.2) water found below the plume, and occupying the entire upper water column during the rest of the year. While there are distinct spring and summer freshwater plumes in the southern off-shelf region and on the northern shelf (and to a smaller degree in the northern off-shelf region), the mixed layer remains fresher than the underlying water throughout the year, which is not the case on the southern shelf during all years (Figure 11).

5 Discussion

The results of this study show pronounced differences in the relationship between winter SIC and spring MLD across different subregions of the WAP and Bellingshausen Sea. Negative correlations between the two variables are found predominantly on the southern WAP shelf, in coastal locations in the north of the model domain and off the WAP continental shelf north of 66°S, while positive correlations dominate the region off-shelf in the western part of the model domain and the region of the shelf break. The following sections discuss a number of potential mechanisms that may give rise to the observed patterns in the SIC-MLD relationship.

5.1 Effect of SIC on air-sea momentum flux

There is non-linearity in how sea ice cover affects ocean surface stress and therefore momentum flux into the ocean. In a study by Martin et al. (2014), momentum flux into the ocean was found to peak at an average of around 80% sea ice coverage across the Arctic Basin (Figure 12). Up to this value, the increased roughness of the underside of sea ice leads to an increase in momentum flux into the ocean with increasing SIC. As SIC increases further, ice strength starts to prohibit the compression and therefore free
movement of ice floes, counteracting the momentum flux increase due to sea ice roughness (Martin et al., 2014). While the maximum momentum flux at 80% SIC found by Martin et al. (2014) is specific to location and ice rheology, other model configurations reproduce a maximum in momentum flux into the ocean at a SIC of approximately 80-95% (Martin et al., 2016). The use of an elastic-viscous-plastic ice rheology in our model produces a similar variability in momentum flux with SIC. This is illustrated in Figure 12 by plotting the mean ocean surface stress against corresponding SIC for all model grid cells at every time step.

Non-linearity in the relationship between SIC and momentum transfer into the ocean contributes to the regional differences in the SIC-MLD relationship shown in Figure 7. The southern shelf and coastal region (negative correlation between spring MLD and winter SIC) commonly have high concentrations of sea ice throughout the year (Figure 12; Table 2). During winters with anomalously high concentration of sea ice, the ocean can therefore become entirely closed off to wind mixing. Without wind mixing contributing to a deepening of the mixed layer during these events, spring MLDs are shallower than during years with continuous winter wind mixing. While brine rejection will have an impact on mixed layer deepening during sea ice formation, the impact of this process may be outweighed by the impact of diminished wind mixing. Several studies provide evidence of wind mixing having a larger effect on upper ocean mixing than brine rejection (e.g. Venables et al., 2013). Increased volumes of spring meltwater in these high-ice years (e.g. 1989; Figure 9) may also support the formation of a shallow spring mixed layer in this region. The opposite is the case during years with anomalously low sea ice cover on the southern shelf: in a region with high average SICs, any decrease in SIC may lead to an increase in ocean surface stress (Figure 12). In combination with a decrease in spring freshwater inputs from sea ice melt to stabilise the water column, this mechanism will lead to a deeper mixed layer in spring.

The negative correlation between SIC and MLD on the southern shelf and along the WAP coast is in agreement with observations from the region (Schofield et al., 2017; Venables & Meredith, 2014); however, the proposed mechanism may also be able to explain the unexpected behaviour in the southern off-shelf region and on the northern shelf. These regions generally experience lower SICs than the southern shelf and are therefore best placed further to the left in Figure 12, in a region of the graph where ocean surface stress increases with SIC in our model. In these regions, years of anomalously low winter SIC may lead to decreased momentum transfer into the ocean, limiting the deepening of the mixed layer. Vigorous winter wind mixing in high-sea ice years may deepen the mixed layer enough to outweigh the impact of increased meltwater input in spring, producing deeper-than-average spring mixed layers. This mechanism could give rise to the unexpected positive correlation between winter SIC and spring MLD found in this study.

Our results imply that wind mixing over the winter season is more important in setting the spring MLD than the input of meltwater in spring. This would be in line with results by Venables et al. (2013). Nevertheless, the input of meltwater in spring does affect the MLD, as demonstrated by a strong negative correlation between spring MLD and spring freshwater flux into the ocean across the model domain (Figure 13a). However, as shown in Figure 13b, the relationship between winter SIC and spring meltwater input is stronger in some regions than others. This pattern is likely caused by a combination of two mechanisms: the timing of the sea ice seasonal cycle; and the transport of sea ice across the model domain leading to net formation of sea ice in some regions and net melting in others. Both mechanisms will be explored in more detail in the following subsections.
5.2 Timing of seasonal processes

While the relationship between SIC and MLD found in this study can be explained by a non-linear relationship between SIC and ocean surface stress, we have not yet taken into account the timing of seasonal processes such as sea ice formation and mixed layer shoaling. While for the purpose of our analysis we have defined the winter season as June, July and August, and the spring season as September, October and November, events such as sea ice formation and melt may vary in time and fall into or out of the designated winter and spring seasons. In addition to interannual variability in the timing of sea ice formation and melt, there are also gradients in the timing of sea ice formation and melt processes across the region due to differences in dynamic and thermodynamic controls across the study region. This leads to an earlier onset of sea ice growth in the south of our model domain and along the coastline, and earlier sea ice melt further north in the model domain and along the sea ice edge. This will have implications for the correlations shown in Figures 5 and 6.

On the southern shelf, sea ice tends to reach its maximum extent before the start of winter, and remains at this extent during spring in most years, with little interannual variability in winter SIC (Figure 7). The mixed layer typically shoals during spring and only reaches its shallowest state after the spring months. The mean spring MLD seems to largely depend on two factors: (1) the depth of the maximum winter MLD, with a deeper maximum winter MLD being related to a deeper mean spring MLD, and (2) the timing of the onset of mixed layer shoaling, with an earlier onset being related to a shallower mean spring MLD. In contrast, SICs on the northern shelf and in the southern off-shelf region only tend to reach their maximum over the course of winter, or even at the beginning of spring. Mean spring MLDs here appear to be dependent on the timing of the onset of shoaling. While the spring MLD could still be sensitive to the maximum winter MLD, there is little interannual variability in the maximum winter MLD in these regions.

In the southern off-shelf region and on the northern shelf, where SICs do not tend to stay constant throughout the winter season (as compared to the southern shelf; Figure 7), anomalously high winter SICs are reached in years where near-maximum sea ice is reached early during the winter, and remains high throughout the winter season. The onset of mixed layer shoaling tends to be late during those years, with deeper-than-usual mean spring MLDs (e.g. 1991). This can explain the positive correlation between winter SIC and spring MLD in these regions. While the timing of the onset of mixed layer shoaling also seems to affect spring MLDs on the southern shelf, there is a much clearer relationship with the maximum winter MLD in this region. In line with the negative correlation between SIC and MLD on the southern shelf, deep mixing events in this region are related to lower than usual winter SICs (e.g. 1991) and may be explained by the mechanism outlined in Section 5.1.

5.3 Sea ice transport

Throughout our discussion so far, we have made the assumption that there is a linear relationship between winter SIC in one region and the volume of spring meltwater input in the same region. However, the transport of sea ice within the model domain is complex, with regions of net formation and net melting showing large variability between years. Averaged over 30 years, there is a pattern of net sea ice formation in coastal regions especially on the southern shelf, and melting off the shelf and on the northern shelf (Figure 8). Figure 13 further demonstrates that high sea ice melt does not always occur in places with high winter SIC. We go on to show that the transport of sea ice within the model domain is not responsible for creating the patterns observed in the SIC-MLD relationship (Figure 5). Three key assumptions are made: (1) the transport of sea ice off the continental shelf is proportional to the total amount of ice production on the shelf,
(2) the classification into high-ice and low-ice years is the same in each region, and (3) regions with deeper winter mixed layers also have deeper spring mixed layers. For the sake of simplicity, we also disregard the impacts of wind mixing for this analysis.

A net formation of sea ice on the southern shelf would produce deeper mean winter mixed layers in this location due to increased brine rejection; a net melting off-shelf and on the northern shelf would produce shallower mean spring mixed layers due to meltwater stabilising the water column. However, the correlations shown in Figures 5 and 6 are calculated separately for each grid cell so rely on departures from mean conditions in each location. Following the aforementioned assumptions, years of large SIC would coincide with an increased transport of sea ice off the shelf and to the north. This transport leads to an increased imbalance between the net formation and melt of sea ice on and off the southern shelf, with deeper than usual mixed layers on, and shallower than usual mixed layers off, the southern shelf. The opposite would be true during low sea ice years, with the freshwater budget becoming more balanced across the regions. Without the effect of wind mixing, this process would produce a positive correlation between winter SIC and spring MLD on the southern shelf, and a negative correlation between the same factors off-shelf and on the northern shelf. This is the opposite to what our results show.

Taking the aforementioned assumptions to be robust, the transport of sea ice across the model domain would have an opposing effect on the SIC-MLD relationship compared to the impact of wind mixing as described in Section 5.1. One process that might form an exception to the mechanism described above is the formation of a polynya within the ice cover. Years of polynya formation would count as years of lower than usual sea ice cover in the specific location of the polynya; however, the formation of the polynya would cause a continuous supply of sea ice further afield, most likely to the off-shelf regions and the northern shelf. The conditions leading to polynya formation (i.e. strong, continuous winds away from the coast) as well as brine formation associated with continuous sea ice production would likely also lead to strong overturning and hence, deep mixed layers. The transport of sea ice may therefore play a significant role in the relationship between winter SIC and spring MLD in regions of polynya formation only.

5.4 Impacts of CDW

There are differences in water column structure below the mixed layer between the shelf and off-shelf environment (Figures 10 and 11). UCDW is upwelled at the WAP shelf break and is therefore found at a shallower depth, but in more diluted form, on the continental shelf. Deep mixing events have the potential to entrain the underlying mUCDW. The mixing of higher density mUCDW into the surface layer would then increase the density of the near surface water, leading to a larger density contrast between the surface water and any spring meltwater. This mechanism would produce strong surface stratification, a faster shoaling of the mixed layer, and an overall shallower mean spring MLD that would require more energy to be broken down. However, Figure 10 shows that in our model, mixed layers do not tend to get deep enough to lead to an entrainment of the warm underlying mUCDW. The presence of mUCDW in the subsurface is therefore unlikely to have an impact on the SIC-MLD relationship found in this study.

5.5 Future implications

Sea ice projections clearly indicate a future decrease in SIC in the WAP and Bellinghausen Sea (Roach et al., 2020; Siegert et al., 2019). The current all-time low in Antarctic sea ice extent (Meier, Stewart, et al., 2021) shows that these changes in the Antarctic environmental system can already be observed today. At present, we find a negative correlation between winter SIC and spring MLD in regions with high winter sea ice cover (i.e. southern shelf), whereas regions with lower winter sea ice cover (i.e. northern shelf
and southern off-shelf region) show a positive correlation between the two factors. Our results suggest that this behaviour is driven by the relationship between SIC and ocean surface stress (Section 5.1; Figure 12). A future decrease in sea ice extent could lead to the WAP continental shelf experiencing lower winter SICs than presently; this could potentially lead to a shift in the relationship between winter SIC and spring MLD towards a state in which anomalously low winter SICs are related to shallow spring mixed layers, and anomalously high winter SICs to deep spring mixed layers.

Changes in the sea ice seasonal cycle, such as a later formation and earlier breakup of sea ice, may also have impacts on the depth of the spring mixed layer (see Section 5.2). While a thorough analysis of the factors that control the onset of mixed layer shoaling is beyond the scope of this paper, it is likely that the earlier breakup of sea ice would result in an earlier onset of mixed layer shoaling. As shown in Section 5.2, an earlier onset of mixed layer shoaling may produce shallower spring mixed layers. This effect however will likely be outweighed by the projected decrease in SIC, with a consequential decrease in spring freshwater input from sea ice melt and change in air-sea momentum flux depending on SIC. These impacts of a decreasing sea ice cover on the depth of the mixed layer may have important impacts on primary productivity and ecosystem functioning in the region.

6 Conclusions

We used a regional coupled sea ice-ocean model to examine the relationship between sea ice and the mixed layer between 1989 and 2018. We found opposite correlations between winter SIC and spring MLD on the WAP continental shelf and the region offshore of the shelf break. While high winter SICs are related to shallow spring MLDs on the WAP continental shelf, there is a distinct region offshore where high winter SICs are related to deep spring MLDs. These results can be explained using the nonlinear relationship between SIC and ocean surface stress. The timing of seasonal events such as the onset of mixed layer shoaling were also found to impact the relationship between winter SIC and spring MLD. The transport of sea ice across the region was carefully examined and rejected as a potential mechanism explaining our results, as was the behaviour of mUCDW on the WAP continental shelf. Our findings have implications for biogeochemical processes in the region in a changing climate.

7 Open Research

All data used in this study is available at 10.5281/zenodo.8183843. MITgcm is available for download at https://github.com/MITgcm/MITgcm. The NSIDC sea ice data used for model validation is available at https://nsidc.org/data/g02202/versions/4/, and WOA data is available at https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18.

Acknowledgments

MJDB was supported in this work by the UK Natural Environment Research Council grant NE/S007407/1. SFH was supported by the UK Natural Environment Research Council through grant NE/K010034/1.
Figure 1. Overview map of the model domain covering the WAP and Bellingshausen Sea as well as the offshore region occupied by the ACC. Shading shows depth, according to the colour bar, with the 1000m depth contour shown in black. Land is shown in white and coastlines in red, with the blue stippled area and blue contour lines showing the locations of ice shelves. Four smaller boxes are highlighted as example regions: Shelf South, Shelf North, Off-shelf South and Off-shelf North. The large box shows the region used for validation purposes, and shown in all surface plots in this paper. ‘MB’ shows the location of Marguerite Bay.
Figure 2. Overview of MLDs calculated by four different methods (temperature threshold: row 1; temperature gradient threshold: row 2; density threshold: row 3; density gradient threshold: row 4) in two locations (Shelf: column 1; off-shelf: column 2), each using three different threshold values, for the year 1990. The MITgcm MLD diagnostic is shown as a black line. All coloured panels show months (starting from January) on the x-axis and depth on the y-axis. Shading denotes density (row 1), temperature (row 2), salinity (row 3) and $N^2$ (row 4) for each of the two locations.
Figure 3. 1989-1998 monthly averaged SIC from NSIDC (first column) and MITgcm-WAP (second column), and the difference between them (MITgcm-WAP minus NSIDC; third column). Maps shown for February (top), May (second row), August (third row) and November (bottom).
Figure 4. 1985-1994 monthly averaged MLD from WOA (first column) and MITgcm-WAP (second column), and the difference between them (MITgcm-WAP minus WOA; third column). Maps shown for February (top), May (second row), August (third row) and November (bottom).
Figure 5. Correlation between winter SIC and spring MLD anomalies (1989-2018). Contour shows the 1000m isobath, i.e. the shelf break. The black stippled area shows correlations significant at $p<0.05\%$ level. The grey stippled area shows locations where on average there is less than one month per year of over 50% SIC.

Figure 6. Correlation between average winter SIC and average spring MLD anomalies by decade: 1989-1998 (left), 1999-2008 (middle) and 2009-2018 (right). The black stippled area shows correlations significant at $p<0.05\%$ level. The grey stippled area shows locations where on average there is less than one month per year of over 50% SIC.
Figure 7. Time series of SIC, MLD and wind speed for each of the boxes shown in Figure 1 for 1989-1998. Dashed line shows wind speed scaled by the sea ice-free area. Average winter SIC and average spring MLD are shown as ‘x’ markers. Green shading denotes winter (June-August), yellow shading spring (September-November), and x-axis ticks are set at January of each year. Note the different y-axis scale for MLD in the Shelf South box. Time series for 1999-2008 and 2009-2018 can be found in Figures S11 and S12.

Figure 8. a) 30-year winter mean freshwater flux out of the ocean from winter sea ice freezing, b) 30-year mean spring freshwater flux into the ocean from sea ice melt, and c) sum of freshwater flux from winter sea ice formation and spring sea ice melt. All for 1989-2018, and showing regional boxes as described in Figure 1.
Figure 9. Time series of monthly mean freshwater flux into the ocean from sea ice melt (top of each panel), and monthly mean freshwater flux out of the ocean from sea ice formation (bottom of each panel) for each of the four regions shown in Figure 1, between 1989 and 1998. Green shading denotes winter (June-August), yellow shading spring (September-November), and x-axis ticks are set at January of each year. Note the different y-axis scales of the panels. Freshwater flux time series for 1999-2008 and 2009-2018 can be found in Figures S13 and S14.
Figure 10. Hovmöller plot of temperature with depth (y-axis) and time (x-axis) for 1989-1998, averaged over each of the four regions shown in Figure 1. MLD in grey. Vertical lines are plotted each January. Corresponding plots for 1999-2008 and 2009-2018 can be found in Figures S15 and S16.
Figure 11. Hovmöller plot of salinity with depth (y-axis) and time (x-axis) for 1989-1998, averaged over each of the four regions shown in Figure 1. MLD in grey. Vertical lines are plotted each January. Corresponding plots for 1999-2008 and 2009-2018 can be found in Figures S15 and S16.
Figure 12. Main panel shows ocean surface stress (at the ice-ocean or atmosphere-ocean interface) depending on SIC from this study (red), and as found by Martin et al. (2014; their Equation 4; blue). The upper panel shows the number of cells (out of all grid cells for all months) that were used to derive the SIC-ocean surface stress relationship in our model for each SIC bin (bin width of 2%). Dashed vertical lines show average winter SICs (1989-2018) for the four regions investigated in this study, as shown in Figure 1.
Figure 13. a) Correlation between mean spring freshwater flux into the ocean and mean spring MLD, and b) correlation between mean winter SIC and mean spring freshwater flux into the ocean. Both for 1989-2018. Boxes show subregions as introduced in Figure 1. Black stippled areas show significance at the $p<0.05\%$ level. Grey stippled areas show locations where on average there is less than one month per year of over 50% SIC.
### Table 1. Correlation coefficients (R) averaged by region

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Shelf North</td>
<td>0.07</td>
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<td>Off-shelf North</td>
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<td>0.27</td>
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<td>0.36</td>
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### Table 2. Sea ice statistics for the time period 1989-2018

<table>
<thead>
<tr>
<th>Region</th>
<th>max. SIC (month no.)</th>
<th>min. SIC (month no.)</th>
<th>mean winter SIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelf North</td>
<td>0.94 ± 0.03 (8.5 ± 0.9)</td>
<td>0.00 ± 0.00 (1.3 ± 0.5)</td>
<td>0.81 ± 0.1</td>
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<td>Off-shelf North</td>
<td>0.37 ± 0.24 (8.4 ± 1.2)</td>
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<td>0.14 ± 0.13</td>
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<td>Shelf South</td>
<td>0.99 ± 0.00 (7.4 ± 1.8)</td>
<td>0.10 ± 0.19 (2.6 ± 2.6)</td>
<td>0.98 ± 0.01</td>
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<td>Off-shelf South</td>
<td>0.96 ± 0.01 (8.4 ± 1.1)</td>
<td>0.00 ± 0.00 (1.7 ± 0.7)</td>
<td>0.85 ± 0.10</td>
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### Table 3. Mixed layer (m) statistics for the time period 1989-2018

<table>
<thead>
<tr>
<th>Region</th>
<th>max. MLD (month)</th>
<th>min. MLD (month)</th>
<th>mean spring MLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelf North</td>
<td>66 ± 7 (8.7 ± 0.8)</td>
<td>13 ± 3 (8.6 ± 5)</td>
<td>47 ± 6</td>
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<tr>
<td>Off-shelf North</td>
<td>101 ± 13 (8.3 ± 1.2)</td>
<td>25 ± 5 (4.6 ± 5.2)</td>
<td>71 ± 11</td>
</tr>
<tr>
<td>Shelf South</td>
<td>140 ± 55 (8.3 ± 1.3)</td>
<td>8 ± 3 (4.3 ± 5.1)</td>
<td>85 ± 36</td>
</tr>
<tr>
<td>Off-shelf South</td>
<td>91 ± 9 (9.3 ± 0.9)</td>
<td>11 ± 3 (6.1 ± 5.5)</td>
<td>69 ± 9</td>
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</table>
Table 4. Freshwater statistics for the time period 1989-2018

<table>
<thead>
<tr>
<th>Region</th>
<th>Freezing$^a$</th>
<th>Melting$^a$</th>
<th>Peak freezing$^b$</th>
<th>Peak melting$^b$</th>
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<tr>
<td>Shelf North</td>
<td>26.3</td>
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<td>November</td>
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<td>Off-shelf North</td>
<td>9.8</td>
<td>15.3</td>
<td>August</td>
<td>February</td>
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<td>Shelf South</td>
<td>82.6</td>
<td>71.7</td>
<td>April</td>
<td>July</td>
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<tr>
<td>Off-shelf South</td>
<td>38.2</td>
<td>50.1</td>
<td>June</td>
<td>November</td>
</tr>
</tbody>
</table>

$^a$Average yearly freshwater flux due to freezing/melting (kg/m$^2$/yr)

$^b$Average month of peak freshwater flux due to freezing/melting
References


