Southern Ocean polynyas and dense water formation in a high-resolution, coupled Earth System Model

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Abstract. ~~Antarctic Bottom Water is an important component of Earth's climate system. Its formation occurs through ocean-atmosphere-sea ice flux interactions in coastal and open ocean polynyas around Antarctica. In this paper , we investigate~~ Antarctic coastal polynyas produce This paper investigates Antarctic dense water formation in the high-resolution version of the Energy Exascale Earth System Model (E3SM-HR). The model is able to reproduce the ~~major~~ main Antarctic coastal polynyas, ~~though they~~ although the polynyas are smaller in area compared to observations. E3SM-HR also simulates several occurrences of open-ocean polynyas (OOPs) in the Weddell Sea ~~,~~ at a higher rate than what the last 50 years of satellite sea ice observational record suggests, but similarly to other high-resolution Earth System Model simulations. Furthermore, the densest water masses in the model are formed within the OOPs ~~,~~ rather than on the continental shelf ~~,~~ as is typically observed. Biases related to the lack of dense water formation on the continental shelf are associated with overly strong atmospheric polar easterlies, which lead to a strong Antarctic Slope Front and ~~hence too little communication between on and off continental~~ too little exchange between on- and off-continental shelf water masses. Strong polar easterlies also produce excessive southward Ekman transport, causing a build-up of sea ice over the continental shelf and enhanced ice melting in the summer season. This~~in turn~~, in turn, produces water masses on the continental shelf that are overly fresh and less dense relative to observations. Our results indicate that high resolution alone is insufficient for models to properly reproduce Antarctic dense water; the large-scale polar atmospheric circulation around Antarctica must also be accurately simulated~~in models to properly reproduce Antarctic dense water formation~~.

1 Introduction

Coastal polynyas are areas of ~~ocean~~ ice-free surface water or thin, newly formed sea ice surrounded by coastline, ice shelves, or consolidated, thick sea ice (Kusahara et al., 2010). They form by divergent sea ice motion, ~~usually~~ in turn driven by strong ~~offshore winds~~, katabatic winds and oceanic currents, and are often associated with coastal features that block the advec-

tion of sea ice from upstream of the polynyas (Roberts et al., 2001; Williams et al., 2007; Tamura et al., 2016). Although small in area compared to the total sea ice zone (<3%; Roberts et al., 2001), these coastal polynyas play an important role in the climate by (i) transporting heat from the ocean to the atmosphere , and thereby affecting mesoscale atmospheric motion (Morales Maqueda et al., 2004; Minnett and Key, 2007), and (ii) strongly modifying water masses through brine re-

25 jection resulting from high rates of surface cooling and sea ice production and surface cooling (Williams et al., 2007). The latter (Williams et al., 2007), and (iii) impacting the biogeochemical cycle (St-Laurent et al., 2019). Point (ii) is a key mechanism of cold dense shelf water (DSW) formation, which leads to the formation of Antarctic Bottom Water (AABW) by downslope transport and mixing with ambient water masses on the continental slope (Williams et al., 2016). AABW production is a key element of the Earth's climate system (Orsi et al., 1999; Johnson, 2008; Marshall and Speer, 2012; Williams

30 et al., 2016) as AABW is an important sink for carbon dioxide and heat from the atmosphere (Sigman and Boyle, 2000). In contrast to coastal polynyas, open ocean polynyas (OOPs) occur far from the coast in the middle of the sea ice pack in winter. These po

Due to logistical difficulties associated with in-situ observation, sea ice production in coastal polynyas and its interannual to decadal variability are not well understood or characterized (Ohshima et al., 2016). Therefore, methods to estimate sea

35 ice production on over large scales have been developed using heat flux calculations based on satellite microwave radiometer observations (Tamura et al., 2006, 2008; Nihashi and Ohshima, 2015; Ohshima et al., 2016). Through the mapping of coastal polynyas and sea ice production around Antarctica, it has been suggested that a strong link exists between sea ice production and bottom water formation and its variability (Ohshima et al., 2013, 2016).

The strong link between sea ice production and bottom water formation is the result of DSW flowing across the continental

40 shelf break downstream of high sea ice production regions (e.g., coastal polynyas). That is, when water masses on the continental shelf are cold and dense salty due to dense water formation and shallow convection, a "dense shelf" condition is established (Thompson et al., 2018). In this situation, DSW can be exported to become bottom water after mixing with ambient water masses on the continental slope during its descent. The dense shelf condition is associated with a westward-flowing Antarctic Slope Current (ASC) and a distinctive V-shaped isopycnal frontal structure (Whitworth et al., 1998), enabling onshore transport

45 of Circumpolar Deep Water (CDW) and export of DSW underneath the V-shaped front. The V-shaped frontal structure is considered to be critical for water mass modification to occur on the continental slope and in setting the correct properties of AABW that accommodates both an onshore transport of CDW (Stewart and Thompson, 2015; Foppert et al., 2019) and the export of DSW (Thompson et al., 2018). However, the westward flowing ASC and distinctive V-shaped front , are not well represented in many fully coupled general circulation models (GCMs) due to their under-resolving of the steep topography of the Antarctic

50 continental slope and/or model biases (Dinniman et al., 2016; Thompson et al., 2018)(Dinniman et al., 2016; Thompson et al., 2018; Lock .

Numerical models with a good representation of processes in coastal polynyas are also useful tools for improving our understanding of AABW formation (Kusahara et al., 2010). In previous GCMs with low horizontal resolution, it has been difficult to explicitly capture coastal polynyas and their impacts on the ocean due to their small areal extent (Stössel and Markus, 2004;

55 Kusahara et al., 2010). Therefore, studies have also been conducted using high-resolution, regional, coupled ocean and sea

~~ice models~~coupled ocean and sea ice models with prescribed atmosphere. For example, sea ice processes and DSW formation have been investigated in the Mertz Glacier polynya (Marsland et al., 2004), Ronne Ice shelf polynya (Årthun et al., 2013), and along the East Antarctic coast (Kusahara et al., 2010) using ~~coupled ocean and sea~~ atmospheric forced coupled ocean-sea ice models. However, these models tend to simulate larger coastal ice production due to the lack of sensible and latent heat flux transferred fr

60 Because sea ice processes in coastal polynyas result from the strongly coupled atmosphere, ocean, and sea ice phenomena, fully coupled modeling is needed in addition to high resolution.

Unfortunately, bottom water formation driven by coastal polynyas is notably difficult to represent in GCMs (Aguiar et al., 2017). Instead, ~~GCMs often~~ many GCMs create AABW through an alternative mechanism, namely open-ocean deep convection (Heuzé et al., 2013; Azaneu et al., 2014; Aguiar et al., 2017). Often when ocean stratification decreases in ocean ~~general~~

65 ~~circulation models~~GCMs, open-ocean, deep convection occurs in the Southern Ocean, allowing heat transport to the ocean surface from the deeper ocean (Aguiar et al., 2017). This vertical heat transfer creates an ice-free region~~: an open-ocean polynya (OOP),~~ i.e. an OOP. In the OOP, saline deep waters release sensible heat to the atmosphere, creating AABW by ~~cooling~~ surface heat loss (Killworth, 1983; Aguiar et al., 2017).

Recently, the U.S. Department of Energy ~~(DOE)~~ has developed a variable resolution, fully coupled Earth system model

70 (ESM), the Energy Exascale Earth System Model (E3SM; Golaz et al., 2019; Petersen et al., 2019; Rasch et al., 2019; Lee et al., 2019). The high-resolution, fully coupled version of E3SM (E3SM-HR; Caldwell et al., 2019), which ~~is being~~ was run with the purpose of participating in the ~~High Resolution~~ High-Resolution Intercomparison Project (HighResMIP v1.0) for CMIP6 (Haarsma et al., 2016), is used in the present study. Unsurprisingly, E3SM-HR reproduces Antarctic coastal polynyas and OOPs with much higher frequency than the standard resolution version of E3SM.

75 In this study, we assess the representation of both types of polynyas in E3SM, compare them with available observational data, and investigate the formation of dense water masses in each type of polynya. In Section 2, we briefly describe E3SM and the reference data sets used for model validation. In ~~section~~ Section 3, we analyze the representation of Antarctic coastal ~~and open-ocean polynyas~~ polynya and OOPs compared to available data sets. Section 4 investigates water mass formation in both polynya types, and in ~~sections~~ Sections 5 and 6, we present a discussion, summary, and conclusions from this study.

80 ## 2 Data and methodology

2.1 The Energy Exascale Earth System Model

For this study, we use both the high- and low-resolution versions of E3SM v1 (E3SM-HR and E3SM-LR, respectively): these simulations are fully coupled and are run with greenhouse gas conditions in the atmosphere that are fixed at 1950 levels. E3SM v1 consists of atmosphere, land, river, ocean, and sea ice components communicating via a flux coupler (cpl7; Craig et al.,

85 2012). The atmospheric component, the E3SM Atmospheric Model (EAM; Xie et al., 2018; Rasch et al., 2019; Golaz et al., 2019; Caldwell et al., 2019), uses a spectral-element atmospheric dynamical core (Caldwell et al., 2019). The land component is the E3SM Land Model (ELM), which is a slightly revised version of the Community Land Model version 4.5 (CLM4.5; Golaz et al., 2019). The river component is the newly developed Model for Scale Adaptive River Transport (MOSART; Li et al.,

2013, 2015; Golaz et al., 2019). The ocean and sea ice components of E3SM v1 are based on the Model for Prediction Across

90   Scale (MPAS) modeling framework (Ringler et al., 2013; Petersen et al., 2019) and share the same unstructured, horizontal grid. The vertical grid of the ocean model is a structured, z-star coordinate (Petersen et al., 2015; Reckinger et al., 2015). While E3SM-HR does not use the Gent-McWilliams (GM; Gent and Mcwilliams, 1990) mesoscale eddy parameterization, E3SM-LR does, with a constant GM bolus eddy diffusivity of 1,800 $\mathrm{m^2\,s^{-1}}$. A more detailed description of the E3SM v1 ocean and sea ice components is available in Petersen et al. (2019) and Turner et al. (2022), respectively. To identify the effect of model

95   resolution on simulation results, we use the same tuning parameters on both high and low-resolution E3SM simulations, as described in Caldwell et al. (2019).

Table 1 describes the horizontal and vertical resolution for each model component. The atmosphere and land models share the same horizontal grid, having 25 km and 110 km horizontal spacing for E3SM-HR and E3SM-LR, respectively. The atmospheric model uses a hybrid, sigma-pressure coordinate with 72 vertical layers and a top of the atmosphere at approximately 60 km

100   for both the ~~low- and high-resolution~~ high- and low-resolution configurations. The land model uses 15 vertical levels for both simulations. For E3SM-HR, the ocean/sea ice mesh features a horizontal resolution varying between 16 km at the equator and 8 km near the poles, and 80 ocean vertical levels with spacing ranging between 2 m at the surface and ~150 m at depth, following Stewart et al. (2017) to resolve the first and second baroclinic modes in the open ocean. For E3SM-LR, the ocean/sea ice mesh has a resolution varying between ~~30 and~~ 60 km in the mid-latitudes and 30 km at the equator and poles, and 60

105   ocean vertical levels, with a layer thickness varying between 10 m at the surface and 250 m in the deep ocean. The river component employs a latitude and longitude grid with uniform grid spacing in both directions of 0.125° and 0.5° for ~~high- and low-resolution~~ high and low resolution, respectively. For more detailed information on time steps and coupling frequency for each component model, refer to Table 2 in Caldwell et al. (2019).

Before performing fully coupled simulations, we run the ocean model in standalone mode for ~~1- and 3-months for E3SM-LR~~

110   ~~and~~ 1 and 3 months for E3SM-HR ~~,~~ and E3SM-LR, respectively, starting from rest and the Polar Hydrographic Climatology (PHC; Steele et al., 2001) temperature and salinity profiles, to slightly spin up the velocity field and damp out high-velocity waves. The results of the stand-alone ocean simulation are used as the initial condition for an ocean/sea ice only, three-year simulation using the Common Ocean Reference Experiment version 2 (COREv2; Large and Yeager, 2009) protocol for interannually varying atmospheric forcing. The sea ice is initialized with a uniform thickness of 1 m at all locations south of

115   70°S and north of 70°N. Finally, the model state from the end of this simulation is used as the initial condition for the ocean and sea ice components in the fully coupled simulations. The atmospheric initial condition is obtained from an earlier high-resolution E3SM simulation run with fixed Sea-Surface Temperature (SST). The land initial condition is interpolated from the year 1950 of a low-resolution E3SM v1 CMIP simulation (Golaz et al., 2019). With these initial conditions, we run E3SM in a fully coupled model for 50 years at both ~~high- and low-resolution~~ high and low resolution for comparison. We use results from

120   the last 30 years of each simulation for the analysis presented here.

2.2 Ocean, sea ice, and atmosphere state estimates

~~Before investigating the dense water formation in Antarctic coastal and open-ocean polynyas, we evaluate E3SM's representation of both types of polynyas. To do this, we compare E3SM results to available data sets including~~ The data sets used here for model evaluation purposes are summarized in Table 2; they include direct observations, reanalyses, and interpolated climatologies for the atmosphere, ocean, and sea ice in the Southern Ocean. For the evaluation of sea ice, we use sea ice concentration from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration version 3 (NCDR; Peng et al., 2013) and sea ice production from Nihashi and Ohshima (2015), which is derived from data from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E). For the evaluation of ~~oceanic properties~~oceanic currents and sea ice concentration, we utilize the Southern Ocean State Estimate (SOSE; Mazloff et al., 2010), a state-of-the-art, data-assimilation product that incorporates millions of ocean and sea ice observations while maintaining dynamically consistent ocean state variables. Given the sparsity of observations in many regions around Antarctica, SOSE offers a comprehensive, physically based estimate of ocean properties that would otherwise be entirely uncharacterized (Jeong et al., 2020). Specifically, we use the SOSE data set with $\frac{1}{6}°$ horizontal resolution, spanning from 2005 to 2010. We also use the World Ocean Atlas 2018 (WOA18; Locarnini et al., 2018; Zweng et al., 2018), which provides a global data product of ~~subsurface ocean temperature~~and salinity. ~~For the evaluation of the~~ ocean temperature, salinity, and density. Considering that both SOSE and WOA18 are based on offshore observational data, we utilize in-s

For evaluating the atmospheric state over the Southern Ocean, we use zonal and meridional wind velocities at 10 m from the European Center for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis product (Hersbach et al., 2019). It should be noted here that the ocean, sea ice, and atmosphere data sets described above represent present-day conditions, whereas the E3SM simulations are representative of model conditions for the 1950s. We compare monthly averaged products from both present-day observations and E3SM simulations, noting that the horizontal resolution of observational data sets – varying between 16 km and 25 km – differs from E3SM simulation output.

2.3 Definition of ~~Antarctic~~ coastal ~~and open-ocean~~ polynyas and OOPs

~~We define coastal polynyas in E3SM model output as areas with modeled sea ice that is "thin", as defined by having a thickness less than 20 cm, and surrounded by coastline and/or consolidated thick sea ice during the freezing season (from March to October). This is consistent with the definition used in several observational studies (e.g., Tamura et al., 2006, 2008; Nihashi and Ohshima, . Thin sea ice is a poor thermal barrier and allows one to two orders of magnitude larger heat loss to the atmosphere than thick ice cover (Maykut, 1978; Nihashi and Ohshima, 2015). Therefore, Antarctic coastal polynyas are areas of very high sea ice production (Markus et al., 1998; Renfrew et al., 2002; Tamura et al., 2008; Nihashi and Ohshima, 2015). In contrast to coastal polynyas, Antarctic open-ocean polynyas occur far from the coast in the middle of the sea ice pack during the winter season. These polynyas are generally observed in conjunction with deep-convection events in the ocean that lead to direct interaction between mid-depth and surface ocean waters. They are also characterized by a strong positive ocean-to-atmosphere heat flux (Kurtakoti et al., 2018). These processes result in areas of ice-free ocean. We define OOPs in E3SM's model output in the same way as~~ Coastal polynyas are areas covered by "thin" sea ice, as defined by having a thickness of less than 20 cm, and surrounded by coastl Our definition of OOPs follows a methodology similar to previous studies (e.g., Kurtakoti et al., 2018), i.e.~~as areas within~~,

we consider areas within the ice pack where ~~modeled~~ open ocean sea ice concentration is less than 15% during the freezing season.

3 Antarctic coastal and open-ocean polynyas

3.1 Coastal polynyas

160 In this section, we investigate the fidelity of Antarctic coastal polynyas simulated in ~~E3SM-HR (and E3SM-LR)~~E3SM (a list of the 13 polynyas is included in Table 3), by comparing model output with available observational data. ~~Cold katabatic winds blowing off Antarctica create sea ice in the Southern Ocean during the freezing season (e.g., as shown for E3SM-HR in Fig. 1a and b).~~ Cold katabatic winds blowing off Antarctica in E3SM-HR (Fig. 1a) push the thick sea ice offshore, leading to open water. Consequ Evident in this figure is that there is more sea ice production near the Antarctic coast compared to further offshore. ~~Cold, salty~~

165 ~~waters generated by high sea ice production near the Antarctic coast are likely to contribute to AABW formation through transport down the continental slope (Fig. 1b). Nihashi and Ohshima (2015) defined 13 major Antarctic coastal polynyas and investigated the polynya area and accumulated sea ice volume of these using AMSR-E (See Table 3).~~ In Fig. 1c, we compare E3SM-HR's accumulated sea ice volume in Antarctic coastal polynyas from March to October and as a function of longitude ~~from March to October from Antarctic coastal polynyas with a satellite estimate (AMSR-E; Nihashi and Ohshima, 2015)~~with

170 the satellite estimate AMSR-E. The AMSR-E data shows that the highest rates of sea ice production occur along the East Antarctic coast, while the Ross Sea at around 180° longitude (Ross Ice Shelf Polynya (RISP)) has the largest total sea ice production. The analysis of Ohshima et al. (2013) suggests that the Cape Darnley Polynya (CDP), located west of the Amery Ice Shelf (around 70°E), has the second-highest ice production around the Antarctic after the RISP. With some exceptions that we will explore below, E3SM-HR generally does well at representing the accumulated sea ice volume in coastal Antarctic

175 polynyas, especially in high sea ice production areas along the East Antarctic coast. ~~Since sea ice production in coastal polynyas is largely caused by the latent heat flux released to the atmosphere, we also find that E3SM-HR shows relatively higher latent heat flux released from the ocean to the atmosphere in East Antarctica compared to the West Antarctic (Fig. 1a).~~ We further find that, over the course of the simulation, E3SM-HR displays interannual variability in total sea ice production from Antarctic coastal polynyas of up to 43% (Fig. 1d). This suggests that E3SM-HR may be useful for ~~the analysis of~~ analyzing Antarctic

180 coastal polynya variability.

In Fig. 2 we plot the mean coastal polynya area and accumulated sea ice volume during the March to October freezing season for each of the 13 polynyas indicated in Fig. 1b ~~, which are~~ and Table 3, simulated by both the high and low-resolution versions of E3SM, and compare them with the observed estimates. In general, E3SM-LR shows very little polynya area or sea ice volume production over the defined coastal polynya region. This is a common limitation in ESMs with low horizontal

185 resolution due to coastal polynyas' small areal extent (Stössel and Markus, 2004; Kusahara et al., 2010). The E3SM-HR shows significant improvement in ~~the representation of~~ representing coastal polynya area and sea ice volume production compared to E3SM-LR. Yet, its sea ice volume production in several coastal polynyas such as the Dalton, Dibble, and Amundsen Polynyas (DaP, DiP, AP, respectively) is much smaller than observed. In reality, these coastal polynyas are strongly affected by the

presence of landfast ice, a feature not yet represented in E3SM. Landfast ice is stationary sea ice attached to coastal features
such as the shoreline and grounded icebergs (Nihashi and Ohshima, 2015). Several previous studies suggested that landfast ice
and glacier tongues play an important role in the formation of some coastal polynyas by blocking sea ice advection of upstream
sea ice into the polynya and thereby facilitating divergent motion (Nihashi and Ohshima, 2015; Bromwich and Kurtz, 1984).
Therefore, a representation of landfast ice may be needed to more accurately capture coastal polynya characteristics. When we
compare the ~~summation~~ sum of polynya area and sea ice volume production for polynyas ~~not strongly~~ that are not associated
with landfast ice (Fig. 2o), it can be seen that E3SM-HR does reasonably well at reproducing sea ice volume production
compared to AMSR-E observations, despite generally underestimating polynya area.

3.2 Open-ocean polynyas

The first observed OOP, the Maud Rise Polynya (MRP), was detected during the period June to October 1973 and ~~reappeared during the period from June to August 1974. The MRP is relatively small in area and occurs above the Maud Rise seamount in the eastern Weddell Sea (Kurtakoti et al., 2018)~~it propagated westward from the Maud Rise seamount into the open ocean at an average ve
In the winters of 1974 and 1975, the MRP extended westward into the central Weddell Sea, initiating a Weddell Sea Polynya
(WSP; Kurtakoti et al., 2018). The WSP is a relatively large ~~, open-ocean polynya~~ OOP in the central Weddell Sea, having
a maximum ice-free area of ~250,000 km^2. More recently, the MRP has been observed intermittently in August 2016 and more
consistently during the winter of 2017 (Fig. 3a–c; note that these observations are shown for reference only and not for the purpose of mod
The 2017 MRP appeared in September and had its maximum extent in November of that year. ~~While similar results were reported by Dufour et al. (2017)~~Similar to a previous study comparing the difference between high- and low-resolution climate model resu
E3SM-LR does not exhibit OOPs at any point in the simulation~~,~~. E3SM-HR does produce MRPs, an example of which
is shown in Fig. 3d–f for model year 54, where relatively low sea ice concentration can be seen around 0° longitude. As
sea ice concentration decreases in the polynya area, the ocean and atmosphere can interact directly. This causes the re-
lease of sensible heat from the ocean to the atmosphere (Fig. 3g–i), ~~thus allowing for dense-water formation in E3SM-HR.~~ which can potentially affect the dense-water formation in E3SM-HR.

~~Unlike in the real world, OOPs occur frequently in some fully coupled ESM simulations with~~ OOPs appear to occur more
frequently in high-resolution ~~(e.g., Kurtakoti et al., 2018)~~model simulations than in the last 50-year record of satellite sea ice
observations (e.g., Kurtakoti et al., 2018; Diao et al., 2022). Even in high-resolution ocean reanalysis products, there are sev-
eral cases of OOPs (for instance, in 2005 in SOSE and in 2004, 2007, and 2010 in ECCO2) that do not appear in satellite
observations (Aguiar et al., 2017). The convective activity ~~that accompanies~~ accompanying OOPs is associated with decreased
stability within the water column, which can be caused by buoyancy changes in surface or deep waters (Azaneu et al., 2014).
~~In addition, the strong polar cyclonic gyre that exists in the Weddell Sea may be a factor in preconditioning this convection process, since it leads to shoaling of the pycnocline and circulation that strongly interacts with the bathymetry near Maud Rise (Gordon and Huber, 1990; Azaneu et al., 2014). Perhaps because of an overly strong cyclonic gyre related to a sub-polar low that is too deep (see Section 4.2a), E3SM-HR produces OOPs in 18 of the 30 total simulation years (see Fig. 4), far more~~

~~frequently than observed. We~~ OOPs formation mechanisms have been investigated extensively in the past. Most studies recognize the exist

For the purposes of this paper, we define the simulated OOP years as those in which either or both MRP and WSP occur, or
in which embayment-like features in sea ice concentration occur in the Weddell Sea (Fig. 4c–f). During non-OOP years, most
of the Weddell Sea is covered with sea ice from September to November (Fig. 4a). ~~During OOP years, however, localized ocean convection associated with enhanced upper ocean salinity and a strong Taylor column near the Maud Rise seamount produces ventilation of subsurface warmer waters, which in turn inhibits sea ice formation within the area where deep convection occurs. Once~~ As reported elsewhere, once an OOP occurs~~in a model simulation, it tends to occur again~~, it has a tendency to re-occur in
subsequent years (Fig. 4g)~~because of~~, due to the ventilation of salty/high-density waters ~~that occurs~~ within the deep convection
area ~~(Kurtakoti et al., 2020). In the following sections, in order to investigate the dense water formation associated with OOP events, which potentially contribute to AABW formation, we compare simulation years with OOP events to none OOP years lacking OOPs.~~ that induces a positive feedback on subsequent convections (Kurtakoti et al., 2020).

4 Dense water formation

The second part of this study is to investigate dense water mass formation processes in the E3SM-HR simulation only, given that E3SM-L

4.1 Water mass transformation in OOPs and continental shelves

~~In the previous section, we found that E3SM-HR can produce not only open-ocean but also coastal polynyas. This implies that E3SM-HR may allow for dense water-mass formation in the Southern Ocean via both types of polynya. Several modeling studies, however, have suggested that ESMs often create bottom water mostly through open-ocean deep convection in the Weddell Sea rather than the more realistic mechanism of dense water formation by sea ice production in coastal polynyas (Heuzé et al., 2013; Azaneu et al., 2014; Aguiar et al., 2017). In~~ In this section, we apply a water-mass transformation (WMT)
analysis to the last 30 years of the E3SM-HR simulation in the Weddell Sea region over both the continental shelf and the open
ocean ~~, to find out~~ to find which polynya type, coastal or OOP, predominantly produces dense water masses in E3SM-HR.
The WMT analysis, first introduced by Walin (1982), quantifies the relationship between the thermodynamic transformation
of water mass properties within an ocean basin and the net transport of those same properties into or out of the basin. This
relationship has been used to characterize the thermodynamic processes that sustain the Southern Ocean overturning in models
(Abernathey et al., 2016). A more detailed description of WMT analysis can be found in Groeskamp et al. (2019). Jeong et al.
(2020) discuss previous applications of WMT to the analysis of low-resolution E3SM simulations.
In Fig. 5a, we show the mean WMT rate over the Southern Ocean produced in E3SM-HR ~~by~~ for all surface fluxes combined
(positive WMT rates indicate that water masses become denser, implying buoyancy loss; negative WMT rates indicate that wa-
ter masses become lighter, implying buoyancy gain). Because we only focus on the WMT rate during the freezing season, from
March to October, positive WMT rates dominate over most of the Southern Ocean~~while slightly negative transformation rates~~

~~are found in some regions~~. Over the continental shelf, the region delimited by the 1000 m isobath in Fig. 5a, we find strong posi-
tive WMT rates, which are the direct result of high sea ice production there (Fig. 1b). These results compare well with observation-based est

The mean WMT rates in latitude and longitude space ~~(Fig. 5a)~~ can be converted into neutral density space (and are shown
in Fig. 5b)for the whole Southern Ocean (grey line), the continental shelf only (green line), and the Weddell Sea (pink line).
The maximum WMT rates over the whole Southern Ocean (≈ 20 Sv) is found at a neutral density of $27.6\,\mathrm{kg\,m^{-3}}$ ~~. In the very
high density ranges above $28.0\,\mathrm{kg\,m^{-3}}$, another region of positive transformation rate can be seen with a maximum WMT
rate of 3.0 Sv at a neutral density of $28.2\,\mathrm{kg\,m^{-3}}$. Positive transformation rates above $28.0\,\mathrm{kg\,m^{-3}}$ are consistent with AABW
formation; Orsi et al. (1999) define Southern Ocean bottom water as having neutral densities higher than $28.27\,\mathrm{kg\,m^{-3}}$.~~ and is
larger than the observation-based estimate (≈ 13 Sv) in Pellichero et al. (2018). In the high density ranges above $28.0\,\mathrm{kg\,m^{-3}}$, a local maxi
As this high-density transformation rate in E3SM-HR is entirely due to WMT over the Weddell Sea, rather than on the conti-
nental shelf (compare green and ~~grey curves~~ pink lines in Fig. 5b), the simulated bottom water is produced through open-ocean
convection in the Weddell Sea only, similarly to what has been found in previous studies (Heuzé et al., 2013; Azaneu et al.,
2014; Aguiar et al., 2017). Over the continental shelf, we also see positive transformation rates, but these occur at relatively
~~light~~ lighter densities, with an average neutral density of $27.5\,\mathrm{kg\,m^{-3}}$, whereas no transformation occurs at densities higher than
$28.0\,\mathrm{kg\,m^{-3}}$. These results are confirmed by the T/S diagrams for the Weddell Sea water column, presented in Supplementary Fig. 1 and

When we consider the WMT rate contributed by several types of surface fluxes separately over the Antarctic continental
shelf and over the Weddell Sea (Fig. 5c and d), the positive transformation rate over the continental shelf results almost entirely
from brine rejection by sea ice production. The positive ~~transformation~~ WMT rate over the deep Weddell Sea, meanwhile, is
mostly due to the surface heat release from the ocean to the atmosphere, especially at relatively high neutral densities above
$28.0\,\mathrm{kg\,m^{-3}}$, which is consistent with the strong ocean-to-atmosphere exchanges that occur in OOPs. We confirm, therefore,
that the coastal ~~and open-ocean polynyas~~ polynya and OOPs simulated in the E3SM-HR have different WMT mechanisms.
However, ~~and~~ as described above, the simulation produces water masses at relatively low-density levels on the continental
shelf, despite the fact that the model does reasonably well at reproducing a large amount of sea ice formation in coastal
polynyas during the freezing season. To investigate this apparent inconsistency, in the next section ~~,~~ we examine E3SM-HR's
hydrographic characteristics in the Southern Ocean.

4.2 Hydrographic characteristics of continental shelves

As the polar ocean is highly controlled by atmospheric dynamics and/or thermodynamics, while freshwater dynamics also make
an important contribution (Hattermann, 2018; Moorman et al., 2020), we start by comparing E3SM-HR's atmospheric surface
(10 m) winds with the ERA5 reanalysis data (Fig. 6a,b). We find that, compared to ERA5, E3SM-HR has stronger atmospheric
surface winds not only along ~~with~~ the Antarctic continental shelf but also in the interior Southern Ocean, which is consistent
with an overly deep ~~(simulated)~~ sub-polar low-pressure system ~~at around 60–70~~south of 60°S (~~figure not shown~~Supplementary
Fig. 2). These overly strong atmospheric winds may produce a strong Antarctic Slope Current (ASC). The ASC is a coherent

circulation feature that rings the Antarctic continental shelf and regulates the flow of water toward the Antarctic coastline (e.g., Jacobs, 1991; Thompson et al., 2018). ~~Indeed, as~~ As seen in Fig. 6c,d, we find a very strong ASC in the E3SM-HR simu-
290 lation, with a speed more than double that in SOSE (~~0.16~~0.34 $\mathrm{m\,s^{-1}}$ in ~~SOSE compared with 0.34~~E3SM-HR compared with 0.16 $\mathrm{m\,s^{-1}}$ in ~~E3SM-HR~~SOSE at 0°). ~~As we discuss in more detail below, this is likely a result of the strong easterly winds over the continental shelf.~~Therefore, we hypothesize that the strong winds over the continental shelf may be one of the drivers of the strong AS

Thompson et al. (2018) defined three Antarctic continental shelf types – fresh, dense, and warm shelves – based on the type of
295 ocean stratification present on the shelf/slope and specific oceanic processes occurring on the shelf. ~~A fresh shelf (East Antarctic sector) is characterized by low salinity on the shelf and strong easterly winds at the coast and offshore, which produce onshore Ekman transport and downwelling.~~A fresh shelf (East Antarctic sector) is characterized by strong easterly winds at the coast and offshore. These processes establish downward sloping isopycnals against the continental slope and a surface intensified front ~~,~~that manifests itself as a strong westward flowing ASC. The stratification associated with fresh shelves is such that warm and saline CDW
300 is prevented from flowing onto the shelf (Thompson et al., 2018). A dense shelf (e.g., the western Weddell Sea and the eastern Ross Sea) occurs when the shelf is relatively cold and dense due to brine rejection as a result of high sea ice formation rates (coastal polynya mechanism). The onshore transport of CDW and preconditioning of shelf waters by DSW formation are important to forr The density distribution is characterized by a ~~"~~V-shape ~~"~~near the continental slope, with convection occurring on the onshore side and the Antarctic Slope Front (ASF) still supporting a westward flowing ASC on the offshore side (although weaker than
305 in the fresh-shelf case). ~~A warm shelf~~Finally, a warm shelf (West Antarctic sector) is characterized by slightly upward sloping isopycnals, which enable easier onshore transport of warm, intermediate depth CDW.

To investigate how these shelf types are reproduced in E3SM-HR, we select three vertical meridional and zonal cross-sections; at ~~12~~18°W (eastern Weddell Sea), ~~35~~63°~~W~~S (western Weddell Sea), and ~~72~~90°W (~~west coast of Antarctic peninsula~~Bellingshause Sea), which are representative of the fresh-, dense-, and warm-shelf types, respectively (the locations ~~for each shelf type~~
310 of the cross-sections are indicated in Fig. 6d). We present the results in ~~Figs. ??- ??~~Fig. 7, comparing the model temperature and ~~salinity profiles with SOSE and with the observational results of Whitworth et al. (1998).~~density profiles with CTD observational data (Heywood and King, 2002; Thompson and Heywood, 2008; Orsi and Whitworth, 2005). For the fresh-shelf type (Fig. 7

~~For the fresh-shelf type (Fig. ??), E3SM-HR simulates an ASC that is almost twice as strong as that simulated by SOSE~~
315 ~~(Fig. ??c,e), with isohaline surfaces strongly tilted downwards in the onshore direction, more so than in the observational results described in Whitworth et al. (1998, compare their Figure 2 with Fig. ??e; note that here isohalines are used as a proxy for isopycnals sinc . As shown in the zonal and meridional wind profiles from the model and ERA5 (Fig. ??a,b), the stronger ASC is associated with easterly winds that are ≈ 2 m s⁻¹ stronger than in ERA5.~~In order to support our hypothesis that strong winds are responsible for the s

320 ~~The dense shelf type occurs downstream of active sea ice formation regions such as the Ross Sea, the western Weddell Sea, the Adélie coast, and Cape Darnley. Cold and salty water masses, induced by brine rejection, flow across the continental shelf break producing AABW. Similar to the fresh shelf type, warm CDW in these regions tilts down toward the seafloor over~~

most of the continental slope. However, as the CDW approaches the shelf break in the dense shelf type, it shoals again (see the "V-shaped" isopycnal surface in Fig. 3b from Thompson et al. 2018). The V-shaped isopycnal surface is critical to water
mass transformation and to setting the properties of AABW (Thompson et al., 2018) because it accommodates both an onshore transport of CDW and the export of DSW. While we do not see the V-shaped isohaline surface in SOSE (Fig. ??c), E3SM-HR also exhibits no V-shaped isohalines, but rather steep isohaline surfaces tilted downward toward the shelf break from offshore, quite differently from observational results at the same location (compare Fig. ??e with Fig. 3 in Whitworth et al. 1998). The E3SM-HR stratification for this case is more similar to the fresh shelf type, with a similar ASC as well (compare Fig. ??d,e with Fig. ??d,e). This is also likely related to stronger model winds compared to ERA5 (Fig. ??a,b), and specifically to a largely easterly component in the model winds that is much reduced in ERA5 north of 74°S. Also, it could indirectly be a result of excessively strong winds advecting freshwater into the Weddell Sea from upstream (Graham and De Boer, 2013), or from the ASF being too strong around the continent and retaining freshwater on the continental shelf (Moorman et al., 2020).

Lastly, the warm shelf type is mainly observed along the coasts of the West Antarctic, particularly in the Amundsen and Bellingshausen Seas. Unlike the fresh shelf type, the ASC is weak or absent over this type of shelf (Thompson et al., 2018) . Coastal atmospheric wind speed is also observed to be relatively weaker than in the East Antarctic. As can be seen in Fig. ??c, SOSE has flat isohaline surfaces tilted toward Antarctica, resulting in warm CDW reaching the continental shelf, consistent with observations (see Fig. 10 in Whitworth et al. 1998 or Fig. 3 in Thompson et al. 2018). Again, E3SM-HR simulates hydrographic conditions that are more similar to the fresh-shelf type, with downward tilted isohalines and a weak westward flowing ASC at the shelf break (Fig. ??e,d). This bias is similarly related to model easterly winds that are twice as strong as those in ERA5 (Fig. ??a).

In summary, as a result of ubiquitous, strong polar easterly winds, we find that E3SM-HR consistently displays only the fresh-shelf type. These overly strong winds ~~also cause overly strong~~ cause enhanced onshore Ekman transport (see Supplementary Fig. 3, particula which in turn ~~affects~~ may affect the advection of sea ice formed during the winter season. As shown in Fig. 9, E3SM-HR's simulated sea ice extent in the Southern Ocean is much less than that from SOSE in all seasons except for JAS (July-August-September) but sea ice volume is ~~similar or even slightly~~ generally larger than SOSE's ~~ice volume. This is likely~~ , and the largest differences are found in the coastal regions. We hypothesize that this is the result of sea ice ~~build up~~ build-up on the continental shelf in E3SM-HR, where sea ice thickness often exceeds 2 m ~~;~~, due to enhanced poleward surface Ekman transport, which prevents sea ice from moving to lower latitudes ~~,~~ where it would potentially melt.

Modeled and observed SST and sea-surface salinity (SSS) averaged over the continental shelf provide additional information regarding the impacts of these ~~same~~ biases. In Fig. 10 we compare shelf SST and SSS from E3SM-HR with ~~that~~ those from SOSE and WOA18. E3SM-HR has a good representation of seasonal SST and SSS variation, but with warmer/fresher and colder/fresher water properties in the summer and winter seasons, respectively, compared to SOSE and WOA18. In summer, the warm, fresh surface water has a neutral density of $26.0\,\mathrm{kg\,m^{-3}}$ in E3SM-HR, compared with more than $27.2\,\mathrm{kg\,m^{-3}}$ in WOA18 and $26.8\,\mathrm{kg\,m^{-3}}$ in SOSE. The possible external sources of the relatively low summer density in E3SM-HR can be excessive precipitation (E-P), runoff, or sea ice melting. Consistent with the sea ice thickness bias discussed above (Fig. 9), we find that the freshwater flux into the ocean from melting sea ice in E3SM-HR is larger than that of SOSE, especially over the

continental shelf and shelf break (Fig. 10b), while precipitation and runoff differences (not shown) are not significant compared to SOSE. Because of extensive and excessive freshwater inputs from sea ice in E3SM-HR, the annual mean sea-surface neutral density is lighter than WOA18 over the continental shelf (Fig. 10d and e). We thus conclude that the overly strong easterly winds are also (indirectly) responsible for the relatively lighter water masses forming on the continental shelf in E3SM-HR.

5 Discussion

There are several phenomena known to be important in the physics associated with coastal polynyas that are challenging to model. Perhaps most importantly, the ASC and its associated cross-shelf stratification play a critical role in establishing water mass and heat transport on and off the Antarctic shelf, as well as in the Earth's climate system in general through their effects on the large-scale ocean circulation, the stability of Antarctic ice sheets, and the global carbon cycle (Thompson et al., 2018). The representation of the ASC in ocean models has been challenging (Dinniman et al., 2016). In low-resolution GCMs, the ASC is not well represented due to inadequate resolution of the steep topography of the Antarctic continental-shelf slope (Thompson et al., 2018). While the ASC is largely absent in low-resolution E3SM simulations (Jeong et al., 2020), it has a much-improved representation in E3SM-HR. This is likely due to the higher resolution of the simulated surface winds, the use of a higher resolution bathymetry, and better reproduction of mesoscale eddy activity over the Antarctic continental shelf and slope. Yet, the results presented in this paper have indicated an overly strong ASC around Antarctica in E3SM-HR, associated with overly Finally, the E3SM sea ice dynamics modeled along the coast also possess no tensile strength, nor interaction with icebergs, both known to be important for shaping coastal polynyas (Fraser et al., 2012). We intend to explore the impacts of tides, landfast ice, and icebergs on polynya formation in future studies using E3SM.

Coupled GCMs are sophisticated tools designed to simulate, understand, and predict the behavior of the Earth's climate system (Laloyaux et al., 2016). ~~The~~ However, the model validation or assessment of climate phenomena from Coupled GCMs has ~~, however,~~ traditionally been compared with uncoupled reanalysis data, as we have done in this study. We may have over-interpreted biases in E3SM relative to uncoupled reanalysis products, given that they also have their own biases, in part because they lack physics-based constraints. Hence, there is a need for methods that are designed to ~~ingest~~ process observations of the atmosphere and ocean in a coupled model in a consistent manner (Laloyaux et al., 2016). Improvements in model capabilities and increases in computing power are enabling the analysis of the Earth's climate system using such fully coupled data assimilation schemes (Penny et al., 2019), and future assessments of E3SM would greatly benefit from such coupled model reanalysis products. Different temporal and spatial resolutions also introduce discrepancies between observations/reanalysis products and model results.

~~Whereas~~ The E3SM simulations presented in this paper use the fixed 1950s atmospheric forcing, which consists of greenhouse gases, C Therefore, the E3SM ~~simulations presented in this paper use the HighResMIP 1950 atmospheric forcing and therefore reflect the~~ simulation reflects the internal variability of a stable climate~~, the~~. The observations with which ~~they are~~ E3SM-HR is compared are for a transient climate. ~~Moreover, the observations presented in this study are~~ They cover the period from 1979 onwards, ~~many from this~~ but they are mostly from the current century, which is at a significantly different point in the in-

dustrial epoch than is represented in our 1950s trace atmospheric model constituents. However, previous studies (e.g., Santer et al., 2008; Notz et al., 2013; Swart et al., 2015) indicated that the trends or mean values in observations and individual model simulations may differ significantly because of ~~random differences in~~ internal variability, rather than differences in response to the external forcing. In addition, Menary et al. (2018) and Jeong et al. (2020) found that the differences between preindustrial and present-day control simulations are much smaller than the differences between different model configurations under the same preindustrial or present-day forcing. Finally, we note that E3SM-HR uses an Antarctic land-sea boundary based on data from the 1990s and 2000s, which includes floating ice tongues that are important for determining the locations of coastal polynyas (and which are also present in the observations used in this study). For all of these reasons, we feel justified in using present-day observations as a metric by which to judge our model output.

~~There are several phenomena known to be important in the physics associated with coastal polynyas that are challenging to model. Perhaps most importantly, the ASC plays a critical role in Earth's climate system as it affects the large-scale ocean circulation, the stability of Antarctic ice sheets, and the global carbon cycle (Thompson et al., 2018). The representation of the ASC in ocean models has been challenging (Dinniman et al., 2016), and it is not well represented in low-resolution GCMs due to inadequate resolution of the steep topography of the Antarctic continental-shelf slope (Thompson et al., 2018). While the ASC is largely absent in low-resolution E3SM simulations (Jeong et al., 2020) it has a much improved representation in E3SM-HR. This is probably due to the higher resolution of simulated surface winds, the use of a higher resolution bathymetry, and better reproduction of mesoscale eddy activity over the Antarctic continental shelf and slope. The ASC, however, is not only determined by atmospheric winds and possibly eddy activity but also depends on tidal flow across the continental shelf break (Stewart et al., 2019), another process currently missing in our ocean model. Similarly, an explicit physical model of landfast sea ice (e.g., Lemieux et al., 2018) is also absent from the model. The E3SM sea ice dynamics modeled along the coast also possess no tensile strength, nor interaction with icebergs, both known to be important for shaping coastal polynyas (Fraser et al., 2012). We intend to explore the impacts of tides, landfast ice, and icebergs on polynya formation in future studies using E3SM.~~

6   Summary and conclusions

In this paper, we have investigated dense water formation in Antarctic coastal ~~and open-ocean polynyas~~ polynyas and OOPs using the fully coupled E3SM-HR ~~simulation~~and E3SM-LR simulations. In terms of sea ice area and sea ice volume, we find that E3SM-HR reproduces the main features of the 13 most important Antarctic coastal polynyas. There are limitations, however, with the representation of several coastal polynyas, which are possibly related to E3SM's current inability to represent landfast ice. This suggests that adding an accurate representation of landfast ice in E3SM-HR will be essential for correctly simulating coastal polynya and for future studies of polynya variability. E3SM-HR also reproduces MRPs, which were observed in the winters of 2016 and 2017 and, prior to that in the 1970s. The model shows good agreement with satellite observations of the 2017 areal extent and time evolution of the MRP. E3SM-HR frequently produces several other types of ~~OOP events~~OOPs,

such as the WSP, ~~a~~ concurrent MRP and WSP events, and embayment-shaped polynyas. Aside from the ~~large embayments~~latter, all of these were observed in the 1970s.

We subsequently investigated dense water formation in E3SM-HR on the continental shelf and in the Weddell Sea using a WMT analysis. We found significant positive WMT rates on the Antarctic continental shelf, which are almost entirely due to brine rejection by sea ice formation there. However, the positive WMT rates occur at lower densities than expected. Instead, the densest water masses are formed in the interior Weddell Sea when heat is transferred from the deep ocean to the surface and then to the atmosphere during OOP events.

We found that E3SM-HR has overly strong polar easterlies, resulting in a strong ASC separating cold and fresh water nearly everywhere on the continental shelf from warm and salty CDW further offshore. Anomalously strong polar easterlies also lead to overly strong southward surface Ekman transport~~and sea ice melting on the continental shelf in the summer season. Possibly because of this, the density of seawater on the continental shelf tends to be too low throughout the year in E3SM-HR, producing a large density contrast between the continental shelf and waters further offshore. Indeed, and as mentioned above, there is no Antarctic Bottom Water formation in the simulated coastal polynyas, despite the fact that the simulated polynyas produce large amounts of sea ice associated with brine rejection. One hypothesis that we hope to investigate in future work is that this occurs because of the low mean densities present~~, sea ice built up near the coast, and consequent excessive sea ice melting on the continental shelf ~~. We suspect that the low mean density is due to melting of excessively thick sea ice in the Summer. The reason for this is that there are overly strong easterlies along the coast and the associated excessive accumulation of ice along the coast due to Ekman dynamics~~in the summer season. This in turn is mostly responsible for the ambient density of seawater on the continental shelf to On the other hand, in the interior Weddell Sea, E3SM-HR allows for an alternative method of deep ocean ventilation via deep ocean convection, strong air-sea interactions, and dense water formation during OOP events, consistent with findings from previous modeling studies (Azaneu et al., 2014; Aguiar et al., 2017; Kurtakoti et al., 2018).

The strong polar easterlies in E3SM-HR are due to an overly deep subpolar low-pressure system around 60–70°S, which also causes an intensification of the cyclonic ocean circulation in the Weddell Sea (Weddell Gyre). Studies of WSPs (e.g., Cheon et al., 2014) suggest that the intensification of the Weddell Gyre is one of the possible pre-conditioning mechanisms for WSPs, due to the Ekman pumping and raising of isopycnals in the center of the gyre. Thus, overly deep sub-polar low-pressure systems may impact both ~~open-ocean polynya~~ OOP phenomena and the water mass formation occurring in coastal polynyas.

Regardless of the biases described above, we have shown here that fully coupled, high-resolution E3SM simulations can partially reproduce Antarctic coastal polynyas, an important advancement given their importance as a source of AABW formation and that AABW formation processes are currently ~~under~~ under or misrepresented in most ESMs. Silvano et al. (2018) suggest that increased submarine melting of Antarctic ice shelves may reduce AABW formation by offsetting salt fluxes during sea ice formation in coastal polynyas, a change that could then prevent full-depth convection and the formation of dense shelf water. This hypothesis is supported by the simulations and WMT analyses of Jeong et al. (2020), where the impacts of explicitly including submarine ice shelf melt fluxes in a low-resolution ESM were explored. Future work should focus on better understanding the impacts of both high spatial resolution and sub-ice shelf melting on simulations of Antarctic coastal polynyas, dense water formation, ocean stratification, and the potential feedback between these processes.

Code and data availability. The data from the high-resolution and low-resolution E3SM simulations are available from https://esgf-node.llnl.gov/search/e3sm/. The ocean temperature and salinity from WOA18 can be accessed at https://www.ncei.noaa.gov/access/world-ocean-atlas-2018. The SOSE dataset can be obtained from http://sose.ucsd.edu/. The E3SM source code and the standard setup files can be obtained from https://github.com/E3SM-Project/E3SM. The data analysis was conducted using the software NCAR Command Language (https://www.ncl.ucar.edu/).

Author contributions. HJ, AT, AR, and MV designed this study. PC, JW, and AM ran the simulations. HJ made the plots, performed the analysis, and wrote a draft of the manuscript. SP, XA, LV, WL, and HP provided important guidance while all the authors discussed and revised the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Horizontal and vertical resolution of E3SM-HR and E3SM-LR. In the case of sea ice, vertical levels refer to the number of thickness categories.

	Component	E3SM-HR	E3SM-LR
Horizontal spacing	Atmosphere / Land	25 km	110 km
	Ocean / sea ice	8–16 km	30–60 km
	River	0.125°	0.5°
Vertical levels	Atmosphere	72	72
	Land	15	15
	Ocean	80	60
	Sea ice	5	5
	River	1	1

Table 2. Atmosphere, ocean, and sea ice state estimate datasets.

Data sets	Variables	Units	Spatial and temporal resolution	Periods	References
AMSR-E	Sea ice production	$m\,yr^{-1}$	20 km, Monthly	2003-10	Nihashi an...
NCDR	Sea ice concentration	N/A	25 km, Monthly	1989-2018	Peng et al.
SOSE	Sea ice concentration	N/A	16 km, Monthly	2005-10	Mazloff et...
	Sea ice thickness	m			
	Temperature	°C			
	Salinity	psu			
	Potential density	$kg\,m^{-3}$			
WOA18	Temperature	°C	25 km, Monthly	1995-2018	Locarnini...
	Salinity	psu			Zweng et...
CTD-1	Temperature	°C	~15 km	Mar. 30 - Apr. 2, 1995	Heywood...
	Neutral density	$kg\,m^{-3}$			
CTD-2	Temperature	°C	~20 km	Feb. 8 - 12, 2007	
	Neutral density	$kg\,m^{-3}$			
CTD-3	Temperature	°C	~50 km	Jan. 17 - 18, 1993	
	Neutral density	$kg\,m^{-3}$			
ERA5	Zonal wind at 10 m	$m\,s^{-1}$	25 km, Monthly	1979-2008	Hersbach...
	Meridional wind at 10 m	$m\,s^{-1}$			

Table 3. 13 major Antarctic coastal polynyas in this study.

Acronym	Polynya name	Polynya area ($10^3\,\mathrm{km}^2$)	Sea ice production ($10^{10}\,\mathrm{m}^3$)
CDP	Cape Darnley	10.3±3.7	13.4±1.3
MBP	Mackenzie Bay	3.9±2.1	6.0±0.6
BaP	Barrier	6.0±2.7	6.2±0.7
SP	Shackleton	7.5±3.6	8.4±0.8
VBP	Vincennes Bay	6.3±2.2	6.4±0.5
DaP	Dalton	3.7±2.0	3.5±0.4
DiP	Dibble	5.5±2.3	5.7±0.9
MP	Mertz	9.7±4.4	13.2±1.9
TNBP	Terra Nova Bay	3.6±2.1	5.9±0.6
RISP	Ross Ice Shelf	17.7±10.6	30.0±2.2
AP	Amundsen	7.7±3.6	9.0±1.4
BeP	Bellingshausen	4.9±2.8	5.5±1.2
RONP	Ronne Ice Shelf	2.3±2.7	3.8±1.6
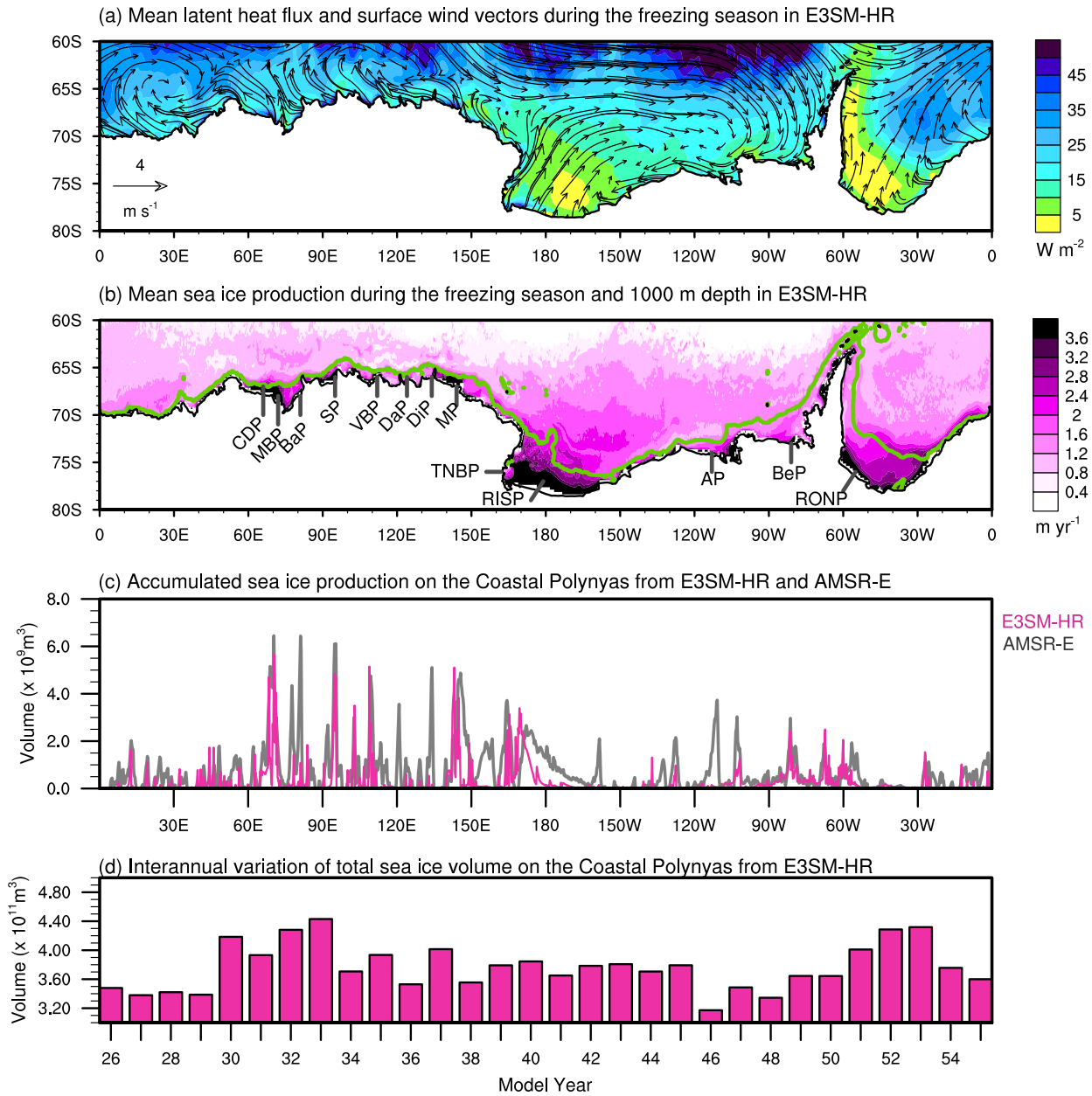
Figure 1. (a) Mean latent heat flux from the sea surface to the atmosphere (shading) and surface wind vectors during the freezing season (March–October) in E3SM-HR. Units of reference for the wind vector are $\mathrm{m\,s^{-1}}$. (b) Mean sea ice production rate during the freezing season (shading) and $1000\,\mathrm{m}$ isobath (contour) in E3SM-HR. Locations of individual coastal polynyas are shown. Definitions of abbreviations can be found in Table 3. (c) Accumulated sea ice volume as a function of longitude from Antarctic coastal polynyas from March to October from E3SM-HR (magenta) and AMSR-E (gray). (d) Total sea ice volume production ~~by~~ per year for all Antarctic coastal polynyas for model years 26 to 55.
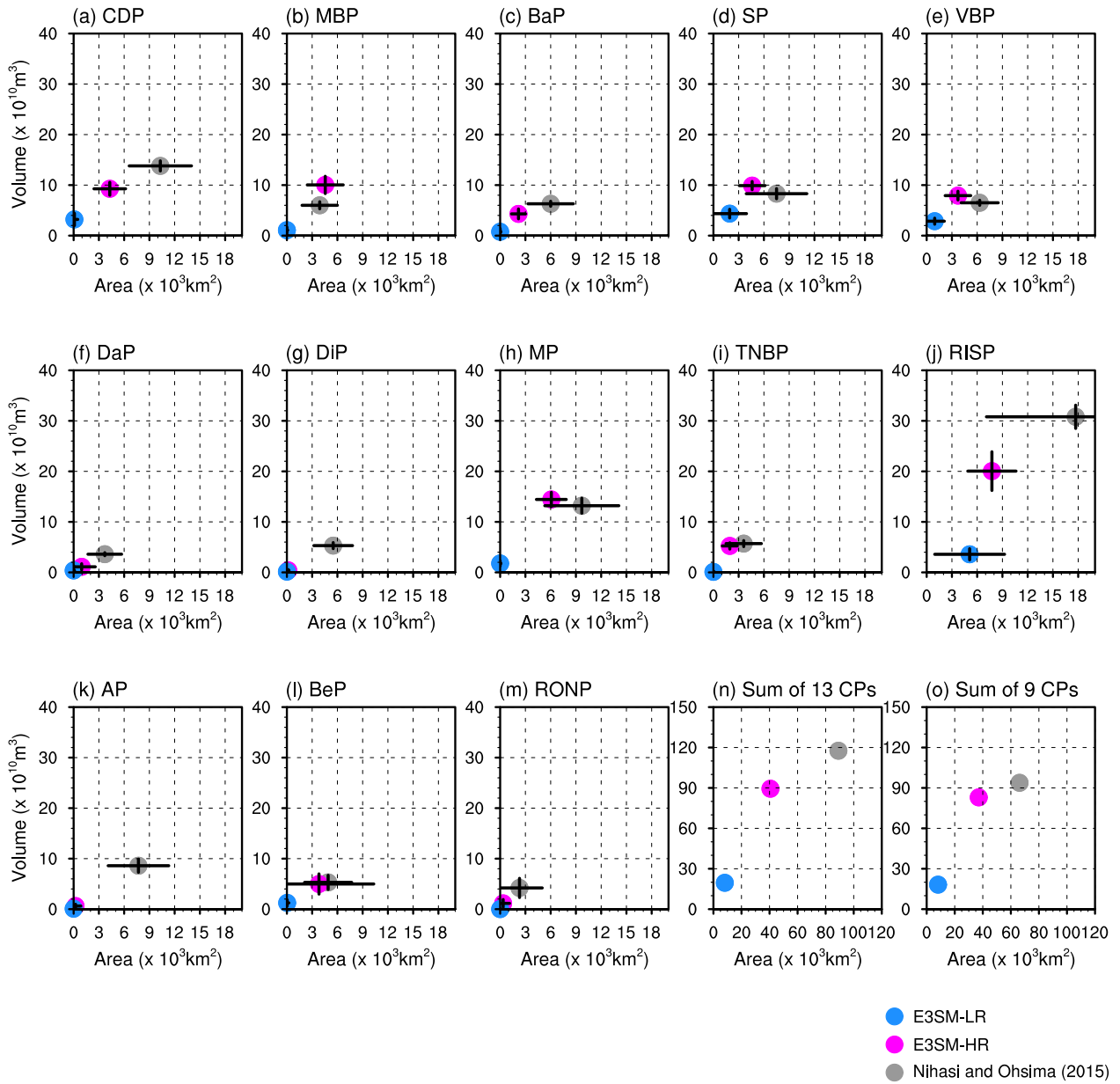
Figure 2. (a–m) ~~AV (Area-Volume)~~ Area-volume diagrams of average polynya area (x-axis) and mean annual volume of sea ice production (y-axis) during the freezing season from March to October for the 13 major Antarctic coastal polynyas. The black bar represents the standard deviation in the annual mean area for each coastal polynya and the grey bar represents the standard deviation of sea ice production for each coastal polynya. (n) ~~Summation of~~ Integrated polynya area and sea ice volume production for the 13 major coastal polynyas. (o) ~~Summation of~~ Integrated polynya area and sea ice volume production for the 9 major coastal polynyas where landfast ice does not play a significant role (BaP, DaP, DiP, and AP are excluded).
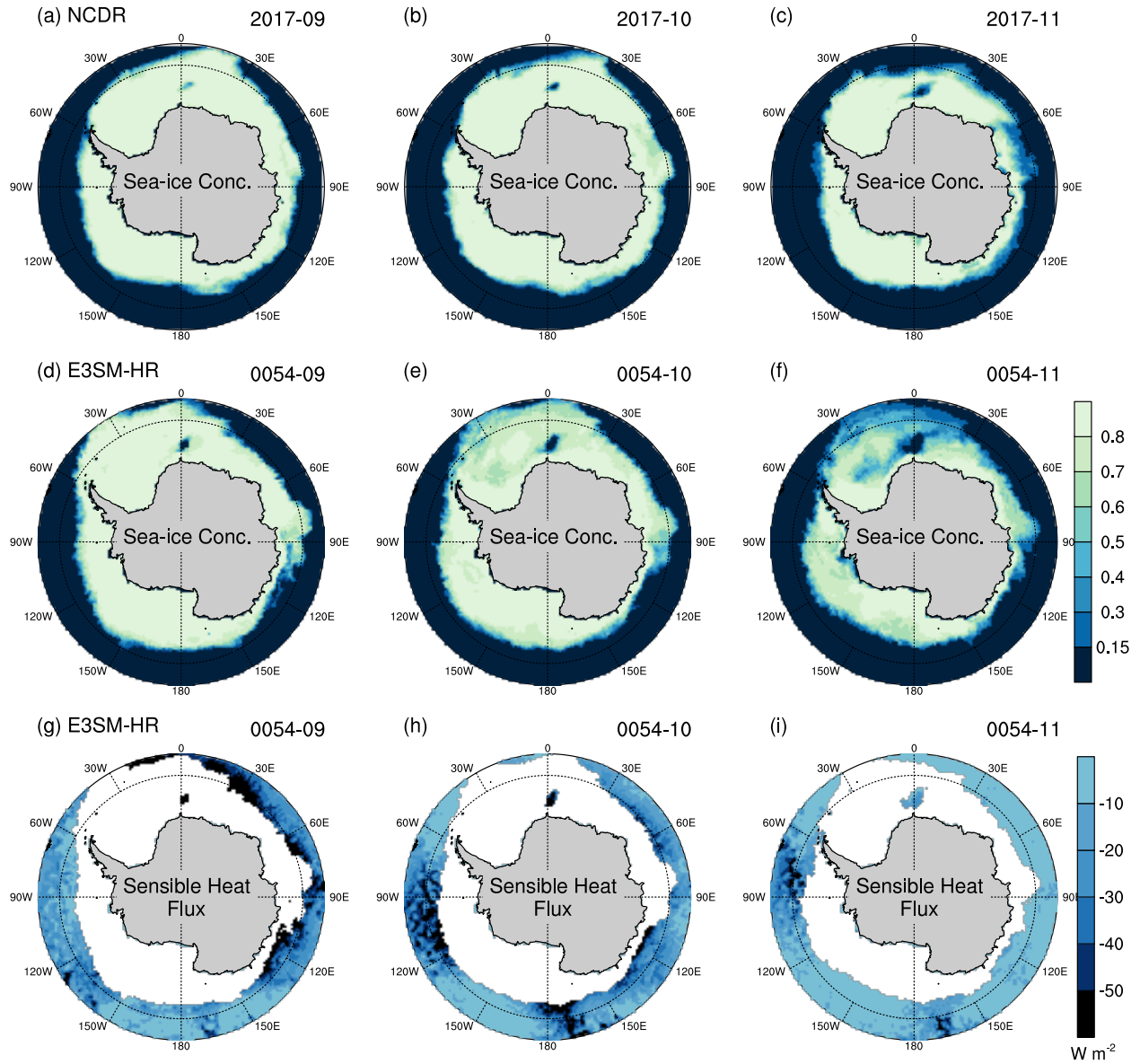
Figure 3. Observed sea ice concentration during the month of (a) September, (b) October, and (c) November from NCDR (~~the observation~~ year 2017) over the Southern Ocean. Simulated sea ice concentration during the month of (d) September, (e) October, and (f) November from E3SM-HR (model year 54) over the Southern Ocean. Simulated sensible heat flux from E3SM-HR during the month of (g) September, (h) October, and (i) November ~~from~~ (model year ~~54.~~ 54). Note that the area where sea ice concentration is larger than 15% is masked out.
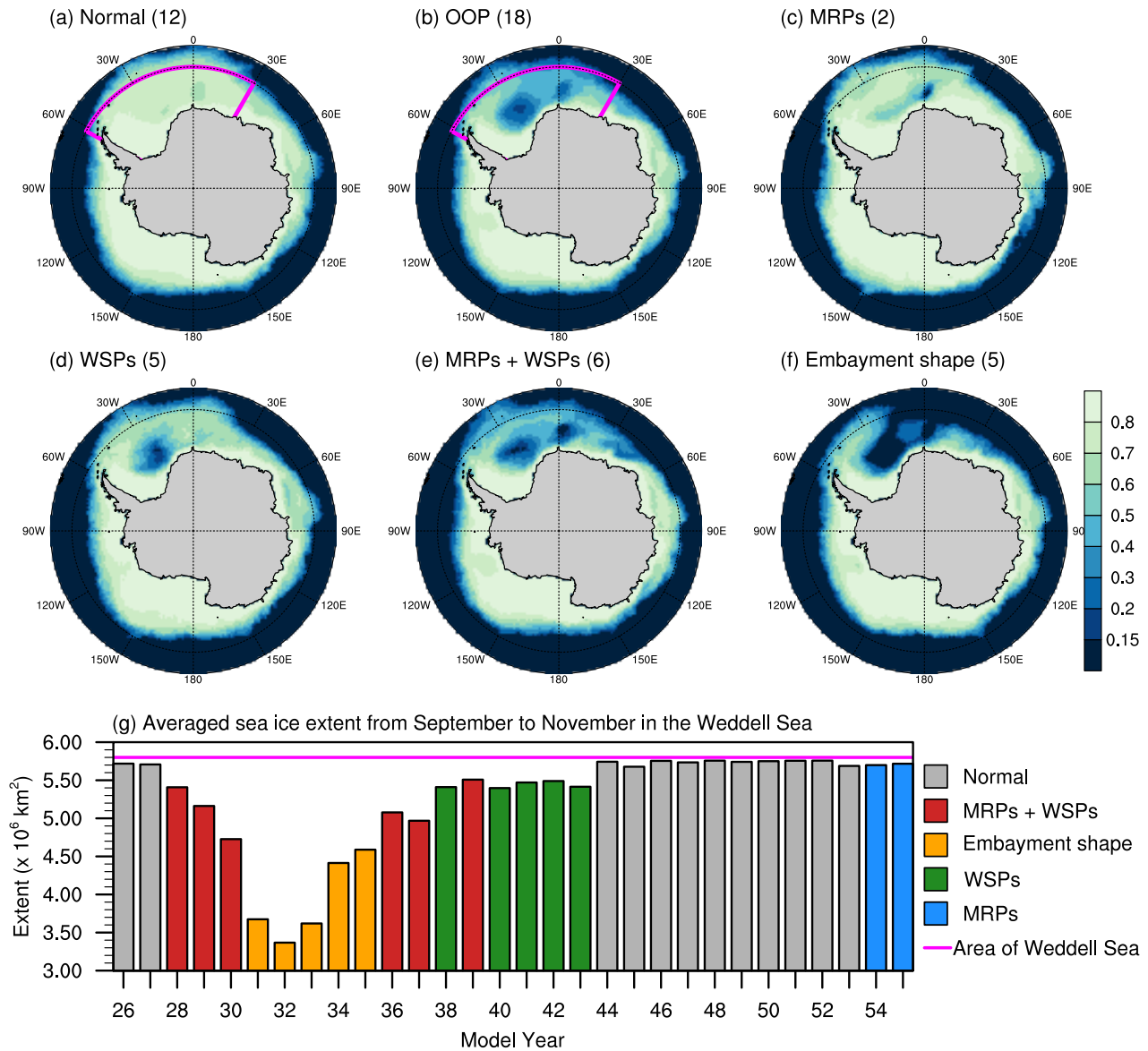
Figure 4. Composite mean of simulated sea ice concentration in E3SM-HR from September to November for years with (a) no OOP (normal year), (b) OOPs (MRPs+WSPs+Embayments), (c) Maud Rise Polynyas, (d) Weddell Sea Polynyas, (e) Maud Rise and Weddell Sea Polynyas, and (f) Embayment shape cases. The numbers in parentheses are the number of years used to compute each composite analysis (years used for the composites can be found in (g)). The OOP years consist of all the cases of (c) Maud Rise polynyas, (d) Weddell Sea polynyas, (e) Maud Rise and Weddell Sea polynyas, and (f) Embayment shapes. The pink ~~boxes in~~ box (a) ~~and (b) indicate~~ indicates the area used to calculate the WMT rate in Section 4. (g) Averaged sea ice extent by E3SM model year from September to November over the Weddell Sea (pink box in (a)). The normal year is denoted by a gray color and the OOP type is denoted by using 4 different colors.
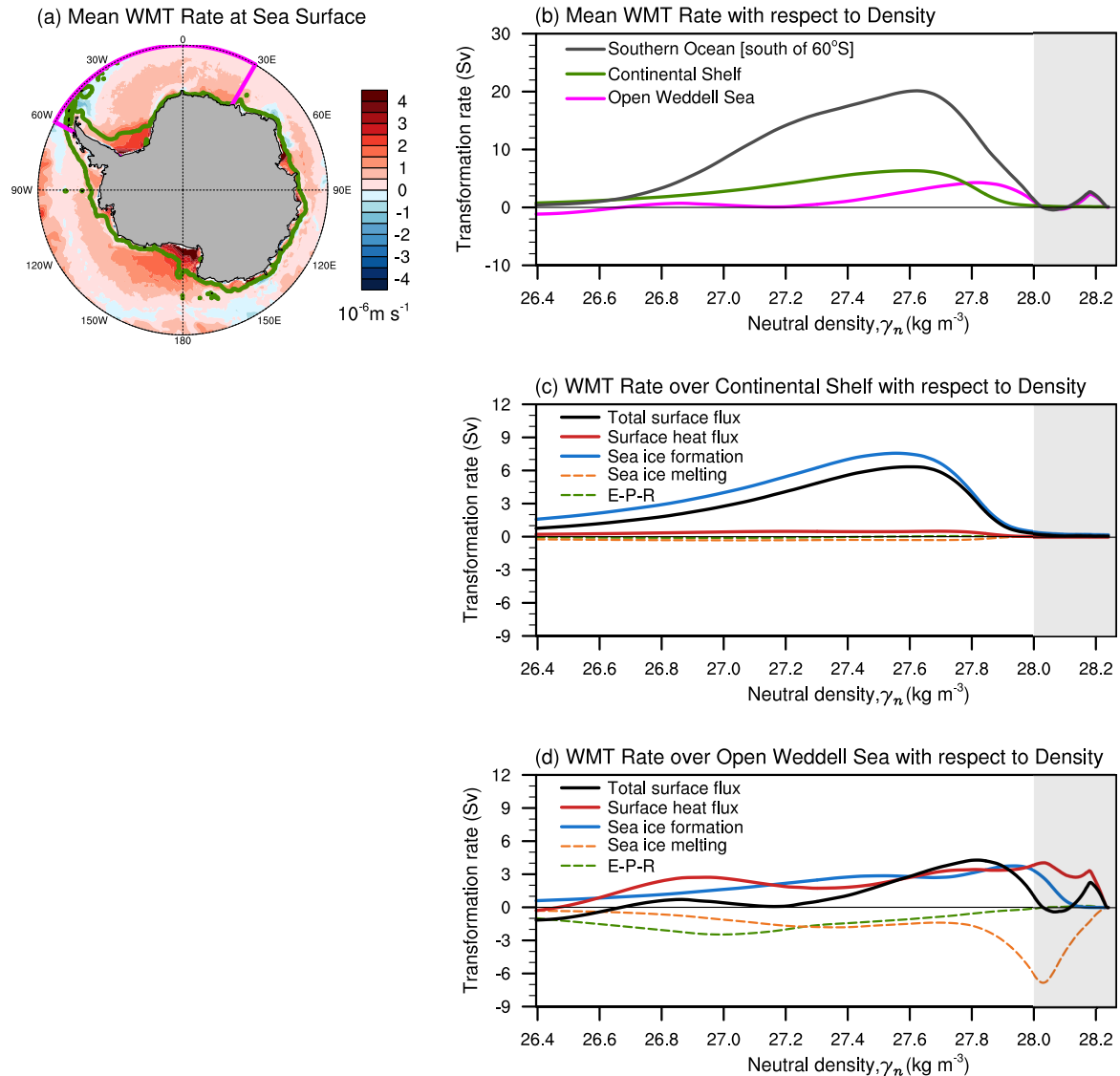
Figure 5. (a) Thirty-year mean water-mass transformation (WMT) rate integrated over all density classes from March to October (freezing season) by total surface fluxes, including surface heat and freshwater fluxes from the E3SM-HR simulation. The green bold contour marks the 1000 m isobath (which defines the continental shelf here) and the pink box in (a) identifies the Weddell Sea as defined in this study. (b) WMT rates with respect to neutral density class summed over the whole Southern Ocean (gray), continental shelf (green), and Weddell Sea (pink). Note that the green and pink curves do not sum to the gray curve. (c) and (d) show WMT rates driven by the total surface flux and its components integrated over the continental shelf and over the open Weddell Sea, respectively. WMT rate driven by the total surface flux (solid black) consists of those induced by surface heat flux (solid red), freshwater flux from sea ice formation (solid blue), sea ice melting (dashed orange), and E-P-R (dashed green; Evaporation, Precipitation and Runoff).
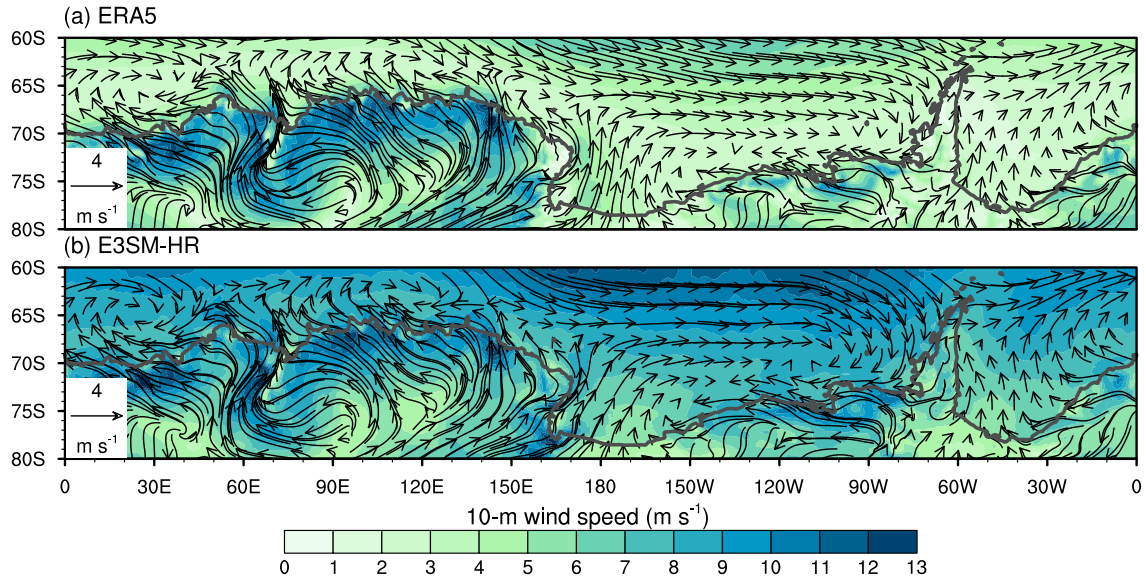
Figure 6. Annual-mean atmospheric surface winds (at 10m) ~~and streamlines~~ from (a) ERA5 and (b) E3SM-HR. Annual mean sea-surface ocean currents from (c) SOSE and (d) E3SM-HR. Shading represents the speed of atmospheric winds and ocean currents. ~~Vector units are ms⁻¹.~~ The locations for each shelf type are indicated by "~~W~~Warm", "~~D~~Dense", and "~~F~~Fresh" in (d) for representing warm, dense, and fresh shelves, respectively.
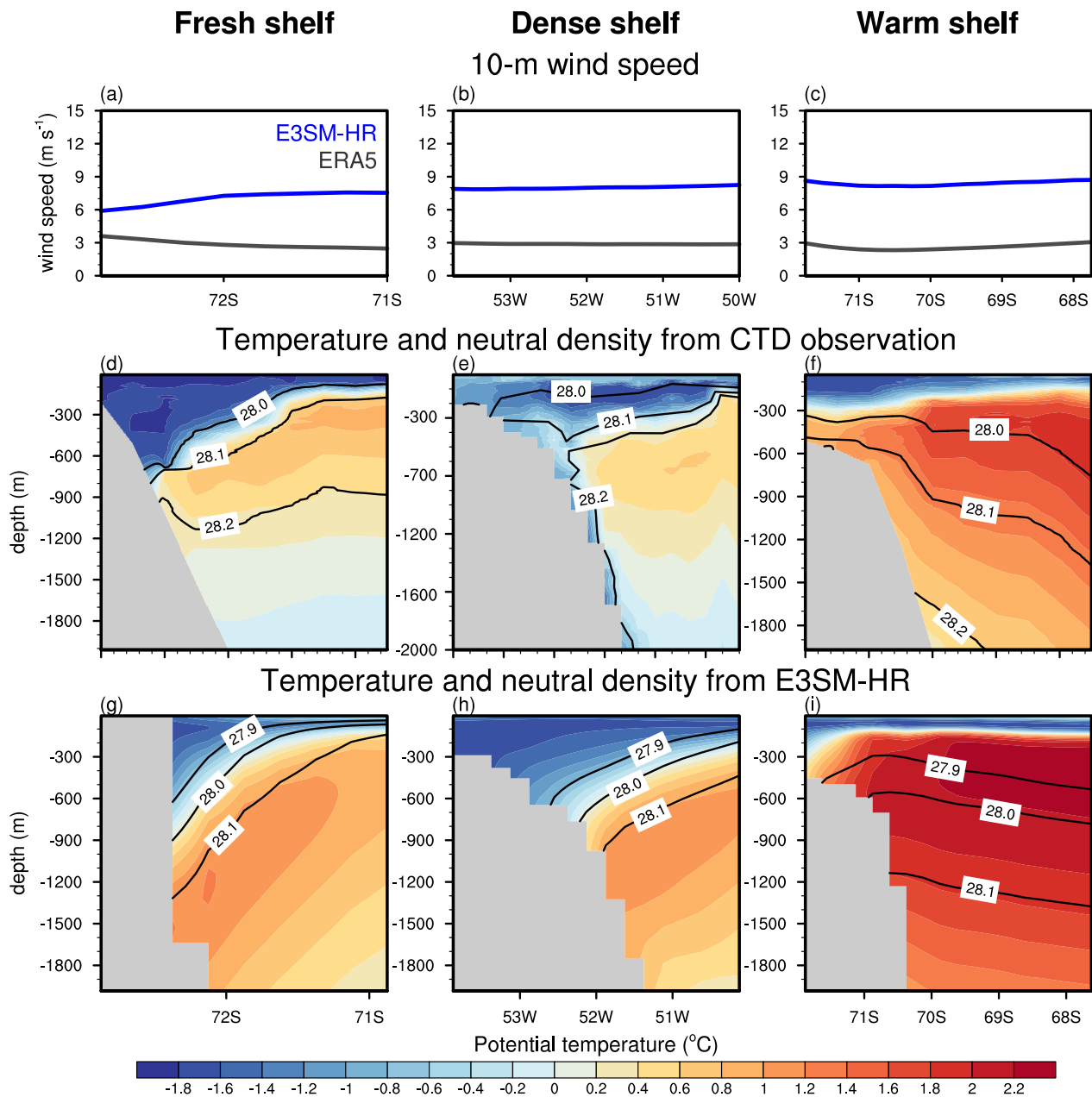
Figure 7. (a, b, c) Atmospheric ~~zonal and meridional~~ wind speed at 10 m ~~and 12°W~~ from ERA5 and E3SM-HR ~~with respect to latitude. Vertical cross-section at 12°W~~ (d, e, f) Measurements of ~~zonal ocean velocity from~~ conservative temperature (~~c~~colors) ~~SOSE,~~ and neutral density (black contours) across the ASC in locations corresponding to each ASC regime: (d) the eastern Weddell Sea (Heywood and King, 2002), (e) ~~E3SM-HR~~the western Weddell Sea (Thompson and Heywood, 2008), and (f) the Bellingshausen Sea (Orsi and Whitworth, 2005). ~~Negative zonal velocity represents westward flow while positive zonal velocity represents eastward flow.~~ (g, h, i) Vertical ~~cross section at 12°W~~ cross-section of ocean temperature (~~shading~~colors) and ~~salinity~~ neutral density (black contours) from an annual average of E3SM-HR simulation. The Left (a, d, g)~~SOSE~~, middle (b, e, h), and Right (c, f, i) ~~E3SM-HR. Salinity contours start at 34.0 psu~~ columns show an example of fresh, dense, and ~~are separated~~**31**~~y 0.1 psu intervals~~warm shelf cases. ~~All figures here~~ Section locations are ~~annual averages. 12°W typically represents the fresh shelf type~~ shown in observations~~Fig. 6.~~
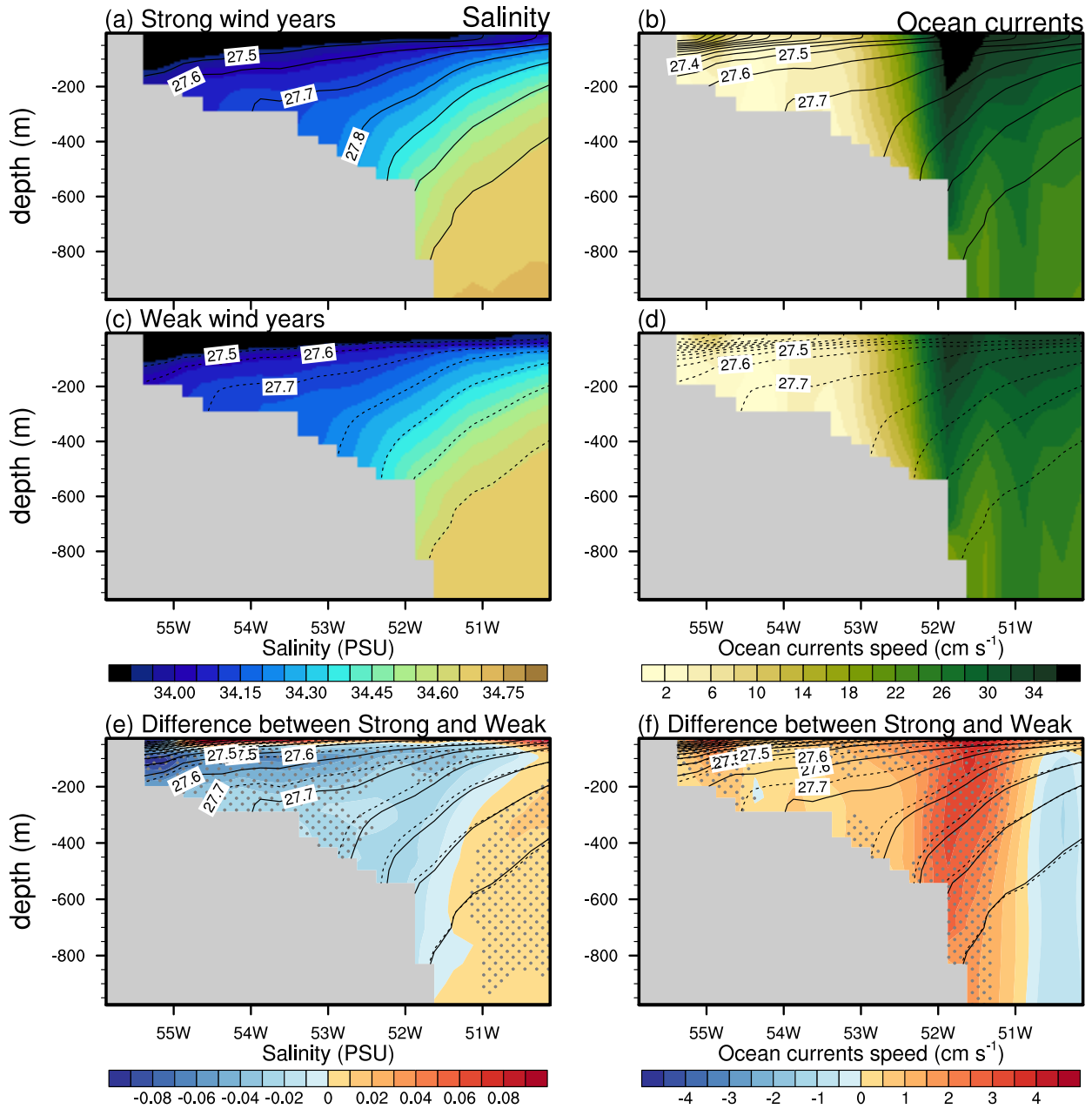
Figure 8. ~~As in Fig~~(a, c, e) Vertical cross-section of salinity (shading) and neutral density (contour lines) for (a) strong-wind years, (c) weak-wind years, and (e) difference between strong and weak wind years from E3SM-HR simulation. ~~?? but~~ (b, d, f) Vertical cross-section of ocean currents speed (shading) and neutral density (contour lines) for ~~35°W~~(b) strong-wind years, (d) weak-wind years, and (f) difference between strong and weak wind years from E3SM-HR simulation. ~~This longitude typically represents~~ For the ~~dense shelf type in observations~~differences, statistically significant values (P < 0.05) are stippled.
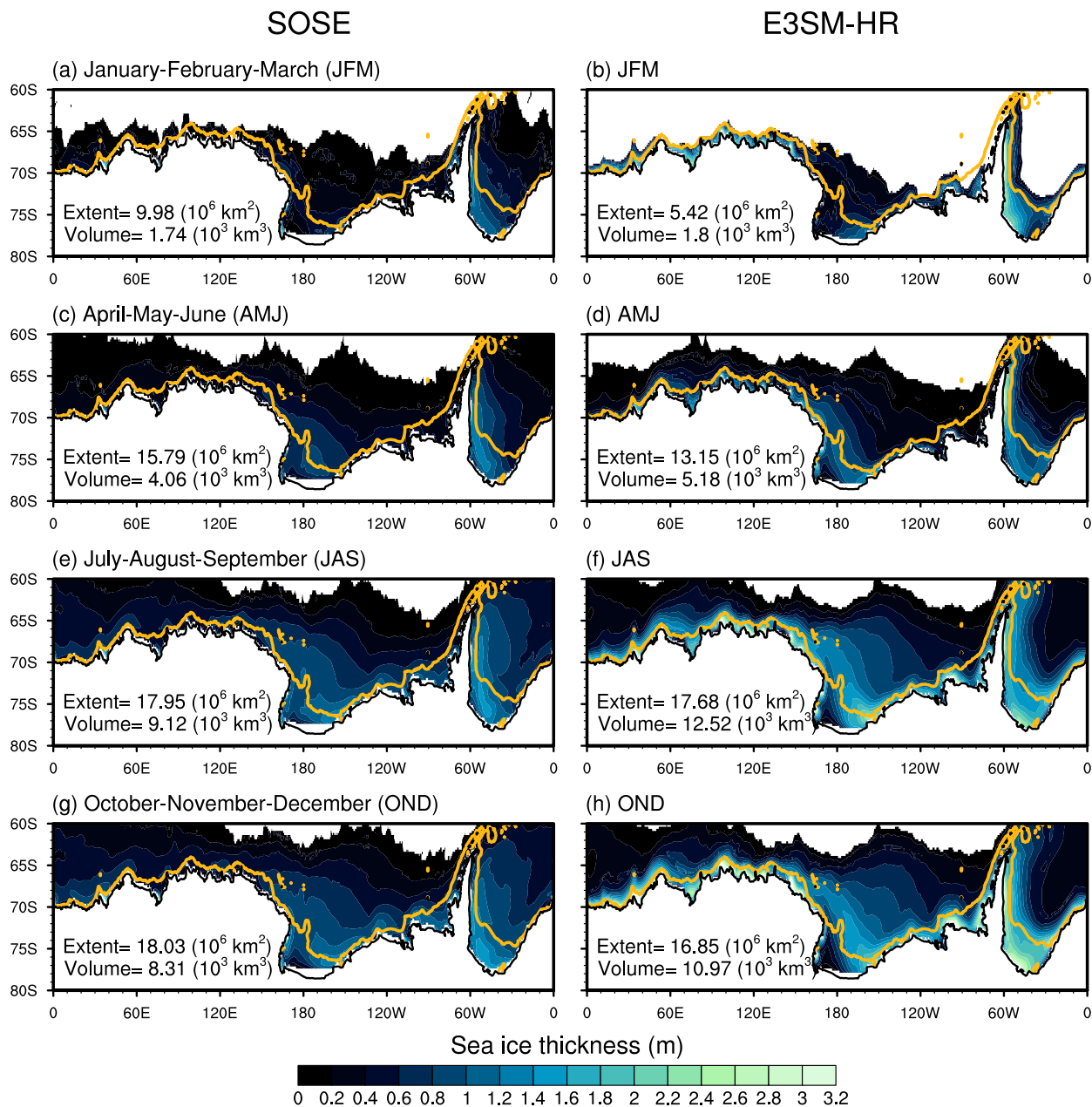
Figure 9. ~~As in Fig~~Seasonal mean sea ice thickness during JFM (January-February-March), AMJ (April-May-June), JAS (July-August-September), and OND (October-November-December) from (a, c, e, g) SOSE and (b, d, f, h) E3SM-HR. ~~?? but for 72°W~~The region where sea ice concentration is less than 15% is masked out. ~~This longitude typically represents~~ The yellow contour line denotes the ~~warm shelf type in observations~~1000 m isobath. Sea ice extents and volumes for each season are also displayed.

~~Seasonal mean sea ice thickness during JFM (January-February-March), AMJ (April-May-June), JAS (July-August-September), and OND (October-November-December) from (a,c,e,g) SOSE and (b,d,f,h) E3SM-HR. The region where sea ice concentration is less than 15% is masked out. The yellow contour line denotes the 1000 m isobath. Sea ice extents and volumes for each season are also displayed.~~
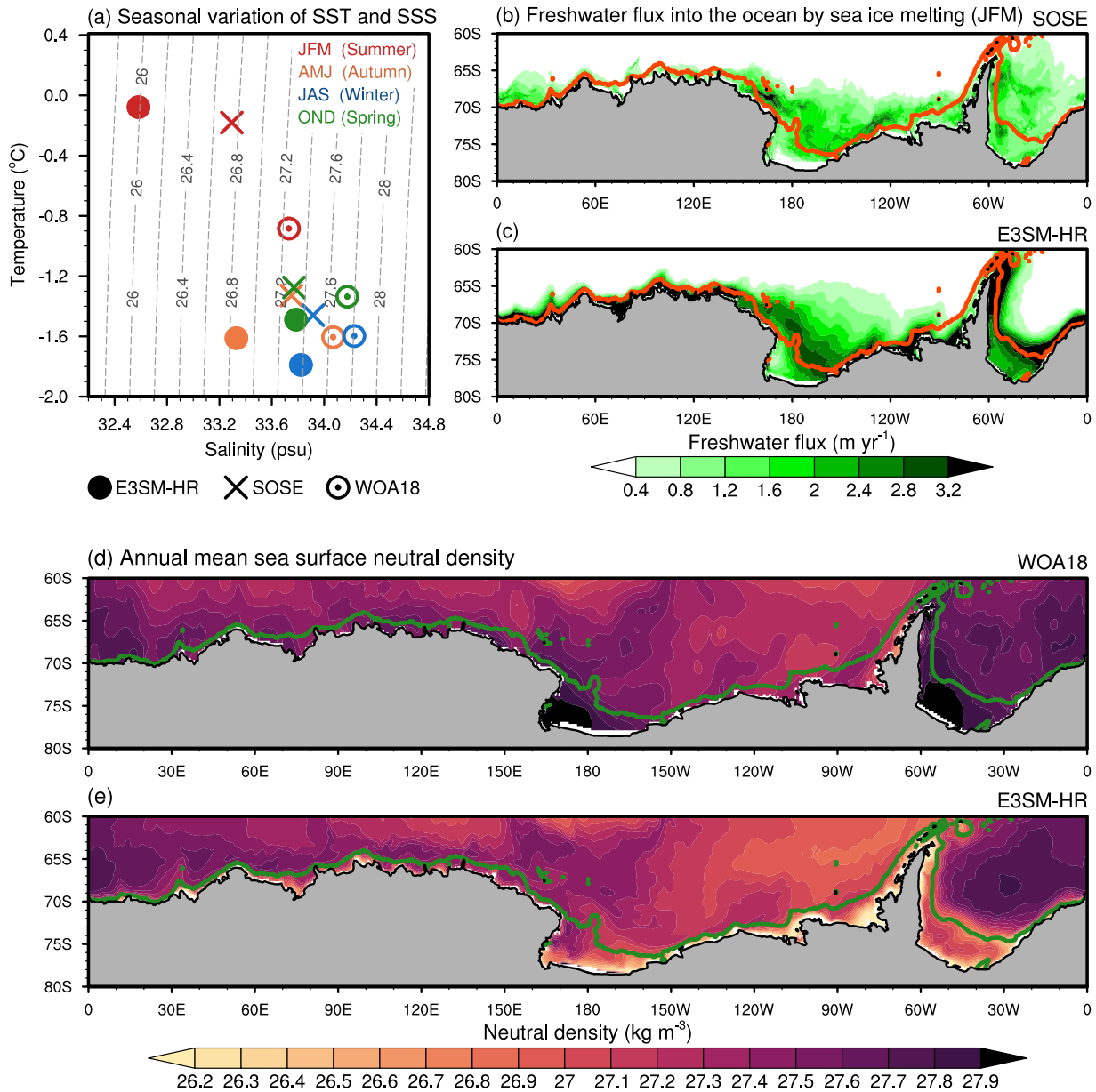
Figure 10. (a) Seasonal and area-averaged Sea-Surface Temperature (SST) and Sea-Surface Salinity (SSS) from E3SM-HR, SOSE, and WOA18 over the continental shelves for the season of January-February-March (JFM, Summer), April-May-June (AMJ, Autumn), July-August-September (JAS, Winter), and October-November-December (OND, Spring). Dashed lines on the T-S diagram are neutral density contours. Seasonal mean freshwater flux into the ocean by sea ice melting for JFM from (b) SOSE and (c) E3SM-HR. Annual mean sea surface neutral density from (d) WOA18 and (e) E3SM-HR. Red (b, c) and ~~gray~~ green (d, e) bold contours represent the 1000 m isobath.