Atmospheric Response to Antarctic Sea-Ice Reductions Drives Ice Sheet Surface Mass Balance Increases

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ABSTRACT: The mass balance of the Antarctic ice sheet is intricately linked to the state of the surrounding atmosphere and ocean. As a direct result, improving projections of future sea level change requires understanding change in the Antarctic atmosphere and Southern Ocean, and the processes that couple these systems. Here, we examine the influence of sea ice cover on the overlying atmosphere and subsequently the surface mass balance (SMB) of the adjacent Antarctic ice sheet. We investigate these processes both over the observational era using the ERA5 atmospheric reanalysis and in ensemble simulations of the Community Earth System Model 2.1 (CESM2) where only sea ice coverage is altered. Comparing extreme high and low sea ice over the satellite era in ERA5 reveals atmospheric and ice sheet SMB anomalies that largely mirror anomalies simulated by CESM2 in response to sea ice loss. Results highlight significant near-surface atmospheric warming in response to sea ice reductions that are particularly pronounced in nonsummer seasons and driven by significant ocean-to-atmosphere turbulent heat fluxes. In areas of sea ice loss, significant ocean surface evaporation increases occur. On the eastern flank of climatological low pressure systems, moisture is readily advected toward the ice sheet, driving positive anomalies in the ice sheet SMB. These results indicate that underestimation of Antarctic sea ice, which is common in many current-generation coupled climate models, may lead to overestimation of the ice sheet SMB and therefore underestimation of Antarctica’s contributions to global sea level.

SIGNIFICANCE STATEMENT: The Antarctic ice sheet is the largest potential source of global sea level rise. Its sea level contributions depend in part on how much snow accumulates across its surface. Through observation-incorporating reanalysis data and climate model sensitivity studies, we find that Southern Ocean sea ice coverage exerts an important influence on the near-surface climate and mass balance of the Antarctic ice sheet. Our results show that reductions in Antarctic sea ice promote enhanced ocean surface evaporation and subsequent increases in snowfall across the Antarctic ice sheet. Because current climate models tend to simulate too little Antarctic sea ice, we conclude they may therefore overestimate Antarctic ice sheet snowfall, leading to underprediction of future sea level rise.

KEYWORDS: Antarctica; Ice sheets; Sea ice; Ice loss/growth; Atmosphere–ocean interaction

1. Introduction

The Antarctic ice sheet (AIS) represents the largest potential source of global sea level rise. Understanding the factors that affect its mass balance is therefore critical for assessing current and future sea level change. Satellite observations indicate that the AIS has lost an average of 150 Gt yr$^{-1}$ since 2002 (Wiese et al. 2019), a rate that has increased over recent decades (Shepherd et al. 2018; Rignot et al. 2019). These losses and their acceleration are attributed to enhanced solid ice discharge in response to melting at the ice–ocean interface (e.g., Smith et al. 2020; Miles et al. 2022; Rignot et al. 2019; Shepherd et al. 2018).

The magnitude of overall AIS mass loss, however, is buffered by a significant net input of mass via snowfall, the dominant term in the AIS surface mass balance (SMB; e.g., van Wessem et al. 2018). Both SMB and ice discharge show significant interannual variation on the order of $\sim 100$ Gt yr$^{-1}$ or more (Lenaerts et al. 2016; Mottram et al. 2021; Rignot et al. 2019). Consequently, year-to-year variability in the ice sheet’s SMB determines the degree to which the ice sheet contributes to global sea level. Projections of future SMB increases in a warming climate (e.g., Dunmire et al. 2022) underscore the central role of SMB in the total mass budget of the AIS and its potential to negate future dynamic mass losses, at least regionally (Edwards et al. 2021). As a result, a robust understanding of the climate system processes responsible for SMB variability is paramount.

Among the factors influencing Antarctic SMB include the state of the ocean surface surrounding the continent. Namely, sea ice coverage limits heat and moisture exchange between the ocean and atmosphere. Moisture source modeling illustrates this effect by revealing that during winter, evaporation is almost entirely absent over the sea ice–covered Southern Ocean (Sodemann and Stohl 2009). Satellite-derived evaporation estimates further reveal a strong coupling between sea
ice and evaporation, with evaporation decreases spatially coinciding with positive trends in sea ice, and vice versa (Boisvert et al. 2020). As a result, sea ice variability may play an important role in the mass budget of the adjacent AIS. This sea ice–atmosphere–ice sheet SMB coupling has been more thoroughly explored in the Arctic, where observational and modeling work links decreases in sea ice to both increased surface melting (Rennermalm et al. 2009; Stroeve et al. 2017; Trusel et al. 2018) and snowfall (Day et al. 2013; Noël et al. 2014; Osman et al. 2021), at least regionally over the Greenland ice sheet.

Limited Antarctic research also supports similar sea ice–SMB links, including that of Bracegirdle et al. (2015), who found that CMIP5 models with larger sea ice area (SIA) declines had greater increases in surface temperature and precipitation. Likewise, Kittel et al. (2018) used a regional climate model and found that large increases in sea surface temperature and decreases in sea ice concentration significantly increased AIS SMB. Their experimental design, however, did not allow for potential atmospheric circulation responses to altered sea surface conditions, nor uptake of heat in a reduced-ice ocean surface, leaving unresolved questions regarding the dynamic response of the atmosphere to sea surface change. Fyke et al. (2017) similarly found that regional AIS precipitation increases occurred when offshore sea ice was low but did not find that these sea ice reductions increased evaporation. Instead, the authors argued that precipitation and sea ice changes found in preindustrial Community Earth System Model (CESM), version 1, simulations reflected common atmospheric dynamics simultaneously driving decreased sea ice and increased precipitation (Fyke et al. 2017). Given this apparent conflict and the specific experimental limitations associated with this previous work, a more detailed assessment of the sea ice influence on evaporation and AIS precipitation is warranted.

Antarctic sea ice cover has experienced significant interannual variability over the satellite era alongside regionally distinct positive and negative trends (Cavaliere and Parkinson 2008; Comiso and Nishio 2008; Parkinson and Cavaliere 2012; Wang and Wu 2021; Parkinson 2019). In contrast to the Arctic, as a whole, Southern Ocean sea ice over the satellite era trended positively until 2016 (Maksym 2019). This period of overall growth has been followed by significant declines in ice extent and area (Eayrs et al. 2021), including a new record low sea ice in February 2023 (Liu et al. 2023). Such large variability in Antarctic sea ice coverage simultaneously raises the question of how this may have influenced the AIS SMB over the satellite era while also presenting an opportunity to assess its covariability with atmospheric processes and AIS SMB.

A robust understanding of sea ice–SMB links is of additional concern given that many current-generation climate models struggle with accurately representing Southern Ocean sea ice. Namely, CMIP5 and CMIP6 models simulate negative sea ice trends despite observations indicating overall ice increases (Roach et al. 2020). While diagnosing the causes for these model–observation disagreements remains an active area of research (e.g., Bintanja et al. 2013; Polvani and Smith 2013; Sun and Eisenman 2021), output from these models is still needed to quantify potential future SMB change. Indeed, sea level projections reported in the IPCC Sixth Assessment (Fox-Kemper et al. 2021) are derived from ice sheet models that use SMB anomalies from global climate models as input (Nowicki et al. 2020; Seroussi et al. 2020). Given this, understanding the potential biases induced by inaccurate representation of sea ice is warranted in the context of narrowing estimates of future sea level rise.

Motivated by the potentially important, but largely unresolved, impacts of sea ice variability on the AIS SMB, here we present evidence of a significant impact of sea ice variability on Southern Ocean evaporation and resulting precipitation falling across the adjacent AIS. Our analysis (methods presented in section 2) relies first on an assessment of observation-incorporating gridded reanalysis data, where significant relationships are found between regional sea ice and ice sheet SMB (section 3a). To fully isolate the response of the atmosphere to sea ice variability, we then turn to climate model sensitivity experiments in which only sea ice is altered. These model results (presented in section 3b) highlight significant increases in regional ice sheet SMB in response to future reductions in Southern Ocean sea ice. We contextualize our results in section 4, discussing that positive anomalies in SMB resulting from sea ice reductions represent a large fraction of the mass that is presently lost via ice discharge across specific regions. We conclude in section 5 that our results highlight the need to accurately represent Antarctic sea ice in models to reduce biases in quantification of contemporary and future AIS sea level contributions.

2. Data and methods
a. Observational era: ERA5

To explore recent linkages between sea ice, the atmosphere, and AIS SMB, we rely on data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 (Hersbach et al. 2020) over the period 1978–2021. ERA5 is a 31-km-resolution, latest-generation global reanalysis product that is known to reliably capture the near-surface climate and SMB of Antarctica (Gossart et al. 2019; Zhu et al. 2021). Limited comparison with buoy observations in the Weddell Sea indicates that ERA5 reasonably captures near-surface meteorological conditions over the sea ice pack (King et al. 2022). ERA5 has likewise proven accurate in representing atmospheric moisture budgets and related processes in the Antarctic (Naakka et al. 2021). For consistency, we also assess variability in sea ice conditions from ERA5, which are prescribed using two EUMETSAT OSI-SAF products based on observations from a variety of satellite platforms (Hirahara et al. 2016).

Given the relative lack of surface meltwater runoff from Antarctica today (e.g., Bell et al. 2018) in both our ERA5 and climate model-based analyses described below, we calculate the AIS SMB as total precipitation minus evaporation and sublimation (i.e., P – E following, e.g., Medley and Thomas (2019), Lenaerts et al. (2019), Gossart et al. (2019), Gorte et al. (2020),
and Mottram et al. (2021)\), and for simplicity, we refer to the calculation of $P - E$ over the AIS as SMB.

b. Climate model simulations

Model sensitivity experiments where only sea ice is altered are especially well suited to identifying physical linkages between the ocean surface, atmosphere, and surrounding regions (e.g., Sellevold et al. 2022; Ayres et al. 2022). As such, we examine atmosphere-only time slice experiments from the Community Earth System Model, version 2.1 (CESM2), produced under the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al. 2019) to evaluate the atmospheric response to Southern Ocean sea ice loss. These simulations encompass two 100-member ensembles, each simulating one year and initialized with only small atmospheric differences. The two ensembles differ only with respect to prescribed Antarctic sea ice. One ensemble (pdSST-piAmSIC, herein the “pre-industrial” scenario) is run with more extensive (preindustrial) Southern Ocean sea ice concentrations and the other (pdSST-futAmSIC, herein the “future” scenario) with reduced sea ice from a globally 2°C warmer world compared to preindustrial. Sea ice in both ensembles was calculated as the 30-yr average sea ice concentration from a 31-model ensemble of CMIP5 models where each model’s 30-yr-mean global air temperature equalled the PAMIP-specified values for preindustrial and future conditions (13.67° and 15.67°C using the historical and RCP8.5 scenarios, respectively). Both ensembles use present-day (1979–2008) SSTs from HadISST (Rayner et al. 2003), unless sea ice concentration decreased by >10% compared to its present-day value, in which case the CMIP5 ensemble mean SST was taken. We chose to compare the response of the model to a larger reduction in sea ice by contrasting preindustrial to future sea ice conditions (rather than comparing present-day to preindustrial or future sea ice where sea ice changes would be smaller). Here, we focus on the differences (i.e., anomalies) between the preindustrial and future scenario ensemble means to assess the Southern Ocean sea ice forcing on the AIS surface mass and energy balances.

Ice sheet surface melt is not explicitly simulated in the CESM2 experiments analyzed here. Thus, we parameterize surface melt using air temperature following the exponential relationship described in Trusel et al. (2015; their Fig. 1), which follows the approach of the Ice Sheet Model Intercomparison Project for CMIP6 (ISIMIP6; Seroussi et al. 2020). This method relates mean summer (DJF) air temperatures to total annual ice sheet surface meltwater production. To qualify these results, we compare surface melt anomalies resulting from sea ice reductions to surface melt rates simulated by the regional climate model RACMO2.3p2 forced by ERA5 (van Wessem et al. 2018). We first regressed the 27-km-resolution RACMO2 melt data to the CESM2 grid resolution before calculating mean annual meltwater production over 2011–20. Given that this analysis does not assess meltwater runoff (and thus melt’s role in SMB), we exclusively evaluate how atmospheric change in response to sea ice reduction could influence surface melt rates.

3. Results

a. Observational-era sea ice–SMB links

1) OBSERVED ANNUAL SEA ICE–SMB COVARIABILITY

Figure 1 uses ERA5 to show two sets of spatial correlations between ice sheet SMB and sea ice fields across five sectors of the Southern Ocean and AIS (defined by Cavalieri and Parkinson (2008)). Across the ocean, correlations are shown between spatially varying sea ice concentration (SIC; shown in blues to reds) and regionally integrated AIS SMB (the ice sheet area within the delineated region). Across the ice sheet, correlations between spatially varying SMB (shown in browns to greens over the ice sheet) and regionally integrated sea ice area (SIA; integrated over the delineated region over the ocean) are indicated. Both correlation sets show strongly negative sea ice–SMB relationships across most sectors, apart from the Indian Ocean sector. In general, the strongest links are found across the West Antarctic and the western Pacific sectors (Figs. 1a,b,e). For the Ross, Bellingshausen/Amundsen,
and Weddell sectors, regional AIS SMB increases occur when SIC largely separated from the coastline is reduced. Conversely, in the western Pacific sector, SMB increases occur when sea ice in contact with the coastlines is reduced.

2) ATMOSPHERIC ANOMALIES DURING RECENT EXTREME SEA ICE YEARS

To assess the atmospheric and SMB conditions during low-sea ice states, we calculated Antarctic sea ice extent (SIE) from ERA5 and ranked years based on their overall annual SIE. In the five lowest years of annual SIE on record (2017, 2019, 2018, 1986, and 1980), the extent was 6% below the long-term (1979–2021) mean. Seasonal decreases were larger in summer (DJF) and autumn (MAM; 13% and 14%, respectively) compared to winter (JJA) and spring (SON; 4% and 2%, respectively). Comparing ERA5’s lowest annual SIE years to highest years (2014, 2013, 2015, 2008, and 2003) enables examination of larger relative changes in sea ice and associated anomalies in atmospheric conditions (Fig. 2). This low versus high “end member” SIE years comparison represents a doubling of the decrease in overall SIE (12%) relative to the average conditions, while distinctions in sea ice changes persist both regionally and seasonally. Especially large negative

Fig. 2. Seasonal anomalies in ERA5 sea ice concentration between the five “end member” years of lowest and highest annually integrated Antarctic sea ice extent over 1979–2021. Outlined/hatched areas indicate where anomalies exceed interannual variability (i.e., 1 standard deviation from the long-term mean).
anomalies in SIC are observed in the Weddell and Ross Seas, whereas increases occur in the Bellinghausen Sea, although these are not uniformly significant across space or time. A strong seasonal character is also observed when comparing low and high SIE years, with large relative decreases of 28% and 27% in summer and autumn, respectively, and 7% and 4% in winter and spring, respectively.

Significant positive anomalies in near-surface air temperature occur when comparing the lowest to highest SIE years, particularly in autumn and winter over areas of significant sea ice reduction (Fig. 3). While warming exists in summer, the magnitude of these positive anomalies is weaker. In spring, when there is little coherent pattern in sea ice change (Fig. 2, SON), positive air temperature anomalies near and over Antarctica are mostly within the range of interannual variability. While the strongest positive anomalies in air temperature occur in regions of sea ice decline (i.e., dotted areas in Fig. 3 and subsequent figures), warming also occurs more broadly. For example, in autumn (Fig. 3; MAM), air temperature increases that exceed interannual variability are observed over wide swaths of the Southern Ocean, extending well beyond the more limited areas of significant sea ice decline. Likewise, positive temperature
changes occur over much of the AIS in summer, autumn, and winter, whereas negative anomalies occur over the AIS in spring, although these changes are almost entirely within the range of interannual variability.

3) ENERGY AND MASS FLUX ANOMALIES DURING EXTREME SEA ICE YEARS

To evaluate the potential impact of sea ice changes on near surface air temperatures, we examine anomalies in the surface energy balance (SEB) its components between extreme low and high SIE years in summer and autumn (Fig. 4). Although these were the seasons with the largest sea ice anomalies (Fig. 2), we find similar, but more modest, changes in winter (Fig. S1 in the online supplemental material). We find the largest individual change in summer is positive anomalies in net shortwave radiation (SW\text{net}), as high albedo sea ice is replaced by low albedo ocean in the lowest SIE years. This results in a net addition of energy to the surface ocean surrounding Antarctica (red areas in the Fig. 4 summer SEB panel). In autumn, increases in SW\text{net} are smaller given the seasonal decrease in incident shortwave radiation. Significant decreases in net longwave radiation (LW\text{net}) over the Weddell Sea in autumn indicate that increased upward longwave emissions from a warmer, less ice-concentrated ocean surface outweigh any increases in downward longwave radiation from a warmer and cloudier atmosphere. The most uniform changes in autumn (and winter; Fig. S1), and those that dominate the spatial pattern in overall SEB anomalies, are to the turbulent fluxes of sensible and latent heat (SHF and LHF; Fig. 4). Significant negative SHF and LHF anomalies indicate increased surface-to-atmosphere heat exchange and evaporation and a resulting nonsummer cooling of the ocean surface in areas of sea ice reductions. This turbulent heat loss from the ocean, in turn, warms the atmosphere and mirrors the hotspots of strongly positive near-surface air temperature anomalies in the eastern Weddell Sea and western Ross Sea (Fig. 3; MAM).

In Fig. 5, we explore potential implications of observed sea ice loss on atmospheric moisture budgets and precipitation. The largest positive anomalies in evaporation occur during autumn and winter in the Ross and Weddell Seas (Fig. 5a), locations of heightened sea ice reductions (Fig. 2), near-surface warming (Fig. 3), and turbulent heat loss to the atmosphere (Fig. 4). Conversely, summer evaporation anomalies tend to be negative and insignificant, despite broad regions of significant summertime sea ice loss. This finding suggests that the summer atmosphere surrounding Antarctica during low SIE years is close to saturation. Indeed, Boisvert et al. (2020) found that summertime evaporation was dictated in large part by the near-surface atmospheric specific humidity, and that warmer, more humid northerly air masses inhibited summer evaporation. Importantly, lack of increased summertime evaporation results in little change to latent heat fluxes, thus allowing positive SW\text{net} anomalies to accumulate and add heat to the Southern Ocean surface (Fig. 4).

Figure 5b examines anomalies in total precipitation (which largely mirrors SMB; Fig. S2 in the online supplemental material) to explore potential links between sea ice reduction, evaporation, and ice sheet SMB. Despite large changes in other atmospheric and SEB parameters, we find little significant precipitation change between end-member sea ice years (Fig. 5b). For example, although significant evaporation increases are associated with reduced SIC in the Weddell Sea in autumn (Fig. 5a; MAM), precipitation increases here are not anomalous (Fig. 5b; MAM). In fact, the only area in autumn displaying significant precipitation increases is the westernmost Ross Sea/easternmost Western Pacific region (Fig. 5b; MAM), a location and time experiencing among the largest SIC reductions (Fig. 2), positive air temperature anomalies (Fig. 3), and increases in evaporation (Fig. 5a). The opposite is true for the easternmost Bellingshausen Sea abutting the western Antarctic Peninsula during autumn (Fig. 5b; MAM), where local precipitation decreases coincide with sea ice increases that counter the overall Southern Ocean reduction during the lowest SIE years (Fig. 2). However, lack of significant
change to other Bellingshausen sector atmospheric parameters (e.g., lack of significant near-surface cooling or evaporation changes) makes it difficult to suggest sea ice variability in this region is a driving factor in governing precipitation variability. Further complicating attribution of sea ice to precipitation change is the fact that precipitation magnitude and its interannual variability are strongly coupled across space in Antarctica, with both being highest along the Antarctic coast (Fyke et al. 2017). Thus, the SMB signal (i.e., precipitation increase from sea ice reductions) is difficult to assess in observations given both large magnitudes and variability in precipitation from year to year across the coastal AIS (e.g., Turner et al. 2019; Donat-Magnin et al. 2020).

b. CESM2-simulated sea ice–SMB links

1) EVALUATING THE REDUCTION OF SEA ICE IN CESM2 SIMULATIONS

The above-described analyses provide an important observational basis for sea ice–atmosphere–SMB links, but ultimately cannot provide causal attribution of anomalies in any atmospheric parameter to sea ice change alone. Given this, we turn now to idealized atmosphere-only simulations of CESM2 in which the atmospheric and SMB response to sea ice reductions can be isolated. The CESM2 ensemble analyzed here compares higher and lower sea ice scenarios (“pre-industrial” and “future”, respectively), prescribed following the PAMIP experimental protocol (Smith et al. 2019; section 2b). Figure 6a shows the annual cycle in the two scenarios and the five highest and lowest observed SIE years from ERA5 (i.e., Fig. 2). This comparison reveals the CESM2 simulations well represent the observed asymmetric seasonal cycle (Roach et al. 2022). While these scenarios represent more extreme sea ice reductions than observed over the satellite era (Fig. 6b), sea ice in the “future” scenario lies well within the range of recently observed sea ice variability. As such, the absolute reduction in sea ice extent and concentration in the “future” scenario is modest in comparison to what might be expected occur over the twenty-first century. Overall, mean seasonal reductions in PAMIP and the ERA5 end members are nearly identical in autumn (MAM) at $-23.5\%$, and similar for summer (DJF: $32\%$ and $25\%$ in PAMIP and ERA5, respectively). In winter and spring, however, PAMIP Antarctic-wide SIE reductions exceed those in the extreme observed years by about $10\%$ ($16\%$–$17\%$ reductions for PAMIP compared to $4\%$–$7\%$ in the observations).

Whereas the lowest recent Antarctic-wide SIE years show a great deal of spatial and seasonal variability, with notable increases in the Bellingshausen Sea (Fig. 2), sea ice is exclusively reduced in the future PAMIP scenarios (Fig. 6c). In summer and autumn, the largest reductions occur in the Amundsen Sea, while more widespread reductions exceeding $20\%$ occur in winter and spring. These more uniform and larger reductions provide the opportunity to assess the degree to which potential future sea ice reductions may impact the high-latitude atmosphere and AIS SMB.

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**Fig. 5.** Seasonal anomalies in ERA5 (a) evaporation and (b) precipitation in extreme low vs high sea ice extent years over the satellite era. Outlined/hatched areas indicate where anomalies exceed interannual variability (i.e., 1 standard deviation from the long-term mean). Stippled areas indicate where significant declines in sea ice are observed (from Fig. 2).
2) ATMOSPHERIC AND ENERGY FLUX RESPONSE TO IMPOSED SEA ICE DECLINE

The CESM2 simulations show significant positive anomalies in near-surface air temperature in response to imposed sea ice reductions (Fig. 7). This warming occurs in all seasons, though it is particularly pronounced in autumn (MAM) and winter (JJA) with temperature anomalies locally exceeding 10°C in areas overlying and southward of larger magnitude (i.e., >15%) reductions in SIC. In summer (DJF), comparatively weak warming (mostly <2°C) is simulated and less spatial coherence exists between localized warming and the larger magnitude sea ice reductions. In all seasons, significant warming extends inland over the AIS, although this is particularly pronounced in autumn and winter. In austral spring (SON), a weak but significant cooling up to −2°C is simulated over the East Antarctic plateau, largely mirroring the cold anomaly observed in spring in the lowest sea ice years (Fig. 3).

Given the similarly pronounced nonsummer atmospheric responses to sea ice reductions as found in ERA5, we first focus on contrasts between the summer and winter atmospheric response to sea ice reductions in CESM2 (Fig. 8). Again, we find a far more muted and variable atmosphere response in summer, with the largest and most spatially extensive (though relatively low magnitude) changes being to the surface specific humidity (Fig. 8). In contrast, a much larger response exists in winter, with large increases surface specific humidity, cloud liquid water content, and corresponding increases in downward longwave radiation occurring in regional hot spots of sea ice reductions including the western Amundsen Sea and eastern Ross Sea. In contrast, the sign and significance of the total cloud cover response to sea ice reductions is spatially variable. This analysis also reveals a sharp contrast in nonsummer cloud liquid water path anomalies, with strongly positive anomalies over reduced sea ice bordered by negative anomalies in liquid-bearing clouds to the north of the sea ice edge.

Figure 9 shows how the SEB and its components change in CESM2 in response to sea ice reductions (analogous to Fig. 4 for ERA5). In summer, the largest change is to net shortwave radiation, as high-albedo sea ice is replaced by a lower-albedo,
less-ice-concentrated ocean surface. This sea ice reduction therefore results in a widespread, large, and significant addition of energy into the surface ocean that is not compensated by the only weakly negative anomalies in other energy flux components resulting from sea ice loss.

The largest and most spatially explicit winter anomalies are for the turbulent fluxes of sensible and latent heat (SHF and LHF, respectively), given negligible incident solar radiation (Fig. 9). Negative turbulent flux anomalies clearly align with areas of reduced wintertime sea ice and indicate increased ocean to atmosphere heat release. Physically, these fluxes represent increased evaporation from the more-open ocean surface (i.e., a process that extracts latent heat from the ocean surface) and a relatively warmer ocean surface compared to the near-surface atmosphere, thus extracting sensible heat from the ocean. Northward of the sea ice edge in winter, the opposite is true: significant positive anomalies in the turbulent heat fluxes indicate atmosphere to ocean heat input (i.e., decreases in evaporation and a reduced air–sea temperature difference). Turbulent heat loss from the ocean in areas of sea ice decline and turbulent heat addition to the ocean beyond the ice edge dominate the total SEB anomaly in winter and this heat loss in regions of sea ice decline likely explains the pronounced near surface atmospheric warming in winter and the lack thereof in summer (Fig. 7).

![Figure 7](image-url)
The influence of sea ice can be seen in net longwave anomalies during winter, though at a smaller magnitude (Fig. 9). While most of the Southern Ocean during winter experiences greater downwelling longwave radiation from the more humid and liquid-bearing cloud-containing atmosphere (Fig. 8), the sign of net longwave anomalies varies regionally. For example, areas of strong sea ice loss experience a negative net longwave flux, indicating upward longwave fluxes from a warmer and broadly more ice-free ocean surface more than compensate for increase downward fluxes. In contrast, upward longwave radiative losses are suppressed in areas of sea ice persistence in the Ross Sea and eastern Weddell Sea, and consequently, these areas experience positive net longwave anomalies (Fig. 9).

In stark contrast to the large changes in the SEB and its components over the ocean, there is relatively little SEB change over the grounded AIS or its ice shelves (Fig. 9). In fact, during summer when surface melt is seasonally greatest,
total SEB anomalies are generally weak or negative, except for some ice shelves in Wilkes Land, East Antarctica. This suggests that sea ice variability may have only a weak radiative influence on surface melting, a finding also supported by ERA5 SEB anomalies during high and low sea ice states (Fig. 4).

3) CIRCULATION AND WIND RESPONSES TO IMPOSED SEA ICE DECLINE

Figure 10 explores the seasonal mean sea level pressure (MSLP) response to imposed sea ice reductions in CESM2. The MSLP response is zonally asymmetric, which is supported by no significant change to the Southern Annular Mode (Fig. S3 in the online supplemental material). There is also a general lack of a clear sea ice forcing of MSLP anomalies. That is, areas of heightened sea ice reduction do not always correspond to areas of significant MSLP change. The most notable exception to this appears in autumn (MAM), where sea ice reductions in the eastern Weddell Sea, coastal Indian Ocean sector, and western Ross Sea are associated with significant reduction in MSLP (Fig. 10). This pattern suggests a thermodynamic “heat low” response, whereby the warmer, reduced ice ocean surface warms the overlying air, making it
less dense and more buoyant, thus lowering MSLP (Ringgaard et al. 2020; Smith et al. 2022; Ayres et al. 2022). Negative MSLP anomalies in areas of sea ice reduction across the Weddell Sea similarly exist in winter (JJA) and spring (SON), and while this MSLP reduction also exists in summer (DJF), it is not the site of large decreases in summer sea ice (Fig. 10). Of all seasons, the largest MSLP anomalies occur in winter (JJA; Fig. 10). This season is marked by significant positive MSLP anomalies over the AIS, with a particularly prominent increase over the Antarctic Peninsula. A similarly strong positive MSLP anomaly occurs over the easternmost Indian Ocean sector in winter.

The large positive MSLP anomalies found during winter project onto the negative phase of SAM (i.e., a reduction in mid-to-high southern latitude MSLP gradient), and indeed are associated with significant weakening of 500-hPa zonal winds surrounding Antarctica (Fig. S3 in the online supplemental material). However, because the weakening of the midtroposphere westerly jet in winter is also driven by deeper MSLP in the Weddell and central/western Indian Ocean sectors offshore East Antarctica, there is no robust winter SAM response (Fig. S3). In fact, there is no significant change to SAM in any season (Fig. S3) given the nonzonal symmetric MSLP response (Fig. 10). This finding contrasts with England et al. (2018), who found more zonally symmetric changes to the midtroposphere westerly wind field in CESM1-WACCM, but are mostly in agreement with the regionally distinct MSLP response found in atmosphere-only experiments of HadGEM3 (Ayres et al. 2022). Since MSLP anomalies offshore West Antarctica are largely insignificant (Fig. 10), we also find no significant change in either the strength or position of the Amundsen Sea low (Fig. S4 in the online supplemental material).

4) IMPACTS OF IMPOSED SEA ICE DECLINE ON ICE SHEET SMB

The above-discussed MSLP anomalies have direct implications for heat and moisture advection to the AIS. For example, high pressure anomalies over the Antarctic Peninsula are known to enhance extreme moisture intrusions into West Antarctica (Maclennan and Lenaerts 2021). Indeed, anomalies in the meridional component of integrated vapor transport (vIVT) indicate significant poleward moisture transport into West Antarctica (Fig. S5 in the online supplemental material), and thus, pressure-driven wind changes readily advect the enhanced moisture generated over the Southern Ocean toward the AIS. Similarly, wintertime positive MSLP anomalies in the easternmost Indian Ocean sector combined with deepening MSLP over the central and western Indian Ocean sector (Fig. 10) promote enhanced northerly winds around 120°E and heat and moisture advection toward the Wilkes Land sector of East Antarctica (Fig. S5). Lower magnitude, but significant, positive anomalies in poleward vIVT also occur on the eastern flank of areas of reduced MSLP over the Weddell Sea in summer, autumn, and spring (Fig. S5). Conversely, the Weddell sector of the AIS is a site of increased vapor transport export from Antarctica, especially in nonsummer seasons (Fig. S5) resulting from lower MSLP over the Weddell Sea and higher MSLP over the Antarctic Peninsula (Fig. 10).

Figure 11 examines SMB anomalies. Negative anomalies (brown colors) exist broadly across the Southern Ocean and are especially pronounced during nonsummer seasons over areas of strong sea ice decline. These areas represent locations where increases in evaporation exceed increases in precipitation, and thus where there is a net addition of moisture to the atmosphere in response to sea ice decline. We note that similar patterns are observed in ERA5 evaporation in response to sea ice reductions, especially in autumn and winter (Fig. 5a).

Significant positive anomalies (greens), where increases in precipitation are the dominant change between high and low sea ice states, are also seen over the Southern Ocean. These positive water budget anomalies primarily exist equatorward of the sea ice edge and largely reflect northward flow from the western flank of climatological low pressure centers (e.g., the Ross–Amundsen and Weddell–Indian Ocean sectors). In these circulation systems, the enhanced evaporation occurring in regions of sea ice loss is converted to increased precipitation over the open ocean.

Over the AIS, the strongest and most significant positive SMB signals occur in autumn (MAM) and winter (JJA) and exist on the southeastward side of the climatological low pressures in central West Antarctica, Dronning Maud Land, and Wilkes Land. Offshore of these regions, especially in West Antarctica, are prominent negative anomalies (i.e., evaporation increases) in areas of substantial sea ice decline. This enhanced evaporation is then readily advected toward the ice sheet, resulting in locally significant precipitation increases and associated mass gains over the ice sheet. We note that remarkably similar evaporation and precipitation anomalies are observed when comparing end-member sea ice years in ERA5 (Fig. 5). Largely in response to the general deepening of MSLP in the Weddell sector of the Southern Ocean (Fig. 10) and the corresponding northward vIVT flux (Fig. S5 in the online supplemental material), a drying of the western Weddell sector of the ice sheet occurs. In this region situated over the Filchner ice shelf and eastward, locally significant negative SMB anomalies occur. Since precipitation is the dominant SMB term, this means less precipitation occurs across this region resulting in a relative SMB loss during the future lower sea ice scenario.

AIS-wide and regional SMB anomalies are shown in Table 1. For the AIS as a whole, a mean increase of 60.3 Gt yr⁻¹ is simulated by CESM2 in response to the imposed sea ice declines. This represents a 1.3% increase over the mean AIS-wide SMB (i.e., including floating ice shelves) from the preindustrial ensemble members (3138 Gt yr⁻¹). The largest changes to SMB are observed over West Antarctica in autumn (MAM) and winter (JJA). Given roughly compensating negative and positive SMB anomalies across the entire year for the East Antarctic basins, the annual SMB anomaly for the AIS is dominated by the mass gain across West Antarctica. Seasonally, SMB anomalies are uniformly negative in summer (DJF) and positive in spring (MAM) across the assessed sectors. During other seasons, mass
gains and losses partially compensate one another across different regions.

For the AIS and individual regions, SMB anomalies lie within the standard deviation of SMB simulated across the 100 preindustrial ensemble members. As such, we consider these SMB anomalies at the ice sheet and broad regional scale to be within the range of simulated natural variability. However, it is clear from Fig. 11 that locally significant SMB anomalies exist that are most highly concentrated in coastal regions. Likewise, these anomalies represent a large fraction of the present-day mass imbalance across West Antarctica, and thus hold important implications for total ice sheet mass balance, as discussed below (section 4).

In response to sea ice loss, surface melt weakly increases across most Antarctic ice shelves and coastal regions (Fig. S6 in the online supplemental material). This is a result of only modest warming that occurs during summer months (Fig. 7; Fig. S6b) and little change to the SEB over the ice sheet (Fig. 9), leading to all melt changes being insignificant at the $p < 0.05$ confidence interval. To place the melt increases into context, comparison with contemporary melt rates simulated by the regional climate–snowpack model RACMO2.3p2 forced by ERA5 reveals that...
melt increases represent a large percent of the annual meltwater production that presently occurs on the AIS (Fig. 5c). For example, parameterized melt increases in response to sea ice loss across some areas of the Ross Ice Shelf and extending inland to West Antarctica are double or greater than the present-day annual melt rates. Considering relatively small melt increases (Fig. 5a) alongside much larger increases in precipitation (Fig. 11), it is unlikely these melt increases would produce runoff. Thus, the dominant SMB signal in response to the imposed sea ice decreases is clearly one of mass gain.

4. Discussion

This research focuses on exploring anomalies in the Southern Ocean atmosphere in response to high and low sea ice states and the impact of these on AIS SMB. A remarkably similar response is found in both the extreme end-member years of Southern Ocean–wide sea ice using ERA5 and in the CESM2 simulations with imposed sea ice reductions. Namely, disproportionate atmospheric responses are found in nonsummer seasons, particularly in autumn and winter, and are characterized by warmer near-surface air temperatures (Figs. 3 and 7), large upward fluxes of turbulent heat (Figs. 4 and 9), and enhanced evaporation in areas of sea ice reduction (Figs. 5a and 11). Our ERA5 findings suggest that increased absorption of shortwave radiation in the ice-reduced summertime ocean surface may be subsequently released as turbulent heat from the more open ocean during nonsummer seasons, a phenomenon well known in the Arctic (e.g., Deser et al. 2010; Screen and Simmonds 2010). Similar patterns are seen in the CESM2 simulations, but our atmosphere-only configuration means that the positive wintertime ocean-to-atmosphere heat fluxes solely result from sea ice reductions and not from added heat in other seasons. Thus, a more coupled model may show even larger winter warming if added energy in summer is able to be stored in the ocean and potentially released in subsequent seasons. While the impact of these heat and moisture anomalies on the ice sheet SMB lie mostly within the range of natural variability over the observational era (Fig. 5b), stronger and more uniform reductions in sea ice are imposed in the CESM2 simulations (Fig. 6a), enabling a clearer signal from sea ice reductions. Indeed, a zonal wave 3–like pattern (Raphael 2004) is apparent in SMB anomalies, where locally significant increases in SMB occur on the eastern flank of climatological low pressure systems in West Antarctica, Dronning Maud Land, and Wilkes Land (Fig. 11). These findings, particularly those from the CESM2 sensitivity experiments, provide clear physical evidence that sea ice reductions can directly enhance regional SMB (Fig. 1).

Our reanalysis and CESM2 results showing links between regional sea ice and SMB can also help explain recent trends and variability in Antarctic sea ice and SMB. Namely, the slight declining SMB trends over the 1990s and early 2000s, followed by a positive shift in SMB starting in 2015 and the 2016 SMB that was among the highest of the last 40 years (Mottram et al. 2021), may be at least partially the result of sea ice variability. Indeed, Antarctic sea ice experienced overall positive trends from the late 1970s to 2014, followed by marked declines initiating in 2016 (Parkinson 2019; Meehl et al. 2019; Eayrs et al. 2021). Negative relationships between evaporation and SIC have been quantified using satellite data, alongside negative overall trends in evaporation during the period of sea ice expansion over 2003 to 2016 (Boisvert et al. 2020). These observations are supported by our findings of significant autumn and winter evaporation increases during low sea ice years (Fig. 5a). As such, decreasing Southern Ocean surface evaporation during the observational era (Boisvert et al. 2020) provides a plausible explanation for the contemporaneous slight decreases in AIS SMB (Mottram et al. 2021). By limiting evaporation, our results suggest that increasing sea ice trends over the satellite era have suppressed the SMB of the AIS, thus enhancing its recent contributions to sea level rise.

Given large variability in the coupled ocean–atmosphere–ice sheet systems of the high southern latitudes, particularly across West Antarctica (Turner et al. 2009), attributing change in one component to the dynamics of another is exceedingly difficult. This is true even in coupled climate model simulations. For example, Fyke et al. (2017) showed regional anticorrelations between SMB and sea ice in long CESM1 preindustrial simulations but attributed these to common atmospheric forcing. The simulations explored here, however, in which only sea ice was altered, clearly demonstrate that sea ice itself is an important driver of atmospheric and SMB change. Our results are further supported by other recent modeling work examining the influence of variability in sea surface conditions on the atmosphere in the high southern latitudes. For example, focusing on the climate system response to imposed sea ice loss in the HadGEM2-GC-LL model, Ayres et al. (2022) found similar lower tropospheric warming and moistening over regions of sea ice loss, and that sea ice loss has widespread implications beyond the Antarctic. England et al. (2018) used CESM1-WACCM and found similar warming and precipitation increases in response to sea ice loss as we do here, although the full impacts of these on the AIS SMB were not assessed. In a more comprehensive and
SMB-focused study, Kittel et al. (2018) found significant positive SMB anomalies in response to imposed sea surface temperature increases and SIC decreases in the regional climate model MAR. A key distinction with our study, however, is that atmospheric circulation was not able to dynamically respond to imposed sea surface conditions; thus, for example, the sea level pressure and geopotential height response and associated changes to moisture transport (which we show to be significant; Fig. 10, Figs. S3 and S5 in the online supplemental material) could not be assessed. Nevertheless, this body of model-based research alongside our reanalysis and model results illustrate that sea ice reductions lead to enhanced ocean-surface evaporation, a warmer near-surface atmosphere, and locally significant increases to the AIS SMB.

It is important to note potential limitations associated with atmosphere-only model simulations investigated here. For example, lack of ocean–atmosphere coupling is known to significantly dampen the response to Antarctic sea ice loss (e.g., Ayres et al. 2022; England et al. 2020). SMB increases resulting from sea ice decline may therefore be larger than quantified here, for example if additional warming and precipitation increases were to occur as observed in coupled simulations (e.g., Ayres et al. 2022). On the other hand, both atmosphere-only and ocean-atmosphere coupled models neglect important ice sheet–ocean–atmosphere interactions with potential implications for ocean circulation and near-surface climate in the Antarctic. Golledge et al. (2019), for example, found that future basal melting of ice shelves leads to ocean surface freshening in a positive melt feedback that cools the high southern latitude atmosphere and ocean surface. Sea ice loss itself could result in enhanced ocean stratification (Ayres et al. 2022), with potential impacts on AIS mass balance. A more thorough examination of the role of sea ice in AIS mass balance would therefore result from assessment of coupled ocean–atmosphere and ice sheet–ocean–atmosphere models.

Given disproportionate warming that occurs in nonsummer months, both in ERA5 (Fig. 3) and CESM2 (Fig. 7), the largest and most significant SMB impact is that to precipitation rather than surface melting. We note as well that melt projections here are parameterized based on air temperature and thus neglect the potentially melt-suppressing impact of enhanced snow accumulation altering the SEB by increasing surface albedo. Nevertheless, a similar study focusing on the Greenland ice sheet that calculated melt based on constraining the SEB found large melt increases in response to Arctic sea ice loss (Sellevold et al. 2022). Likewise, Kittel et al. (2018) found significant Antarctic surface melt increases resulting from larger imposed sea ice declines and sea surface temperature increases. Furthermore, it is important to recognize that our analysis here is one without transient anthropogenic radiative forcing. In the future, Antarctic sea ice is projected to decline (Roach et al. 2020) in tandem with anthropogenically driven near-surface atmospheric warming (Bracegirdle et al. 2020). And as such, a relatively modest summertime warming in direct response to sea ice reductions (e.g., Fig. 7) would superimpose upon a broader atmospheric warming signal. Given melt-temperature nonlinearity (Trusel et al. 2015, 2018) and the importance of the melt–albedo feedback across Antarctica (Jakobs et al. 2021)—wherein melting can trigger a positive feedback that both sustains and intensifies and annual meltwater production—even moderate warming resulting from sea ice loss could hold important implications for melt, SMB, and ice shelf evolution.

Sea ice–induced positive SMB anomalies found here represent a large fraction of the mass that is currently lost through ice discharge to the ocean. For example, the 60 Gt yr\(^{-1}\) positive SMB anomaly in response to reduced sea ice across the West Antarctic sectors (Table 1) equates to about 45% of the recent annual mass lost via discharge from West Antarctica (\(\sim 132\) Gt yr\(^{-1}\) over 2009–17; Rignot et al. 2019). Likewise, our estimated mass gain via enhanced snowfall over the Wilkes Land (western Pacific) sector of \(\sim 9\) Gt yr\(^{-1}\) equates to about one-quarter of the recent discharge from this region (\(\sim 37\) Gt yr\(^{-1}\); Rignot et al. 2019). An AIS-wide 60 Gt yr\(^{-1}\) mass gain would equate to 40% of the annual GRACE-observed mass imbalance since 2002 (Wiese et al. 2019), underscoring the importance of regionally significant mass anomalies in response to sea ice variability. While the relative sea ice declines assessed here are larger than recently observed, sea ice coverage in our “future” scenario closely aligns with satellite-era sea ice extent (Fig. 6a). As a result, larger future declines in sea ice (e.g., Roach et al. 2020) may produce even larger snowfall increases across the AIS. Another important consideration is that the mass gain in response to sea ice loss is not spatially uniform (Fig. 11). Enhanced snowfall in response to future sea ice decline may therefore hold implications for ice dynamics via altering gravitational driving stresses (e.g., Scott et al. 2009), which should be more fully assessed using higher spatial resolution climate models able to better resolve coastal elevation gradients and numerical ice flow models. Nevertheless, with future declines in Antarctic sea ice, an expected response should be regional increases in snowfall that at least partially compensate dynamic-driven mass losses.

5. Conclusions

This research underscores that accurate simulation of the near-surface climate and SMB of the AIS relies on a realistic representation of the ocean surface surrounding the continent. Namely, findings here suggest that systematic underestimation of sea ice in coupled climate models (Bracegirdle et al. 2015; Roach et al. 2020) may result in overestimation of precipitation across the ice sheet, and thus an underestimation of future AIS contributions to global sea level. Likewise, satellite-era increases in Antarctic sea ice have likely reduced precipitation across the AIS, enhancing its recent contributions to global sea level rise. On the other hand, negative sea ice biases in models would likely enhance surface melt. As leading coordinated ice sheet modeling experiments impose ice shelf collapse timing based on surface melt parameterized from GCM near-surface air temperatures (Nowicki et al. 2020), model biases in sea ice hold important implications for understanding the timing and magnitude of ice sheet mass loss resulting from ice shelf collapse. Clearly, these results indicate that understanding the causes of biases in the model...
representation of Antarctic sea ice are of paramount importance to reducing uncertainty in Antarctic sea level projections.

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Data availability statement. ERA5 data are available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). CESM2 data are available from the Earth System Grid (https://esgf.llnl.gov/).

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