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## Observed and projected trends in Antarctic sea ice

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Antarctic sea ice extent has increased over the ~36-year satellite record, in striking contrast to the observed decline of the Arctic sea ice cover over this period (e.g., Parkinson and Cavalieri 2012). Concurrent with Antarctic sea ice expansion has been an overall cooling of the Southern Ocean surface. These trends may seem at odds with greenhouse gas-induced warming over recent decades and, disconcertingly, are not reproduced by the historical simulations of comprehensive global climate models (e.g., Turner et al. 2013; Hobbs et al. 2015). Here,

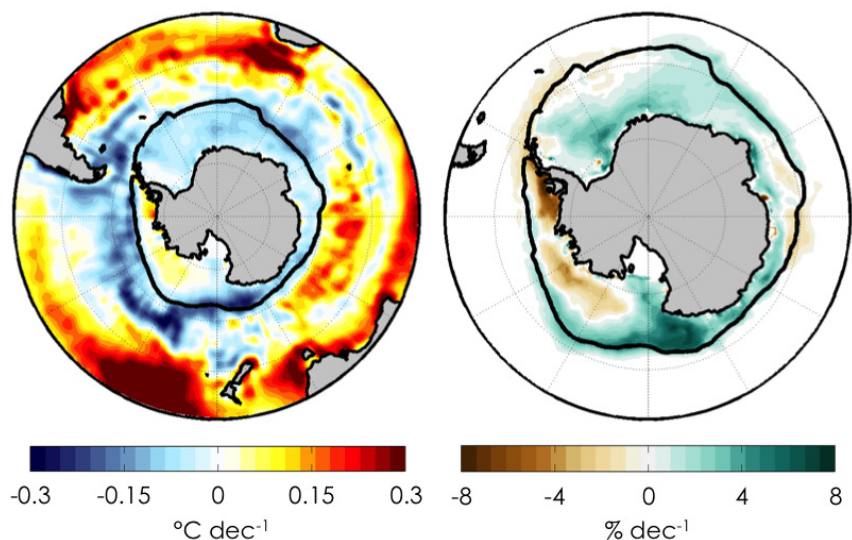
we review the recent progress toward understanding the response of the Southern Ocean to climate forcing, and argue that the community's results are converging on a solution to the apparent conundrum of Antarctic sea ice expansion. We propose that while a variety of different factors may have contributed to Southern Ocean changes over recent decades, it is large-scale atmospheric circulation changes—and the changes in ocean circulation they induce—that have emerged as the most likely cause of the observed Antarctic sea ice trends.

**Observations of recent Southern Ocean change**

Before we delve into the possible mechanisms driving recent Southern Ocean changes, we want to describe the observations in more detail to establish a baseline that any such mechanisms must explain. Figure 1 shows sea ice concentration and sea-surface temperature (SST) trends over the era of continuous satellite observations (1979-present). While both fields show regions of increasing and decreasing trends over this period, the total sea ice extent has increased, and SSTs have largely cooled, south of the Antarctic Circumpolar Current (ACC). Notable exceptions are the regions of decreasing sea ice concentration in the Amundsen and Bellingshausen Seas, which overlie increasing SSTs—though we note that the sign of the trends in these regions has changed after about year 2000 (not shown). Although the patterns of trends in sea ice concentration and SST vary with season, the association between sea ice and SST generally prevails in every season and region (we show only the annual means here for brevity and because the signal to noise is greater than in the seasonal means). Further, we see that the spatial patterns of sea ice trends are closely mirrored by trends in SSTs that extend beyond the sea ice edge over a much larger area of the ocean—typically out to the southern flank of the ACC.

Taking a cue from Fan et al. (2014), we see that this tight relationship between total sea ice extent and Southern Ocean SSTs (south of 50°S, the approximate latitude of the ACC) appears to hold over a much longer observational period as well (Figure 2). The sea ice cover in September of 1964 (recently recovered from the Nimbus I satellite by Meier et al. 2013) was more expansive than at any

time since the start of the continuous record from passive microwave satellites— consistent with Southern Ocean SSTs that were at or near their coldest levels. In the early 1970s, an early microwave satellite and the Navy-NOAA ice charts indicated the sea ice was in between the extent in 1964 and post 1979 (see e.g., Kukla and Gavin 198; Zwally et al. 1983). Overall, the Southern Ocean has warmed slowly (by ~0.02 per decade south of 50°S) relative to the global ocean (~0.08 per decade) since 1950. The spatial



**Figure 1.** Linear trends of annual-mean SST (left) and annual-mean sea ice concentration (right) over 1980-2014. Sea-surface temperature is from NOAA’s Optimum Interpolation Sea Surface Temperature dataset (version 2; Reynolds et al. 2002). Sea ice concentration is from passive microwave observations using the NASA Team algorithm ([https://nsidc.org/data/seaice\\_index/archives.html](https://nsidc.org/data/seaice_index/archives.html)).

and temporal relationships in Figures 1 and 2 imply that Antarctic sea ice trends should be viewed in the broader context of trends over the whole of the Southern Ocean, and that trends in sea ice and SSTs likely share some common driving mechanisms. That is, a key constraint on any mechanism proposed to drive the observed Southern Ocean changes is that it must allow for both the characteristics of sea ice trends and the coincident patterns of large-scale SST trends, simultaneously.

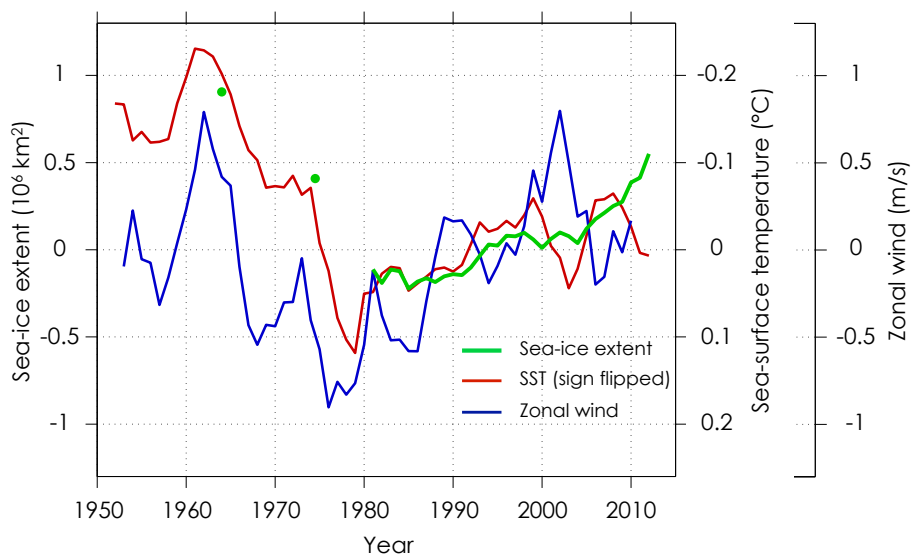
In light of the above observations, we organize the rest of our discussion around several guiding questions, which we see as relating to distinct physical mechanisms that have, together, acted to produce the observed Southern Ocean trends.

**Mechanisms of delayed Southern Ocean warming**

Why has the Southern Ocean been so slow to warm over the 20th century (Figure 2), relative to the global ocean and the Arctic? Recent work suggests that the primary cause of delayed surface warming is the mean divergence of seawater at the Southern Ocean surface, which is then refreshed (or buffered) by the upwelling of unmodified water from depth (Marshall et al. 2014a,b; Armour et al. submitted); hence the majority of heat taken up at the Southern Ocean surface is diverged with the mean circulation to the north, and, to a lesser extent, downward along the Antarctic continental shelf. A secondary source of delayed warming is reduced surface buoyancy loss owing to a combination of increased downward heat flux, increased precipitation minus evaporation, and reduced sea ice growth near Antarctica—each acting to increase upper ocean stratification and inhibit convection and vertical mixing, in turn reducing the upward flux of heat from warmer waters at depth (Manabe et al. 1991; Russell and Rind 1999; Gregory 2000; Kirkman and Bitz 2011).

Global climate models (GCMs) robustly simulate much slower warming and less sea ice loss over the Southern Ocean than in the Arctic under global warming (e.g., Manabe et al. 1991; Stouffer 2004; Kirkman and Bitz 2011; Li et al. 2012; Marshall et al. 2014a,b). Within GCM

simulations, delayed warming of the Southern Ocean surface is seen to be a fundamental response of the ocean to anomalous surface heat and freshwater fluxes induced by greenhouse forcing. We argue that because this response is broadly consistent with observations (Armour et al. submitted), climate models seem to be adequately representing the above mechanisms of delayed Southern Ocean warming. Importantly, it is against this background of very gradual warming—rather than the rapid warming seen in the Arctic—that the mechanisms of Southern Ocean surface cooling and sea ice expansion must be understood and evaluated.



**Figure 2.** Time-series of anomalies in the total annual-mean Antarctic sea ice extent, annual-mean Southern Ocean SST (averaged south of 50°S), and DJF (December-January-February) zonal-mean zonal wind over 50-70°S. The sea ice extent in 1964 is the September 1964 anomaly from the Nimbus 1 satellite (Meier et al. 2013). The sea ice extent in 1974 is an average of 1973-1976 from the electrically scanning microwave radiometer ([https://nsidc.org/data/smmr\\_ssmi\\_ancillary/area\\_extent.html](https://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html)) and the Navy-NOAA Joint Ice Charts (Ropelewski, 1983). The sea ice extent from 1979 and onward is from passive microwave observations using the NASA Team algorithm ([https://nsidc.org/data/seaice\\_index/archives.html](https://nsidc.org/data/seaice_index/archives.html)); SST is from NOAA's Extended Reconstruction Sea-Surface Temperature dataset (version 3b; Smith et al. 2008); and zonal wind data was provided by D. Schneider from the study of Fan et al. (2014). All anomalies are taken with respect to their 1980-2010 means.

### Mechanisms of Southern Ocean surface cooling and sea ice expansion

What has driven the apparent variation in Southern Ocean conditions about this gradual warming trend (Figure 2), and what has driven the recent period of surface cooling and sea ice expansion (Figure 1) in particular? One possible cause of sea ice expansion is increased freshwater input to the ocean from Antarctic ice loss (Bintanja et al. 2013)—primarily from basal melt of ice shelves—which could act to cool the sea surface via increased stratification and decreased deep ocean convection as described above. However, Pauling et al. (submitted) point out that best estimates of the current mass imbalance of Antarctica's ice sheet and shelves is at most about one-fifth the magnitude of the present-day anomaly in precipitation minus evaporation south of 50°S, relative to preindustrial, as simulated by climate models. Indeed, Liu and Curry (2010) argue that this increase in precipitation is responsible for sea ice expansion, but the question remains as to why climate models do not reproduce the observations given that they do robustly simulate increased precipitation over the Southern Ocean.

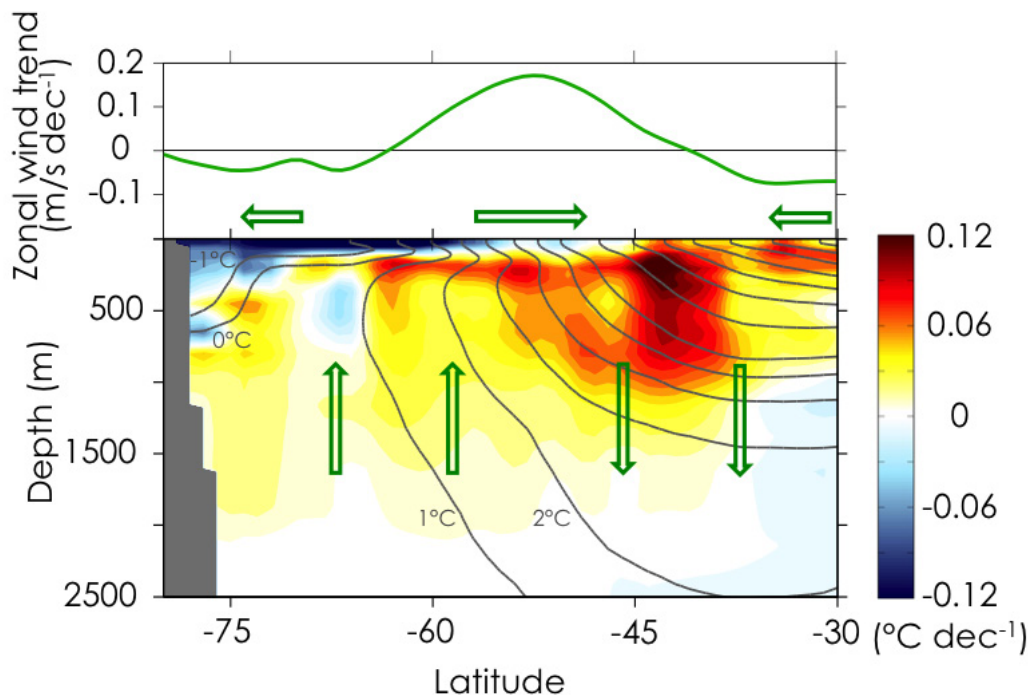
Moreover, both Swart and Fyfe (2013) and Pauling et al. (submitted) find that enhanced freshwater input to the Southern Ocean does not cause significant sea ice expansion within their simulations—even when the magnitude of freshwater flux far exceeds that applied by Bintanja et al. (2013). One important factor in the sea ice response to freshwater forcing may be the degree to which the Southern Ocean is deeply convecting. Based on the findings of Swart and Fyfe (2013) and Pauling et al. (submitted), we speculate that models that show little deep Southern Ocean convection over recent decades—consistent with observations (e.g., de Lavergne et al. 2014)—would also show little sensitivity to increased freshwater input from Antarctica. Altogether, these studies suggest that freshwater forcing is not the primary cause of the observed sea ice expansion.

Perhaps the most substantial Southern Hemispheric climate signal has been the strengthening and poleward

shift of westerly winds since the late 1970s (Figure 2). This trend—often characterized as a strengthening of the Southern Annular Mode (SAM)—is thought to be primarily driven by stratospheric ozone depletion (Polvani et al. 2011a), but may also reflect natural variability (Deser et al. 2012; Thomas et al. 2015). As noted by Thompson et al. (2011), the observed correlation between SAM and SSTs on interannual timescales—wherein a strongly positive SAM is correlated with Southern Ocean surface cooling—suggests that the trend in SAM may be responsible for the observed SST and sea ice trends.

Yet, GCMs have thus far been unable to reproduce this proposed connection—perhaps, in part, due to the fact that their historical westerly wind trends are typically too weak, lack the correct seasonality, or lack the correct spatial patterns compared to the observed (Swart and Fyfe 2012; Haumann et al. 2014). This discrepancy between observed and simulated wind trends is plausibly due to a combination of (i) errors in the prescribed (or simulated) magnitude, spatial pattern (Vaughan et al. 2009), or temporal resolution (Neely et al. 2014) of stratospheric ozone depletion and (ii) natural variability in SAM (Deser et al. 2012; Thomas et al. 2015).

Further complicating matters, climate models tend to show *enhanced* Southern Ocean surface warming and sea ice loss in response to ozone depletion (Sigmond and Fyfe 2010; Bitz and Polvani 2012; Smith et al. 2012; Sigmond and Fyfe 2014; Haumann et al. 2014). Clarification on this front can be gleaned from the results of Ferreira et al. (2015), who showed that two opposing sea ice trends should be expected in response to a strengthening of westerly winds: the immediate response is enhanced Ekman advection of surface waters, which transports colder waters northward and drives surface cooling south of the ACC; the longer-term response is upwelling of relative warm waters to the surface from depth, induced by anomalous wind-driven divergence of surface waters south of the maximum wind anomaly, as shown in Figure 3. Thus, while the initial response to a strengthening of westerly winds is that of surface cooling and sea ice expansion, the long-term response is that of surface warming and sea ice loss.



**Figure 3.** Trends in annual, zonal-mean ocean potential temperature and zonal-mean zonal winds over 1980-2014. Black lines are contours of the climatological zonal-mean mean ocean temperature averaged over 1980-2014. Green arrows are a schematic representation of the approximate ocean circulation that has been induced by the westerly wind trends. Generally the ocean temperature trends can be linked to anomalous advection of the ocean mean state temperature by these anomalous currents. The wind trends have driven anomalous northward surface currents that transport relatively cold waters to the north, driving surface cooling south of  $\sim 45^{\circ}\text{S}$ . The wind trends have further driven anomalous divergence at the ocean surface, and hence anomalous upwelling, south of  $\sim 55^{\circ}\text{S}$ ; over much of this region, ocean temperature increases with depth, so this amounts to enhanced upwelling of relatively warm waters. North of about  $\sim 55^{\circ}\text{S}$ , the winds have driven anomalous convergence, and the subsurface flow appears to be that of enhanced subduction. The annual and zonal-mean winds trends are from ERA-Interim (Dee et al. 2011).

The timescale at which the upper ocean transitions from the fast surface cooling to the eventual warming in response to westerly wind forcing is of critical importance to sea ice trends (Marshall et al. 2014b). Yet, it differed markedly between the two models analyzed in Ferreira et al. (2015), with the comprehensive climate model in their study transitioning over just a few years, and the more idealized model transitioning over decades. The timescale appears to be largely set by the climatological meridional temperature gradient at the ocean surface, which governs the magnitude of the initial cooling, and by

the temperature gradient between the sea surface and deep ocean, which governs the rate of slow warming (Ferreira et al. 2015).

It is not known what the Southern Ocean response to westerly wind trends should be, but following Fan et al. (2014) we can look to the observations since 1950 as a guide (Figure 2). As noted above, Southern Ocean SSTs have decreased concurrently with an increase in zonal-mean westerly winds since  $\sim 1980$ . While the wind data are sparse (see Fan et al. 2014), the time-series of zonal-mean wind shows an intriguingly strong *decrease* in strength from about 1950 to 1980, concurrent with a significant increase in SSTs and decrease in sea ice extent from 1964 to the beginning of the satellite era. We view

these observations as strong evidence that the observed trends in Southern Ocean sea ice and SSTs since 1950 have been primarily driven by changes in atmospheric circulation.

These results further lead us to speculate that it may be biases in the ocean components of comprehensive climate models that are the main reason they exhibit Southern Ocean warming and sea ice loss in response to ozone depletion, which is at odds with the observed trends over recent decades. We suggest that a strong



test of this mechanism would thus be the simulation of stratospheric ozone depletion within those climate models that accurately simulate the observed Southern Ocean mean state (i.e., the climatological temperature gradients in Figure 3).

Another suggestion is that the recent sea ice expansion can be explained by natural variability alone, based on GCM simulations (Polvani and Smith 2013; Zunz et al. 2013; Mahlstein et al. 2013). Yet, much of the natural variability of Southern Ocean sea ice extent in models is driven by changes in the strength of deep ocean convection (e.g., Latif et al. 2013). While variability in deep ocean convection is an intriguing mechanism for sea ice expansion, it seems inconsistent with the observations, which do not appear to reflect such changes over the satellite era. However, the possibility remains that natural variability has contributed substantial westerly wind trends over recent decades (Deser et al. 2012; Thomas et al. 2015) and, in turn, to sea ice expansion.

#### **Mechanisms driving the observed local-scale patterns of sea ice change**

What has driven the local-scale patterns of sea ice and SST trends over the satellite era? Holland and Kwok (2012) argue that winds, especially the meridional component, are the principle cause of regional sea ice trends, and that changes in sea ice advection have been a dominant factor in driving the apparent sea ice loss around West Antarctica. Trends in surface winds over the Southern Ocean also impact ocean waves, and an overall decrease in wave heights has been related to a reduction in the breakup of sea ice (Kohout et al. 2014). While local-scale wind and wave forcings appear to be factors in driving the observed pattern of sea ice trends, it is less clear how changes in sea ice motion and breakup can cause concurrent trends in SSTs. One possibility is that sea ice trends are able to modify SSTs through sea ice-ocean feedbacks (Goosse and Zunz 2014). However, such mechanisms do not account for the concurrent trends in Southern Ocean SSTs that extend far beyond the sea ice edge (Figure 1). We thus view these wind and wave height changes as the proximate causes of local-scale patterns

of sea ice change, as opposed to fundamental drivers of sea ice and SST trends over the whole of the Southern Ocean.

Recent changes in atmospheric circulation patterns, and hence winds, over the Southern Ocean have been linked to teleconnections via atmospheric Rossby waves emanating from the tropical Pacific and/or Atlantic (e.g., Ding et al. 2011; Li et al. 2014; Simpkins et al. 2014; Schneider et al. 2015). Many have attributed patterns of warming and cooling in the tropics to natural variability, so perhaps we should not expect GCMs to reproduce the observed patterns of local-scale wind changes over the last few decades. Moreover, even if a simulation should randomly exhibit reasonable tropical variability, the teleconnections to the Antarctic may be poor if the location or strength of the atmospheric subtropical and mid-latitude jets is biased. Indeed, several recent studies have found fault with the ability of CMIP5 models to simulate recent decadal-scale trends in Antarctic circulation features such as the Amundsen-Bellinghousen Seas Low (Hosking et al. 2013). Given these findings, it is perhaps no great surprise that GCMs are unable to capture the local-scale patterns of Antarctic sea ice trends.

#### **What is the future of Antarctic sea ice?**

Given the inconsistencies between observed and simulated trends over recent decades, it is natural to ask, should we trust model projections of Antarctic sea ice over the 21st century? Our answer is: both yes and no. While stratospheric ozone is expected to recover, the westerly winds are likely to continue to increase in strength and shift poleward due to rising greenhouse gases alone (e.g., Kushner et al. 2001; Arblaster et al. 2011), though perhaps at a slower rate than has been observed (Polvani et al. 2011b; Bracegirdle et al. 2013; Barnes et al. 2014). We anticipate that, in time, the dominant effect of westerly wind enhancement will almost certainly be the slow, surface warming response described by Ferreira et al. (2015), which climate models seem able to simulate. Thus, although there is a wide spread in their projections, we believe that climate models are at least simulating the correct sign of the 21<sup>st</sup> century changes: a decline in the

total Antarctic sea ice cover. However, natural variability in large-scale Southern Ocean winds may prove to be an important driver of sea ice trends on timescales of years to decades. Moreover, model deficiencies in simulating the spatial pattern of local wind changes, in combination with substantial variability associated with teleconnections from the tropics, may continue to preclude accurate projections of the regional patterns of sea ice trends for the foreseeable future.

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