# What processes drive Southern Ocean sea ice variability and trends?

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Sea ice in the Southern Ocean exhibits substantial year-to-year variability in addition to a small long-term increase in recent decades (Comiso and Nishio 2008; Eisenman et al. 2014; blue line in Figure 1). The modest increase in Southern Ocean sea ice is a stark contrast to the significant declines in Arctic ice extent seen over the same time period over which global temperature has risen (Serreze et al. 2015). The delayed anthropogenic warming of the Southern Ocean relative to surface temperature increases in other regions is robustly predicted by climate models, and the underlying mechanism is well understood; the energy input to the surface of the Southern Ocean by anthropogenic forcing is transported equatorward by the basic-state ocean overturning circulation as surface water advects northward and is replaced by upwelled water that has not been exposed to the surface since long before the influence of anthropogenic forcing (Armour et al. 2016). Thus, one expects the delayed warming of the Southern Ocean to result in a muted signal of sea ice decline relative to the Arctic that may not be detectable above natural variability. While the observed increase in Southern Ocean sea ice extent is within the range of natural variability simulated by unforced coupled climate models (Polvani and Smith 2013), coupled climate models unanimously simulate Southern Ocean sea ice reductions under current levels of anthropogenic forcing (Turner et al. 2013).

The question remains as to what processes drive the observed year-to-year variability and long-term trends in Southern Ocean sea ice. A myriad of coupled atmosphere/ocean/cryosphere processes have been proposed:

- Stratospheric ozone depletion is leading to sea ice expansion as a result of intensified surface westerlies over the Southern Ocean (Thompson and Solomon 2002), and the associated equatorward Ekman ice transport (Turner et al. 2009) .

- Ozone depletion is leading to sea ice retreat at longer timescales induced by the same enhanced surface westerlies (Bitz and Polvani 2012; Sigmond and Fyfe 2010), due to increased upwelling of warmer subsurface waters (in the salinity stratified Southern Ocean) by Ekman suction (Ferreira et al. 2015).

- Sea ice expansion from reduced interaction between the surface ocean and the subsurface warm waters due to increased ocean stratification as a result of either freshwater discharge from Antarctic glaciers (Bintanja et al. 2013), decreased surface salt input via brine rejection (Zhang 2007), or increased regional precipitation (Liu and Curry 2010).

- Wind changes of unknown origin are altering ice production in regions of anomalous wind convergence (Zhang 2014) and ice drift (Holland and Kwok 2012).

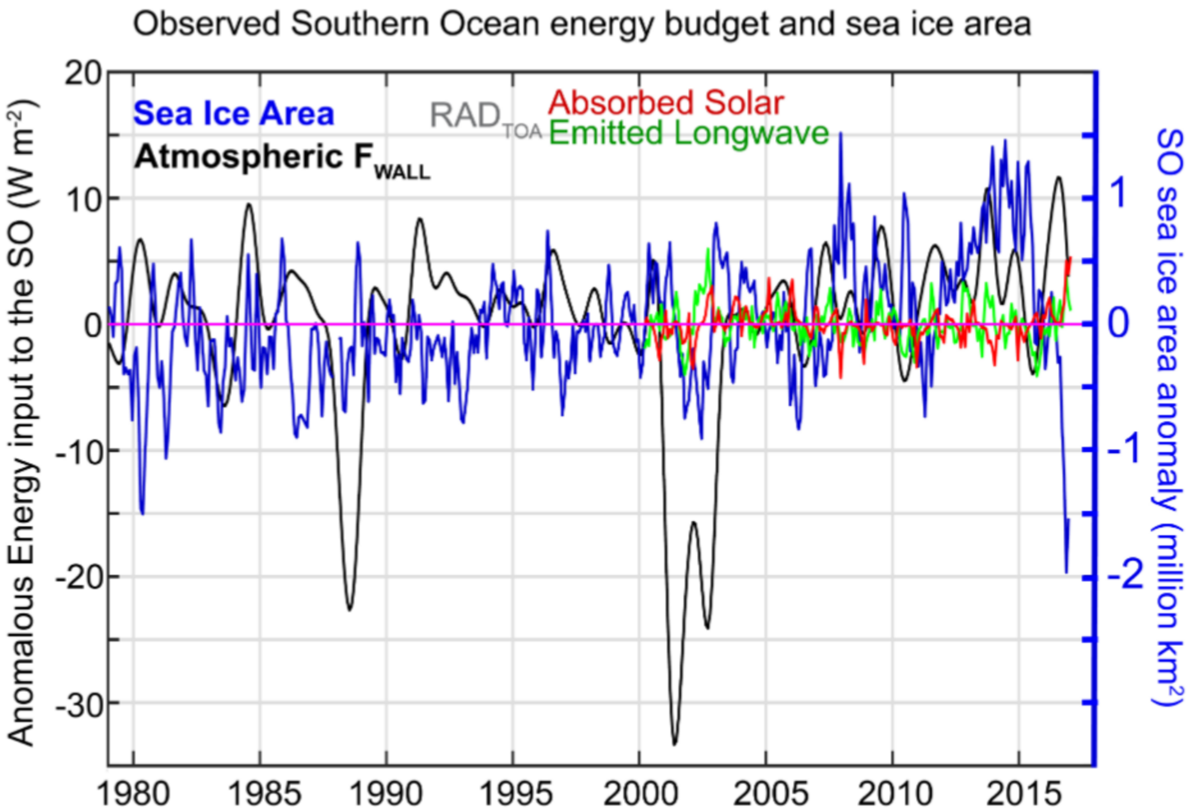


**Figure 1.** Time series of observational based estimates of anomalous Southern Ocean sea ice area (blue – from the National Sea Ice Data center (Fetter and Fowler 2006)) and energy fluxes into the Southern Ocean. The black line shows the $F_{WALL}$ expressed as the resultant average heating over the polar cap in $Wm^{-2}$ (monthly data has been low-pass filtered with a cut off period of 6 months). The anomaly in Southern Ocean average net shortwave radiation at the TOA (red) and outgoing longwave radiation (green) are calculated from CERES (Wielicki et al. 1996) energy balanced and filled data.

Clearly, there is no consensus on a mechanistic understanding of the processes that drive Southern Ocean sea ice variability. Furthermore, much of our understanding of Southern Ocean sea ice variability is borne from the use of coupled model simulations in which the relative roles of ocean circulation, atmospheric circulation, radiative processes, and their mutual interaction with sea ice growth and decay may not represent reality. The modeling of these processes is especially difficult in the Southern Ocean given significant model biases in simulating the mean state properties of the region. Specifically, the thermal stratification of the Southern Ocean (Kostov et al. 2016) and the amount of solar radiation reaching the Southern Ocean's surface (Trenberth and Fasullo 2010) differ drastically between models and are biased relative to the observations. Given the biases in the simulated basic properties of the Southern Ocean in models, the physical processes that drive sea ice variability in coupled models may not occur in nature, while mechanisms that are absent in model simulations may be of central importance to the variability of Southern Ocean sea ice.

## A pathway forward: The energetic signature of Southern Ocean sea ice variability

The growth and decay of Southern Ocean sea ice is influenced by ocean processes, atmospheric circulation, and radiative processes. We argue that the primary driver of sea ice variability can be identified from analysis of the (anomalous) energy budget of the Southern Ocean associated with an ice loss event, as summarized in Figure 2a-c. The energy budget of the Southern Ocean climate system (defined as the region between 55°S and 70°S) is composed of three primary terms: (i) the net radiative input into the top of atmosphere ($RAD_{TOA}$); (ii) the energy flux across the interface between the ocean-sea ice and the atmosphere (SHF) and; (iii) the poleward atmospheric energy flux across into the region ($F_{WALL}$). We now consider the resultant changes in the above energy fluxes associated with three different sequences of events leading to a sea ice loss event (reverse signs for an ice growth event), with each driven by an initial change in a different component of the system:

### *Mechanism One: Ocean Driven Sea Ice Loss*

Changes in ocean dynamics — such as thermal stratification, vertical energy fluxes by enhanced upwelling, or lateral energy fluxes — lead to enhanced energy input to the surface ocean resulting in ice loss (Figure 2a). As a result, the warmed and exposed ocean surface heats the atmosphere via enhanced upward

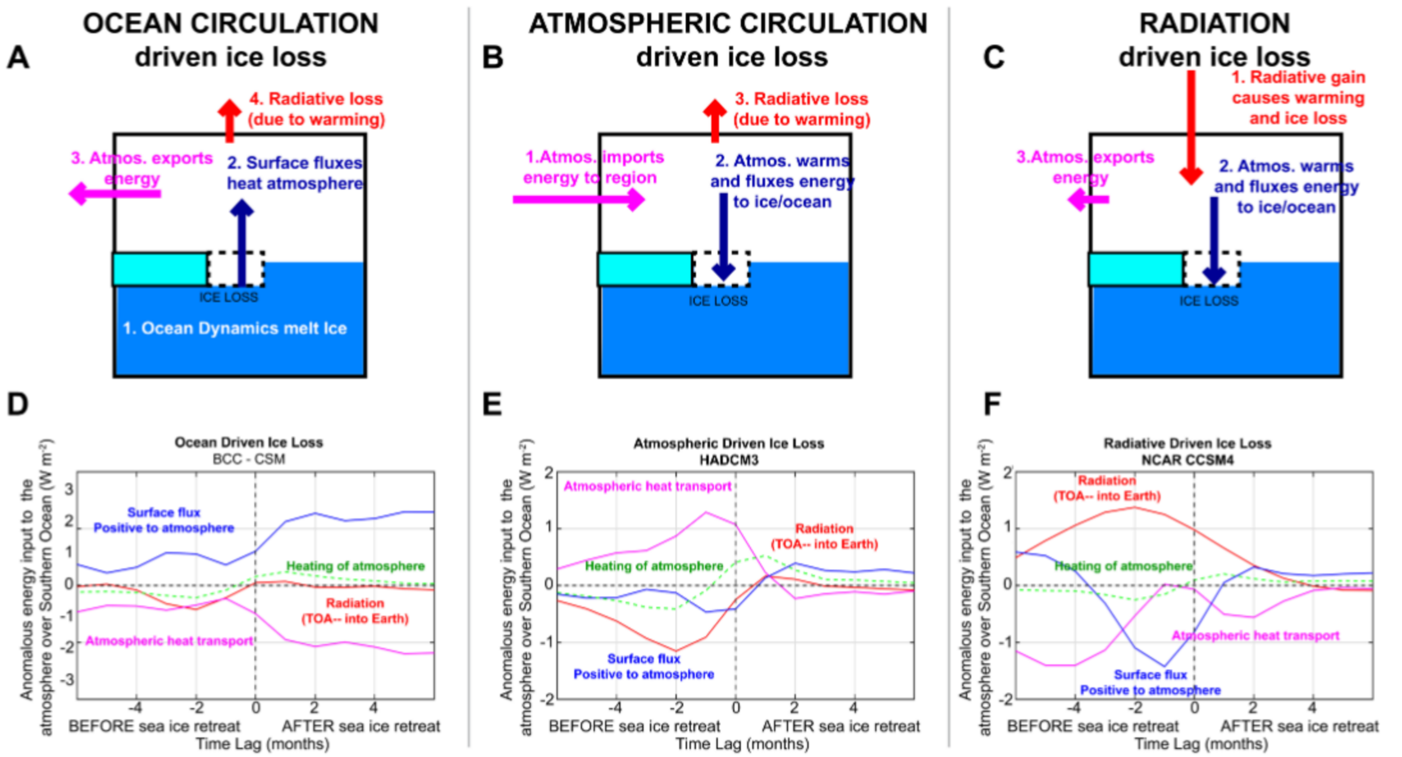


Figure 2. Schematic of the different proposed mechanisms of Southern Ocean sea ice loss and the oceanic/atmospheric/radiative energy fluxes associated with each mechanism. Numbers indicate the chronological order of events in each mechanism: sea ice driven by (left panel) ocean circulation changes resulting in upward surface energy fluxes (blue arrow), (middle panel) atmospheric circulation (purple arrow), and (right panel) radiative processes (red arrow). The lower panels show coupled climate model simulations where sea ice loss events are driven by each of the above mechanisms. Each line shows the energy flux anomaly ($Wm^{-2}$) into the Southern Ocean region (spatially averaged poleward of 55°S) associated with a 2 standard deviation (σ) sea ice loss event.

turbulent energy fluxes (SHF). The atmosphere heats up and exports the anomalous energy via circulation anomalies (a negative $F_{WALL}$ anomaly) and radiatively via the Planck feedback. We note that the initial perturbation to the oceanic circulation may have been provided by a local wind stress anomaly and that we will distinguish this case from the changes in atmospheric energy transport (discussed below).

***Mechanism Two: Atmospheric Circulation Driven Sea Ice Loss***
Atmospheric circulation anomalies (originating as, for example, internal modes of tropically forced anomalies (Ding and Steig 2013) or mid-latitude circulation changes) drive an enhanced energy input to the atmosphere above the Southern Ocean (i.e., a positive $F_{WALL}$ anomaly; Figure 2b). The atmosphere heats up and energy is fluxed downward to the surface via enhanced downwelling longwave radiation and reduced upward sensible energy fluxes resulting in ice loss (a negative SHF). There is a loss of $RAD_{TOA}$ via the Planck feedback.

***Mechanism Three: Radiation Driven Sea Ice Loss***
Changes in local atmospheric optical properties (e.g., a reduction in Southern Ocean cloud cover) and surface albedo result in enhanced radiative input to the system ($RAD_{TOA}$), heating both the atmosphere and the surface — via an enhanced downward radiative surface energy flux — resulting in ice loss (Figure 1c). The enhanced radiative input is mainly stored in the ocean while some is fluxed away in the atmosphere (negative $F_{WALL}$) and damps the initial radiative input via the Planck feedback.

From an energy budget perspective, the driver of the sea ice loss can be identified from the process that adds energy to the atmosphere leading up to the sea ice loss. In this simplified framework, the driver of sea ice loss can be identified from the energy flux anomalies preceding, during, and following an ice loss event. What mechanism leads to Southern Ocean sea ice loss events in coupled climate model simulations? We demonstrate here that unforced Southern Ocean sea ice variability — defined as year-to-year changes associated with internal variability in the absence of external radiative forcing — simulated in long coupled climate model control runs (CMIP5; Taylor et al. 2012) exhibit all three theoretical mechanisms of sea ice loss introduced above.

The primary mechanism of sea ice variability differs between coupled climate models; ocean dynamics (Figure 2d), atmospheric energy transport (Figure 2e), and radiative processes (Figure 2f) can each serve as the dominant mode of sea ice variability in different climate models. In ocean-driven sea ice loss, oceanic processes impart energy to the surface that melts sea ice and provides upward surface energy fluxes to the atmosphere prior to the sea ice anomaly (note the positive values of the blue line in Figure 2d). In contrast, in sea ice loss driven by the atmospheric circulation, the atmosphere imports energy to the Southern Ocean prior to the sea ice anomaly (note the positive values of the purple line on the left of Figure 2e). In radiation driven ice loss, the net radiation delivers energy to the Southern Ocean prior to the sea ice loss (the positive values of the red line preceding the ice loss in Figure 2f).

Figure 2 demonstrates that the dominant mechanism of sea ice variability differs fundamentally between different coupled climate models. An analysis of CMIP5 models suggests that sea ice variability is dominated by ocean processes in about one third of the models, atmospheric circulation in one third, and radiation in one third. Given the diversity of mechanisms driving Southern Ocean sea ice loss in state-of-the-art coupled climate models, what is the dominant driver of Southern Ocean year-to-year sea ice loss in the observational record? Furthermore, can identifying the dominant mechanism of sea ice loss in nature help us to select the climate models that best represent the observed system to better inform our projections of future changes in Southern Ocean sea ice under global warming?

### Preliminary results: Observed relationship between Southern Ocean sea ice loss events and energy fluxes

We present a preliminary analysis of the interannual variability of the Southern Ocean energy budget associated with sea ice variability. Surface energy fluxes over the Southern Ocean are poorly constrained in observations. Thus, we focus on the relationship between the input of energy to the Southern Ocean via the atmospheric circulation ($F_{WALL}$) and the radiative anomalies associated with sea ice loss/gain events. The atmospheric energy flux across 55°S ($F_{WALL}$) is calculated from the vertical and zonal integral of the meridional moist static energy (MSE, the sum of latent, sensible, and potential energy) calculated from ERA interim six hourly data (Dee et al. 2016), using the methodology of Donohoe and Battisti (2013). We express $F_{WALL}$ variability as the resultant average heating (energy flux divergence) applied to the Southern Oceam by dividing $F_{WALL}$ by the surface area of the polar cap. The year-to-year variability (defined by low-pass filtering monthly anomalies with a six month cutoff period) of $F_{WALL}$ is on the order of 13 $Wm^{-2}$ ($2\sigma$). In the summer of 2001, $F_{WALL}$ was reduced by 30 $Wm^{-2}$ (half the climatology) in atmospheric energy input to the region peaking in the summer of 2001. Anomalies in the $F_{WALL}$ primarily result from changes in the strength of transient eddy sensible energy fluxes over the middle and lower troposphere, although stationary eddies in the stratosphere make a non-negligible contribution to the year-to-year variability (and likely do not have the same impact on surface climate as comparable magnitude fluxes in the lower troposphere).

Radiative anomalies — calculated from the CERES data from 2000 (Loeb et al. 2009) — make a substantially smaller ($2\sigma$ = 3.3 $Wm^{-2}$) contribution to the interannual variability of the Southern Ocean energy budget as compared to $F_{WALL}$ (red and green lines in Figure 1). During sea ice loss events, there is a modest increase in absorbed solar radiation on the order of 1 $Wm^{-2}$, due to the reduced surface albedo (+1.9 $Wm^{-2}$) that is counteracted by enhanced cloudiness and cloud reflection (-0.9 $Wm^{-2}$). We emphasize that, given the small magnitude of radiative variability observed over the Southern Ocean compared to the impact of atmospheric processes, radiative processes cannot be the primary driver of Southern Ocean climate variability. The mechanism outlined in Figure 2c is not supported by our interpretation of the observational record.

The above results suggest that the dominant anomalous energy balance associated with observed Southern Ocean sea ice loss events is between the atmospheric energy input and surface energy fluxes. But are the atmospheric circulation anomalies driven by ice loss events associated with ocean and/or ice dynamics (as in Figures 2a,d) or are the ice loss events triggered by atmospheric energy input that is triggered remotely (as in Figures 2b,e)? There is no consistent lead/lag relationship between $F_{WALL}$ and Southern Ocean sea ice in the preliminary observational record shown here. This result suggests that there may be different flavors of Southern Ocean-wide ice loss events, some triggered by local dynamics and others responding to remote forcing. In future work, we hope to look more closely at the spatial structure (longitudinal and vertical) of the relationship between sea ice loss events, the resultant surface energy fluxes, and atmospheric circulation changes.

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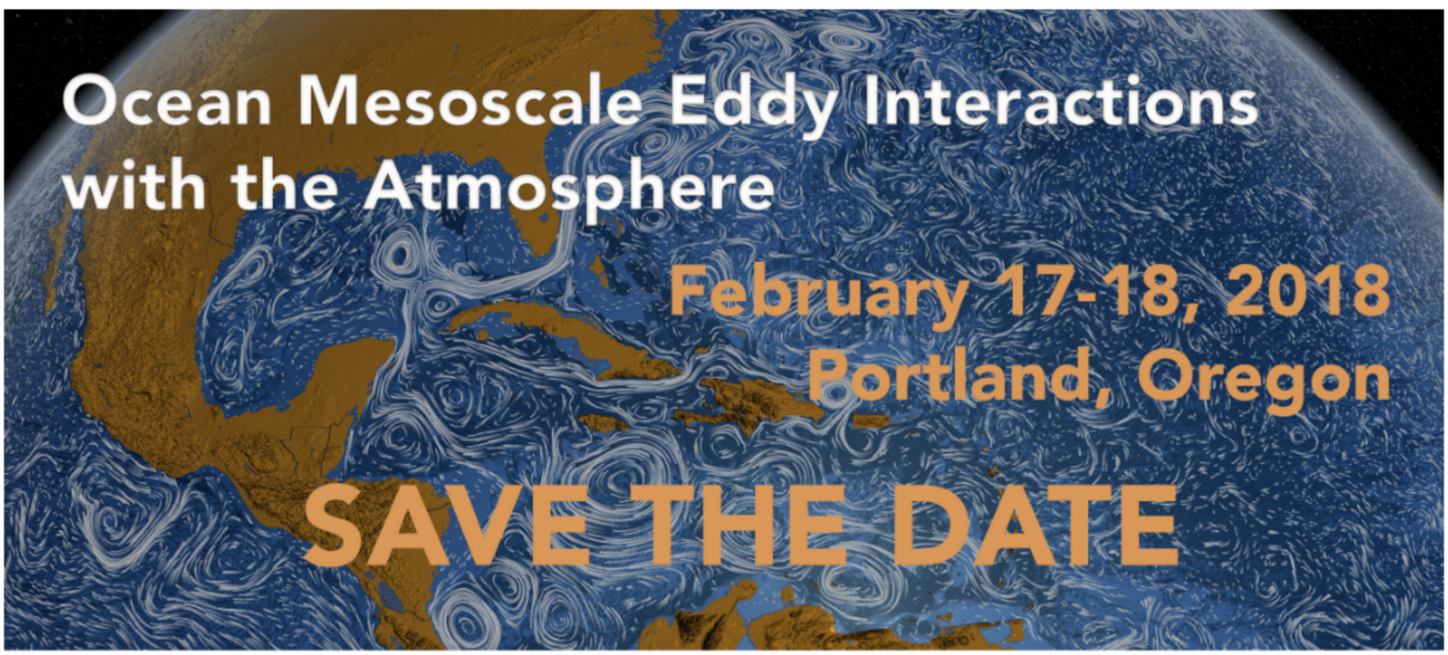


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Aaron Donohoe (U. Washington)

### Understanding & Predicting Climate Teleconnections

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