What processes drive Southern Ocean sea ice variability and trends? Insights from the energy budget of the coupled cryosphere-ocean-atmosphere system.

Project Description

1 Motivation and background

1.1 Introduction

Sea ice in the Southern Ocean (SO) has undergoes immense interannual variability in addition to a small long term increase in recent decades (*Comiso and Nishio*, 2008; *Eisenman et al.*, 2014). The observed record represents the combined effects of natural modes of atmosphere/ocean/cryosphere internal variability, the response to the ozone hole and the response to global warming. Much work has focused on the mechanisms underlying the long term upward trend in SO sea ice despite the global mean surface temperature increase. The following drivers of long term SO sea ice trends have been proposed: 1. Ozone depletion has resulted in an intensification of the surface Westerlies over the SO (*Thompson and Solomon*, 2002) leading to sea ice expansion (*Turner et al.*, 2009) via equatorward Ekman ice transport; 2. 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 sub-surface waters (in the salinity stratified SO) by Ekman suction (*Ferreira et al.*, 2015); 3. Reduced interaction between the surface ocean and the subsurface warm waters due to increased ocean stratification as a result of either to 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); 4. Delayed warming of the SO relative to the rest of the globe due to the basic state ocean overturning circulation (*Armour et al.*, 2016), 5. Wind changes of unknown origin altering ice production in regions of anomalous wind convergence (*Zhang*, 2014) and ice drift (*Holland and Kwok*, 2012) and 6. Random occurrences of natural variability (*Polvani and Smith*, 2013).

Clearly, there is no consensus on a mechanistic understanding of the processes that drive SO sea ice variability on long timescales. Furthermore, much of our understanding of SO 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 SO given significant model biases in simulating the mean state properties of the region. Specifically, the thermal stratification of the SO (*Kostov et al.*, 2016) and the amount of solar radiation reaching the Earth's surface (*Trenberth and Fasullo*, 2010; *Donohoe and Battisti*, 2012) differ drastically between models and are biased relative to the observations. Given the biases in the simulated basic properties of the SO in models, the physical processes that drive sea ice variability in the models may not occur in nature and other mechanisms that are absent in model simulations may be of central importance to the variability of SO sea ice. The goal of the proposed work is to gain an understanding of the physical mechanisms responsible for year-to-year SO sea ice variability from the observational record. We seek insight into this problem through the lens of the energy budget of the coupled cryosphere/ocean/atmosphere system which facilitates a quantitative comparison of the relative importance of air-ocean turbulent fluxes, radiative processes and large-scale dynamic energy transports in the atmosphere and ocean.

1.2 Scientific framework

The growth and decay of SO sea ice is impacted by ocean processes (i.e. lateral and vertical energy fluxes and changes in stratification), atmospheric circulation and radiative processes. Below, we hypothesize three potential sequences of events leading to a sea ice retreat event, each driven by an initial change in a different component of the system. For the sake of conceptual argument in this proposal, we discuss sea ice variability in terms of the processes associated with a "typical" ice retreat event. The sign/direction of all energy fluxes can be reversed to discuss a "typical" ice expansion event. As summarized in Fig. 1, each theoretical mechanism has a unique signature in the area averaged energy fluxes to the SO.

1. *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. As a result, the warmed and exposed ocean surface heats the atmosphere via enhanced upward turbulent energy fluxes. The atmosphere heats up and exports the anomalous energy via circulation anomalies and radiatively via the Planck feedback (Fig. 1A). 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.
2. *Atmospheric Circulation Driven Sea Ice Loss:* Atmospheric circulation anomalies (i.e. internal modes of variability, the response to sea surface temperatures in the tropics (*Ding and Steig*, 2013), mid-latitude circulation changes) result in an enhanced energy input to the atmosphere above the SO. The atmosphere heats up. Energy is fluxed downward to the surface via enhanced downwelling longwave radiation and reduced upward sensible energy fluxes resulting in ice loss. The top of atmosphere radiation increases via the Planck feedback (Fig. 1B).
3. *Radiative Driven Sea Ice Loss:* Changes in atmospheric optical properties (e.g. a reduction in cloud cover) and surface albedo result in enhanced radiative input to the system, heating both the atmosphere and the surface – via an enhanced downward radiative surface energy flux– resulting in ice loss. The enhanced radiative input is mainly stored in the ocean while some is fluxed away in the atmosphere and damps the initial radiative input via the Planck feedback (Fig. 1C).

We note that, from an energetic 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*. Thus, in this simplified framework, the driver of sea ice loss can be identified from the energy flux anomalies preceding, during, and following an ice retreat event. In the presented framework a "typical" ice retreat event is defined as a two standard deviation (σ) anomaly in the SO domain averaged sea ice concentration – hereafter, the ice concentration index. Energy flux anomalies associated with (preceding/following) ice retreat events are computed from a linear regression between the normalized (lead/lagged) ice concentration index and the (de-seasonalized) energy flux anomalies.

We demonstrate here, that unforced SO 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 without anthropogenic forcing (CMIP5 *Taylor et al.*, 2012) exhibit all three theoretical mechanisms of sea ice loss introduced above. The dominant mode of sea ice variability is driven by ocean dynamics in some models (Fig. 1D), atmospheric energy transport in other models (Fig. 1E), and radiative processes in still other models (Fig. 1F). In

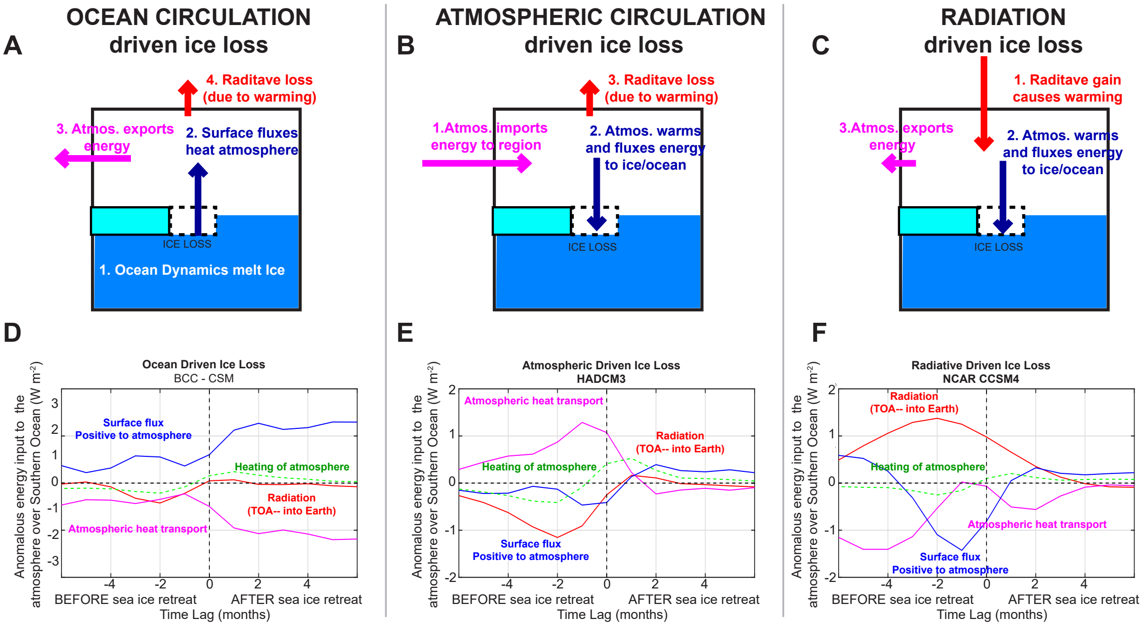

Figure 1: Schematic of the different proposed mechanisms of Southern Ocean sea ice loss and the oceanic/atmospheric/radiative energy fluxes associated with each mechanism. Numbers indicate the chronological order of events in each mechanism: sea ice driven by (left panel) ocean circulation changes resulting 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 into the SO region (spatially averaged poleward of 55°) associated with a 2 standard deviation (σ) sea ice loss event.

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 Fig. 1D). In contrast, in sea ice loss driven by the atmospheric circulation, the atmosphere imports energy to SO prior to the sea ice anomaly (note the positive values of the purple line on the left of Fig. 1E). Lastly, in radiation driven ice loss, the net radiation delivers energy to the SO prior to the sea ice loss (the positive values of the red line preceding the ice loss in Fig. 1F).

Fig. 1 clearly demonstrates that the dominant mechanism of sea ice variability differs fundamentally between coupled climate models. A preliminary analysis of CMIP5 models suggest that sea ice variability is dominated by ocean processes in approximately one third of the models, atmospheric circulation in one third of the models and radiation in one third of the models. Given the diversity of mechanisms driving SO sea ice loss in state of the art coupled climate models, what is the dominant driver of SO 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 SO sea ice under global warming? These questions form the basis of this proposal.

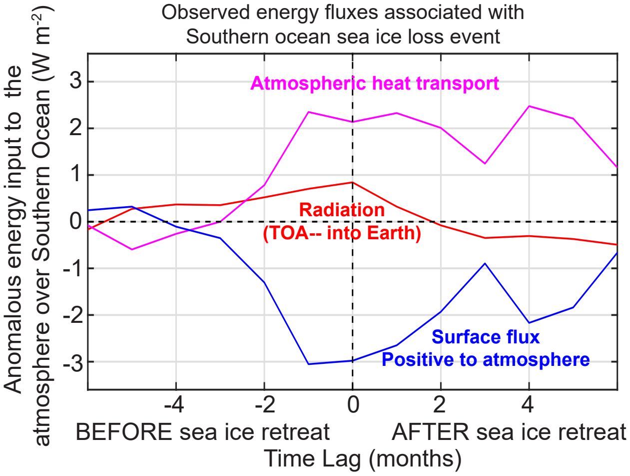

Figure 2: Observational based calculation of energy fluxes into the SO (poleward of 55°) associated with area averaged sea ice loss event defined as a 2σ domain wide NSIDC (*Peng et al.*, 2004) ice concentration anomaly. The months preceding the sea ice loss event are to the left and those after the event are to the right. The radiation is taken from CERES (red), the F_{WALL} (purple line) and atmospheric column energy tendency (dashed green line) from NCEP calculations, the surface heat flux (blue) is the residual of the atmospheric energy budget.

2 Scientific questions and approach

The key scientific question of this proposal is: what mechanism is the dominant driver of SO sea ice variability in nature? The diversity of mechanisms responsible for sea ice loss in climate models provides a fortuitous opportunity to pursue this question by examining why the ocean/atmosphere/radiative drivers of sea ice loss dominate in each model, what specific processes and model features determine the dominant mechanism of sea ice loss, and where the observed climate system lies in the spectrum of model behavior. Our approach to this question is three pronged: 1. we will examine the mechanisms of year-to-year SO sea ice loss in observations through the lens of the energy budget of the coupled system, 2. we will analyze the specific processes responsible for the differing mechanisms of sea ice loss in models (ocean/atmosphere/radiative) and evaluate which models best represent the observed system in the key processes and 3. we will perform simulations in a climate model wherein sea ice loss is initiated by forcing each the ocean surface layer (with both heating and wind stresses anomalies), the lateral atmospheric energy input and the radiation to test the sensitivity of sea ice loss to each process and validate our interpretation of the drivers of sea ice loss from the coupled energy budget.

2.1 Observed year-to-year drivers of SO sea ice loss

What energetic processes precede SO ice loss events in the observational record? Preliminary results (see methodology in Section 3.1) indicate that a SO domain wide (poleward of 55°S) ice loss events are preceded by and concurrent with atmospheric energy input to the domain (Fig. 2) resulting in a downward energy flux into the surface and small radiative input associated with the darkening of the surface (see Section 3.3). We note that, the sparseness of SO ocean and surface energy flux observations precludes the direct determination of oceanic surface energy fluxes. Rather, our approach calculates the surface heat fluxes from completing the atmospheric energy budget (the residual) given the energy fluxes (and storage) into the atmospheric column. The robustness of these results to different observational data-sets and methodologies of energy flux calculations will be evaluated as part of our proposed work.

2.2 Specific processes responsible for mechanisms of ocean/atmosphere/radiative driven sea ice loss

Our scientific framework discussed above has broadly simplified the SO climate system into ocean processes, atmospheric dynamics and radiative processes. Within each of these categories, specific physical processes which vary spatially and in time (both seasonally and the contrast in behavior between year-to-year variability and long term trends) are essential to determining the amplitude of the sea ice retreat in response to different drivers. We note that, our interpretation of the differing drivers of sea ice loss from the spatially averaged energy fluxes (Fig. 1) is also supported by spatial maps of energy fluxes associated with ice loss events (Fig. 3); the sign of the energy fluxes in the vicinity of ice loss (blue contours) differs between the ocean, atmospheric and radiatively driven cases (c.f. the sign of the surface fluxes between the left and middle columns of Fig. 3). Here, we discuss the detailed processes that determine how sensitive sea ice is to each oceanic, atmospheric and radiative drivers. In the proposed work, we will analyze the drivers of SO sea ice loss both in the year-to-year variability and the longer timescale response to external forcing and ask: how does the diversity of essential processes in the short term variability (i.e., as seen in the instrumental record) relate to inter-model differences in the long term response of SO sea ice to global warming?

2.2.1 Essential mechanisms of ocean driven sea ice loss

The strength of surface westerlies over the SO covaries with the Southern Annular Mode (SAM) with pronounced month-to-month (*Marshall*, 2003) variability in addition to longer term trends associated with ozone loss (*Thompson and Solomon*, 2002). The impact of increased westerly wind stress on sea surface temperatures is a two timescale problem; at the faster timescale, enhanced equatorward Ekman drift advects cold water and sea ice to lower latitudes cooling the surface and expanding sea ice (*Turner et al.*, 2009). At the longer timescale, high latitude Ekman suction causes upwelling of warm sub-surface waters resulting in surface ocean warming and sea ice loss (*Ferreira et al.*, 2015). The time it takes for the initial (drift induced) cooling to be overwhelmed by the (upwelling induced) warming – hereafter the transition timescale– varies drastically between climate models (from 3 years to an infinite timescale *Kostov et al.*, 2016). Differences in the transition timescale are due to inter-model differences in the simulated mean state (unperturbed, time mean) thermal stratification of the SO in the models. Because the response of the sea ice to surface wind stress anomalies can be thought of as a convolution of the time history of the wind stress and the time evolving thermal response (cooling then warming) of the ocean, the amplitude of the sea ice response to wind stresses depends not only on the magnitude and persistence of the wind anomalies but, also, critically on the above transition timescale. Thus, the mean state thermal stratification may provide a clue as to why models exhibit varying magnitudes of sea ice variability resulting from wind driven ocean circulation. Furthermore, if the thermal stratification of the mean state SO does control the amplitude of oceanic driven sea ice loss, a comparison of the observed mean state thermal stratification to that in the models may constrain which models realistically represent the year-to-year variability and long term response of SO sea ice. This is one of two so called potential “emergent constraints” identified in this proposal in which inter-model differences in future projections are correlated with a measurable variable in the current climate. “Emergent constraints” are powerful tools because they allow *variables that can be observed today* to be used to narrow the range of realistic climate model projections by *eliminating models that do* *not adequately represent the physics relevant for future changes.*

Ocean convection potentially plays a critical role in delivering energy to the surface ocean (from the warm sub-surface water) and melting sea ice and has been proposed as the cause of the observed Weddell Polyna (*Martinson et al.*, 2010). In this mechanism, brine rejection associated with sea ice growth causes the surface water to increase in salinity and density and sink (i.e., haline induced vertical convection). Warmer subsurface water mixes to the surface inducing sea ice melt. This mechanism occurs over oceanic regions that are preconditioned with a shallow surface layer above the pycno-cline. The mean state stratification of the ocean and oceanic advection of the preconditioned water play key roles in the magnitude and persistence of the convectively-driven polynas, all of which could differ between models. Additional mechanisms of convectively-driven, polyna-like sea ice retreat include the divergence of surface winds (*Goosse and Fichefet*, 2001), interactions of currents with the seafloor bathymetry (*Beckmann et al.*, 2001) and freshwater input via precipitation and glacial runoff (*Marsland and J.O.Wolff*, 2001).

Overall, the delivery of energy to the surface ocean (and the subsequent sea ice melt) via ocean currents and convection encompasses a rich set of physical processes that rely on the basic state ocean and surface boundary forcing (e.g. winds and freshwater fluxes). Differences in the representation of any of these processes could explain the model diversity in the magnitude of ocean driven ice retreat in the SO.

2.2.2 Essential mechanisms of Atmospheric driven sea ice loss

Sea ice loss driven by atmospheric circulation requires modes of atmospheric variability that flux energy into the atmosphere above the SO and the subsequent communication of these changes to the ocean surface via the radiative-convective adjustment of the atmospheric column to the anomalous energy flux convergence. In the observed climatology, the net radiative cooling of the SO is balanced by lateral energy transport primarily (90%) in the atmosphere and secondarily (10%) in the ocean (*Trenberth and Caron*, 2001). The vast majority (85%) of the climatological atmospheric energy import to the SO is the net result of sensible energy fluxes in passing, synoptic weather disturbances (transient baroclinic eddies *Trenberth*, 1991) with a modest contribution (15%) from stationary waves and an opposing equatorward energy flux in the atmospheric overturning circulation (*Donohoe and Battisti*, 2013).

Very little, if any, work has been done on interannual variability of the atmospheric energy flux into the SO which we will hereafter call F_{WALL}. *Previdi et al.* (2013) analyzed the variability of F_{WALL} into the Antarctic continent (70°S) which likely encompasses very different set of dynamics than the energy flux from the mid-latitudes into the sea ice region. Key questions include: How big is the year-to-year variability of F_{WALL} and how much do variations in the storm tracks versus stationary eddies and overturning circulation of the atmosphere contribute? Preliminary analysis of the energy fluxes preceding ice loss events in models in which atmospheric driven ice loss dominates shows that anomalous energy is imported in a zonal wavenumber 2 pattern (Fig. 3E) suggesting stationary eddies play a key role. This is supported by the preliminary analysis presented in Section 3.4 of this proposal and is consistent with the work of *Ding and Steig* (2013) who argue that Rossby waves emanating from tropical sea surface temperature anomalies exert the primary control on large scale atmospheric circulation impacting Antarctica and the SO.

More importantly, at what vertical level of the atmosphere does the anomalous energy input to the region enter? The wintertime atmospheric inversion (*Pavelsky et al.*, 2011) effectively isolates the surface from the upper atmosphere. As a result, energy entering the atmosphere at upper levels will primarily be radiated to space and have a minimal impact on the surface. In contrast, low level atmospheric energy fluxes will efficiently heat the surface; recent work in the Arctic has suggested anomalous low level moisture fluxes (i.e., latent heat convergence) cause surface amplified warming and play a pivotal role in transient warming events and long term polar amplification (*Woods and Caballero*, 2016). Thus, the vertical structure of F_{WALL} may offer new observational and model insights into the sensitivity of sea ice loss to atmospheric drivers.

2.2.3 Essential mechanisms of radiative driven sea ice loss

We demonstrated above that a subset of coupled climate models simulate sea ice loss events that are driven (preceded) by radiative input into the Arctic (Fig. 3C,L). We formulate two (alternative) working hypothesis to explain this mechanism of sea ice loss:

1. Sea ice loss events are preceded by SO domain wide cloud anomalies – caused by changes in, for example, local vertical motion or boundary layer physics – that deliver radiative energy to the atmosphere and/or surface. Specifically, radiative input to the region could be caused by either a decrease in summertime cloud cover, resulting in an enhanced solar input to the surface, or an increas in wintertime cloud cover resulting in enhanced longwave heating of the surface (*Shupe and Intrieri*, 2014)
2. A small (random) initial sea ice loss causes enhanced absorbed solar radiation in the darkened surface. The additional (radiative) energy input to the surface of the region of initial ice melt drives additional sea ice loss in adjacent regions. As a result, the magnitude of the initial radiative perturbation increases as more of the surface darkens and continues to do so until the atmospheric/ocean dynamics and Planck feedback remove energy from the region of sea ice melt. The net impact of sea ice loss on the surface energy fluxes is a tug of war between the competing cooling influence of the enhanced upward turbulent energy fluxes and the warming impact of enhanced solar absorption at the surface. If the latter warming impact is larger in magnitude, there is a net positive energetic feedback and initial sea ice loss in one region may add energy to the surface ocean to facilitate sea ice loss in adjacent regions. From the perspective of the energy budget framework presented here, this may be diagnosed as “radiatively” driven sea ice loss since the radiative gain associated with the sea ice loss yields a net surface energy flux into the ocean.

To distinguish between the two hypotheses above, we will separate the direct impact of sea ice loss to the radiative anomaly measured by the satellite at the TOA from that associated with cloud variability using the recently developed methodology of *Donohoe and Battisti* (2011). We can compare how much solar energy is gained by the surface to the turbulent energy lost during sea ice loss events to ask if sea ice loss events are self sustaining from a surface energy budget perspective using this same framework. We hypothesize that the answer to that question may depend on the simulated basic state radiative properties of the atmosphere which is biased (*Trenberth and Fasullo*, 2010) and differs substantially between models (*Donohoe and Battisti*, 2012) in the SO.

2.3 Isolating the sensitivity of sea ice loss to different drivers

The energetic processes preceding sea ice loss events is telling, we have argued, of the mechanisms driving sea ice loss. To validate this method of diagnosing drivers of sea ice loss, we propose

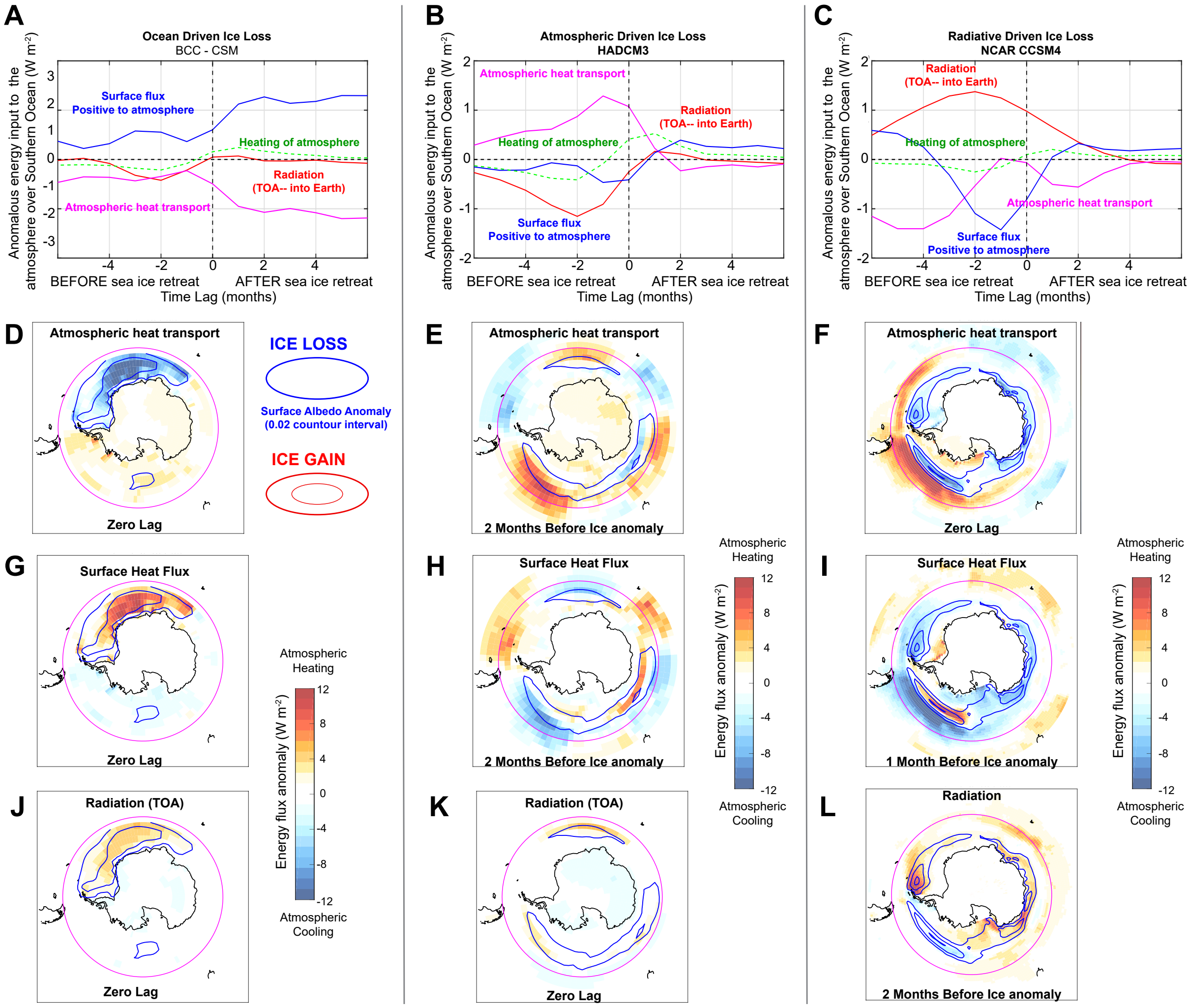

Figure 3: Energy flux anomalies associated with a Southern Ocean sea ice retreat events (2σ) in unforced climate model simulations. The three columns represent climate models where the ice loss events are driven by (left) oceanic processes, (middle) atmospheric circulation and (right) radiative processes. The upper panels show the area averaged energy flux anomaly in the months preceding (negative lags on the left) and after (positive lags to the right) an ice retreat event. The surface energy flux to the atmosphere is shown in blue, the atmospheric energy flux into the region is shown in purple, the net radiation into the top of the atmosphere is red and the energy that goes into heating the atmospheric column is in green. The lower panels show spatial maps of the anomalous energy fluxes associated with sea ice loss events in colors and the pattern of ice concentration anomalies in contours (contour interval of 0.02) with blue contours indicating ice loss.

a series of model experiments where we will perturb the individual (ocean/atmosphere/radiation) components of coupled climate models to induce sea ice loss: (i) we will add energy or mechanical forcing (wind stresses) to the ocean surface, (ii) we will mimic enhanced atmospheric energy import the SO and (iii) we will alter the radiative input to the region. These experiments will determine the relative efficiency of radiative, atmospheric F_{WALL} and oceanic energy fluxes are in causing sea ice loss (*Rose et al.*, 2013). We will apply idealized forcings that oscillate periodically in addition to step function changes on the forcing to isolate the sensitivity of sea ice to both year-to-year variability and long term changes of the various mechanisms. The purpose of these experiments is two-fold: (i) we can compare the magnitude of the modeled response of sea ice to forcing mechanisms (wind stresses, ocean heating, atmospheric energy fluxes, radiative processes) and then ask, given the magnitude of variability of each of these mechanisms in the observational record, how big should the impact on sea ice be and (ii) we expect that an *a posteriori* energy flux analysis will reveal that the mechanism used to initiate the sea ice loss imparts energy to the system preceding the sea ice loss event. Thus, these experiments will validate the approach/framework used in the proposal since *we know which component of the system is driving sea ice variability and should be able to isolate this driver from the energetic analysis*. Additionally, the long term changes in the step function driving experiments will demonstrate the impact of ice changes on the large scale circulation (F_{WALL}) and the global implications of SO sea ice changes.

3 Proposed work, methodology and preliminary results

This work consists of three main tasks, each aimed at the end-goal of understanding the processes that drive SO sea ice variability from the framework of the energy budget of the coupled climate system and assesing the fidelity of isolating drivers and responses within that framework: (i) the observational analysis of energy fluxes associated with SO sea ice loss events including isolation of the direct impact of ice loss on radiative processes and analysis of the vertical structure of atmospheric energy transport, (ii) analysis of these same processes in coupled climate models to gain an understanding of why the mechanisms driving ice loss events in models differ from those seen in nature and how these mechanisms inform the projected long term sea ice response to external forcing and (iii) idealized forcing model simulations to isolate the sensitivity of sea ice loss to different drivers and validate the use of the energy budget to separate drivers from responses.

3.1 Observed drivers of sea ice loss events

The energy budget of the coupled SO climate system includes the following processes: radiative fluxes at the TOA, lateral atmospheric energy fluxes, energy storage in the atmospheric column, surface energy fluxes (radiative and turbulent), lateral oceanic fluxes and changes in ocean heat content/stratification. *Serreze et al.* (2007) attempted to close the coupled energy budget of the Arctic and found that the surface energy fluxes required to close the climatological seasonal energy budget of the ocean from calculations of lateral fluxes and ocean heat storage were inconsistent (errors of order 10 W m^{-2} in the domain average) with both direct surface heat flux estimates and those implied from the residual of the atmospheric energy budget. Given the sparseness of ocean observations in the SO, we therefore suspect that ocean reanalyses are not reliable for the interannual energetic analysis pursued here. Instead, our primary strategy is to calculate the surface turbulent energy fluxes as a residual of the atmospheric energy budget to provide a self-consistent and closed energy budget. This strategy was proposed by *Trenberth* (1997), was recently updated by *Donohoe and Battisti* (2013) and, in regions where reliable direct calculations of surface energy fluxes exist, are highly accurate (correlation of 0.9 *Liu et al.*, 1985-2012). In the proposed work, we will revisit the consistency of our atmospheric based calculations with ocean reanalysis calculations as a secondary strategy and consistency check. Here we outline the details of our primary calculations:

- **Radiation:** TOA and surface (*Rutan et al.*, 2001) radiation from CERES (*Wielicki et al.*, 1996) spanning 2000-2016 will primarily be used. We will examine if the reanalysis radiation is consistent with CERES over the region to allow a reliable extension and joining of the CERES and ERBE (*Barkstrom and Hall*, 1982) records as was recently done by (*Allan et al.*, 2014)
- **Atmospheric Energy Transport and storage:** Lateral atmospheric energy flux will be calculated from the 6 hourly fields in three separate sets of reanalysis: NCEP reanalysis (*Kalnay et al.*, 1996), the recently released Modern-Era Retrospective Analysis V2 (MERRA– *Bosolivich et al.*, 2015) and ERA-interim (*Dee et al.*, 2011). We expand on the novel methodology we will use in Sec. 3.1.2
- **Surface Energy Fluxes**: Surface radiative fluxes are provided by CERES (*Rutan et al.*, 2001). The turbulent energy fluxes are calculated as a residual of the atmospheric energy budget (above). These will be compared to bulk parametrization estimates and ocean reanalysis products to check for consistency.

A vital component of our proposed work is to assess if the broad conclusions on the drivers of SO sea ice loss events (Fig. 2) are consistent across all three sets of reanalysis and whether our methodology provides robust conclusions above the observational uncertainties. Furthermore, do the spatial patterns of atmospheric energy input (convergence) and energy fluxes into the surface relative to where sea ice has melted match our interpretation of sea ice loss initiated by atmospheric energy transport deduced from the domain averaged analysis?

3.1.1 Isolating the direct radiative impact of sea ice loss in the satellite record

We will isolate the direct impact of sea ice loss on TOA radiation using the methodology of *Donohoe and Battisti* (2011). In short, their method treats the atmosphere as single layer with an (isotropic) reflectivity (R) and absorptivity (A). The values of A and R are (uniquely) solved for given observations of the (upwelling and downwelling) solar radiation at surface and TOA. One can then trace sunlight as it reflects between the clouds and surface (Fig. 4A). The solar radiation reflected back to space is partitioned between rays that have bounced directly off of clouds and those that have been reflected off the surface. To first order, the impact of the surface albedo on the TOA equals the value of surface albedo multiplied by the atmospheric shortwave transmissivity (1-R-A) squared. The squared dependence results from the fact that in order for the radiation reflected by the surface to impact the TOA the light must travel downward through the atmosphere, be reflected and then travel upward through the atmosphere.

In the proposed work, we will apply this methodology to the interannual and inter-seasonal variability of the SO satellite radiation record from CERES (2000-2016). Preliminary result shown in Fig. 4 suggest that sea ice retreat events (2σ) are associated with a modest net increase (+0.9 W m^{-2}) in absorbed solar radiation due to reduced surface albedo over the region of lost ice (+1.9

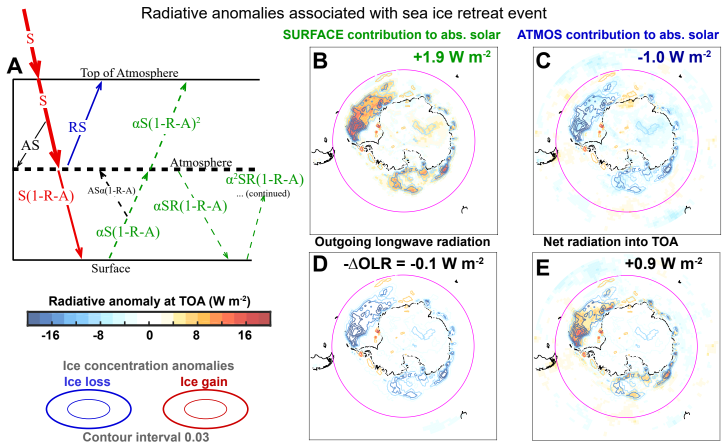

Figure 4: Top of atmosphere radiative anomalies associated with a 2σ SO ice concentration anomaly event. The absorbed solar radiation change is partitioned into components associated with changed is surface solar reflection (green) and those associated with changes in atmospheric reflection using the isotropic model of *Donohoe and Battisti* (2011) as summarized by the schematic in (A). The TOA changes shown are (B)surface and (C) atmospheric contributions to absorbed solar radiation, (D) negative outgoing longwave radiation and (E) net radiation into the TOA. Contours show the anomalies in (NSIDC) sea ice concentration with a contour interval of 0.03 and blue contours indicating ice loss.

W m^{-2} – Fig. 4B) that is partly countered by increased cloud reflection (-1.0 W m^{-2}) and a very small increase in outgoing longwave radiation (0.1 W m^{-2}) associated with surface warming. Thus, changes in radiation during SO ice retreat events appear to be dominated by the direct response to surface darkening and slightly damped by increased cloud reflection. This is in stark contrast to the Arctic, where cloud reduction during ice loss summers play a fundamental role in radiative anomalies and amplify the radiative impact of surface darkening resulting in enhanced surface warming (*Kay et al.*, 2008; *Kay and L'Ecuyer*, 2013). We will validate the performance of the isotropic shortwave model for partitioning surface and atmospheric radiative contributions using a series of experiments with altered cloud cover and surface albedo in the a single column radiative transfer model (*Key and Schweiger*, 1998). Preliminary results suggest that the partitioning of radiation between atmospheric and surface processes via the isotropic shortwave model is highly accurate in the high latitudes.

3.1.2 The vertical structure of atmospheric energy transport

Recently, *Donohoe and Battisti* (2013) developed a novel methodology for calculating the vertical structure of atmospheric energy fluxes from observational reanalysis data. Their method decomposes atmospheric energy fluxes into components associated with the mass overturning circulation of the atmosphere, stationary eddies (that have an associated northward flow at one longitude and a compensating southward flow at another longitude) and transient eddies (storms) and is based on the pioneering work of *Lorenz* (1953). The computation of F_{WALL} via this methodology is in very close agreement with the more standard mass flux corrected form of the calculation (*Trenberth and Stepaniak*, 2003) but allows for the added insight into the vertical structure of atmospheric energy flux anomalies and circulation structures that give rise to F_{WALL} anomalies.

Preliminary calculations from the NCEP reanalysis (*Kalnay et al.*, 1996) suggest the expected result that climatological F_{WALL} into the SO (across 55°) is dominated by transient eddies (storms) in the lower atmosphere with small contributions from stationary eddies (c.f. the colors in the left middle and upper left panels of Fig. 5). However, the year-to-year variability of F_{WALL} has comparable contributions from stationary and transient eddies (right panels). Moreover, much of the

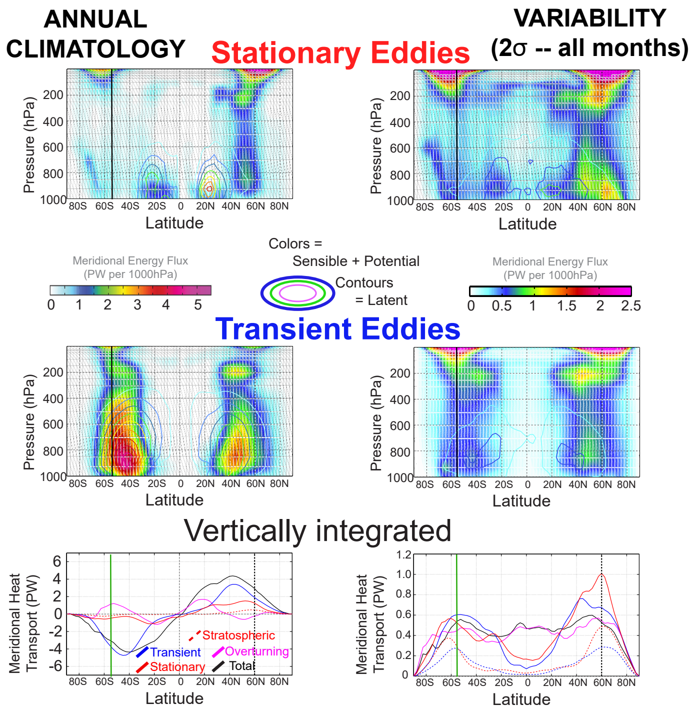

Figure 5: The vertical and latitudinal structure of F_{WALL} in the climatology (left panel) and year-to-year variability (2σ). The upper (middle) panel shows the stationary (transient) eddy energy transport in units of PW per 1000 hPa such that vertically averaging gives the resultant vertically and zonally integrated atmospheric energy flux in PW (10^{15} W) shown in the lower panel. The dry (potential plus sensible) energy transport is shown in colors and the contours are the moisture (latent) transport with the same colorbar. The vertically integrated energy transport also includes a contribution from the (purple) mass overturning circulation (to which no vertical structure is ascribed) and subdivides the transient and stationary eddies into contributions from the stratospheric circulation – defined as above 200 hPa (dashed blue and red lines respectively).

F_{WALL} variability is in the stratosphere (note the purple bulls eyes in the stratosphere in the upper right panel of Fig. 5). The climatological stratospheric contribution to F_{WALL} in the Arctic was previously suggested by *Overland and Turet* (1994). To our knowledge, our analysis is the first to recognize the impact of year-to-year variability of the upper troposphere and stratospheric circulation on the atmospheric energy input to the SO. We speculate that stratospheric energy fluxes most likely make a small imprint on the surface climate in the absence of a downward propagation method (*Baldwin and Dunkerton*, 1998) and, thus, considering the variability of the tropospheric only component of F_{WALL} may lead to new insights into the connection between sea ice and atmospheric circulation. We will test the communication of upper versus lower atmospheric energy flux convergence to the surface by adding atmospheric heating to a single column radiative model coupled to the surface (GFDL model) and note the impact on surface temperature. This will provide a basis for weighting the F_{WALL} anomalies by their vertical structure to calculate a better metric for the influence of the atmospheric circulation on surface climate.

3.2 Drivers of sea ice variability in an ensemble of coupled climate models

The diversity of mechanisms driving year-to-year SO sea ice variability seen in Fig. 3 will be further explored in the CMIP5 (*Taylor et al.*, 2012) ensemble. We will perform a more detailed analysis of both the unforced variability with long (500 year) pre-industrial control simulations and also analyze the simulated response of SO sea ice to historical and idealized abrupt ($4XCO_2$) forcing simulations that are readily available in the CMIP archive. Key questions to ask are:

1. Are the various mechanisms (ocean/atmosphere/radiation) of sea ice loss evident within *the same climate model* (at different timescales) with different amplitudes?
2. What determines a models preference for ocean/atmosphere/radiatively driven sea ice variability? Specifically, do differences in the mean state (e.g. ocean thermal stratification, cloud

biases resulting in different atmospheric solar transmissivities) dictate how strongly the variability in a given component of the system impacts sea ice growth/decay? Alternatively, does the amplitude and persistence of the internal variability (e.g. year-to-year variations of F_{WALL} and the vertical structure of these variations) differ substantially between models?

3. Does the *preference of a given model toward ocean/atmosphere/radiative-driven sea ice variability* determine the amplitude (spatial characteristics and global telecommunication) of future changes in SO sea ice?

We will use the same tools that were used to diagnose the observational record – the isotropic shortwave model described in Section 3.1.1 and analysis of the vertical structure of F_{WALL}– will be used to answer the above questions. In addition, coupled climate model output allows for a detailed analysis of the ocean processes responsible for ice loss that was not possible in the observations.

This work has the potential to develop two important "emergent constraints" for the future of SO sea ice – the use of observational data to narrow the uncertainty model projections of future climate change: 1. Mechanisms of sea ice variability that result from a mean state bias in the simulation of the SO are not realizable in nature and will not contribute to future changes; 2. If mechanisms of year-to-year sea ice variability in climate models are correlated with the simulated long term response to external forcing (CO_2), the observed mechanisms of year-to-year variability can inform which model projections are most realistic.

3.3 Idealized forcing experiments in climate models to isolate oceanic, atmospheric and radiative drivers of sea ice

The work proposed up to this point has emphasized *a posteriori* diagnosis of the drivers of SO sea ice loss events in observations and (unforced/forced) coupled model simulations using the energy flux framework. Here, we propose an alternative set of experiments whereby we initialize sea ice loss in a model by perturbing either the ocean, atmospheric circulation or radiation in an oscillatory manner (to mimic the processes driving year-to-year ice variability) and as a step-function change. We will analyze the magnitude and persistence of the sea ice response to the various forcing mechanisms and the sensitivity to the spatial and temporal patterns of the forcing. Furthermore, since we know the process that was responsible for the sea ice change, an *a posteriori* analysis of the energy fluxes associated with sea ice loss events (akin to what we can do in the observational record) will validate our interpretation of the drivers of sea ice loss from the coupled energy budget framework. All simulations will be performed with the National Center for Atmospheric Research (NCAR) Community Earth System Model Version (CESM) with the Community Atmosphere Model version 5 (CAM5) in coupled and slab ocean configurations. Dr. Blanchard will perform the simulations and will request a separate allocation for time on the Yellowstone cluster from NCAR's Computational Information Systems Laboratory (CISL).

We will choose perturbations that are idealized but representative of the spatial/temporal structure of variability of each component seen in the observational record. The magnitude of the forcing will be a factor of three larger than the internal variability seen in the observations so that we can both robustly detect the sea ice response over the noise (internal variability) in the model yet still expect perturbations to be sufficiently linear with respect to the forcing such that we can scale the responses to that expected from the magnitude of variability in nature. Oscillatory forcings with periodicity between 2 and 5 years will be applied over simulations of length 10 times the periodicity to isolate the sensitivity of sea ice to year-to-year forcings (i.e., the sea ice response we should expect in the observational record). Additionally, abrupt step function forcings of the same mechanisms will be applied to analyze the sensitivity of sea ice to long term drivers. The details of the different forcing experiments are provided below:

- **Oceanic drivers:** The ocean will be forced in 2 ways to initiate sea ice loss: thermodynamically and mechanically. The role of lateral energy flux convergence will be mimicked by adding heating to the surface mixed layer. Additionally, mechanical forcing will be simulated by adding a zonally invariant constant to the wind stress feed to the ocean coupler. This allows the impact of surface wind stresses on the ocean dynamics to be isolated from atmospheric circulation anomalies.
- **Atmospheric drivers:** Atmospheric heating at various levels and with different spatial distributions (zonally invariant, zonal wavenumber 2) will be added to the atmosphere to mimic variations in lateral energy fluxes in the atmosphere. Additionally, we will perturb the low level moisture tendency to isolate the impact of moisture intrusions from energy flux convergence as was suggested by *Woods and Caballero* (2016) and *Nicolas and Bromwich* (2011)
- **Radiative drivers:** We will modify cloud radiative properties (both longwave and shortwave) over the SO to mimic the role of radiative variability. Candidate mechanisms to induce cloud radiative changes include scalar multiplication of the cloud liquid and ice water sent to the radiative coupler, local insolation modification and changes in the shallow convection detrainment which increases the supercooled water in the SO in the CESM (*Kay et al.*, 2016)

4 Broader Impacts

Scientific: This research is important for developing understanding of the fundamental processes driving SO sea ice year-to-year variability and long terms trends. It will allow for the amplitude of unforced variability to be compared to that expected from external (anthropogenic forcing) to answer: what processes have led to the modest expansion of SO sea ice in recent decades and is the attribution of this signal to external forcing significant above the internal variability? More importantly, what will happen to sea ice in the SO in future decades and how sensitive is the ice to anthropogenic forcing? To this end, the proposed work will provide two “emergent constraints” to improve future projections of SO sea ice: 1. the sensitivity of sea ice to mean state biases in climate models and 2. a comparison of the amplitude and mechanisms of ocean/atmospheric/radiative driven year-to-year variability between observations and models will inform which models are more likely to realistically simulate future sea ice changes.

Education and outreach Every spring, Seattle’s Pacific Science Center hosts between 5,000 and 10,000 visitors for the Polar Science Weekend (PSW) which features a variety of hands-on activities presented by scientists from the Polar Science Center at the University of Washington. PSW brings students, teachers and families face-to-face with active scientist and provides an excellent opportunity for polar scientists to share our work, understanding of the polar climate system and the challenges the region faces under global change in an informal and fun setting. We will design a module explaining the response of SO sea ice to natural variability and external (anthropogenic) forcing. This module will attempt to communicate the interplay of the slow global response to increasing CO_2 superimposed on the year-to-year variability of regional climate which is a key challenge in communicating climate change science.This project will also support the career development of two early career scientists (Donohoe and Blanchard).

5 Working timeline

YEAR ONE: ○ Perform observational calculations of F_{WALL} in MERRA and ERA reanalysis ○ Partition CERES radiation into atmospheric and surface components with isotropic shortwave model ○ Analyze pre-industrial CMIP5 simulations to look for simultaneous mechanisms of sea ice variability within the same model and relationship between driver amplitudes and mean state biases ○ Begin idealized CESM simulations to test for sensitivity of ice to cloud parameters and atmospheric/ocean heating and surface wind stresses
YEAR TWO:○ Test robustness of observed energy flux phasing to different reanalysis data ○ Look for consistency between the surface energy fluxes inferred from the residual of the atmospheric budget and ocean reanalysis and bulk parametrizations ○ Analyze mechanisms of ice variability in historical and $4XCO_2$ simulations ○ Relate mean state properties and mechanisms of internal variability to long term ice response to external forcing in CMIP models ○ Continue idealized CESM simulations by examining sensitivity to spatial structures and periodicity of the forcing ○ Test sensitivity of ice loss to the vertical structure of atmospheric heating in single-layer radiative transfer model ○ Prepare publications on observational calculations and diversity of mechanisms in CMIP models
YEAR THREE: ○ Analyze vertical structure of F_{WALL} in CMIP5 models and sensitivity of sea ice to the vertical level of convergence ○ Diagnose the surface albedo feedback and radiative impact of clouds in CMIP5 models using the isotropic shortwave model ○ Final idealized CESM simulations examining sensitivity to vertical structure of F_{WALL} ○ Prepare publications on long term trends in CMIP5 and the magnitude of response to idealized forcing in CESM simulations

6 Prioir NSF Results

Axel Schweiger: ARCS- 0629360 “Collaborative Proposal: The Roles of Clouds and their Accomplices in Modulating the Trajectory of the Arctic System” \$ 271,972.00, 09/01/06-09/01/11. P.I.s Francis, J.A. (Rutgers), Vavrus S. (U of Wisconsin) and Schweiger, A. (University of Washington). We discovered new, important links between sea ice changes, arctic clouds, and atmospheric transport using a combination of reanalysis, satellite data and models. The role of clouds, both as drivers and responders, to sea ice variability was established. Links to lower tropospheric static stability were found. Using a combination of data and models, the project also quantified the uncertainty in the change in total sea ice volume in the Arctic. Many highly cited publications provide evidence for the scientific merit of the results. Broader impacts include participation in 5 annual Polar Science Weekend (PSW) events (see Broader Impacts Section of this proposal). Collaborations with Bonnie Light (PSC) yielded a PSW activity that engaged students and the general public to explore the ice-albedo feedback and is now a semi-permanent display at the Pacific Science Center. A web site, visualizing Arctic sea ice volume change, partially supported by this project, draws up to 8000 unique visitors/month. PIOMAS ice volume time series has had 3000 registered downloads and is used by an active group of citizen scientists. Publications resulting from award (7): *Lindsay et al.* (2009); *Schweiger et al.* (2008b); *Schweiger et al.* (2008a); *Vavrus et al.* (1983); *Zhang et al.* (2008); *Zhang et al.* (2010); *Schweiger et al.* (2011).

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