Arctic sea ice loss and the Arctic radiation budget viewed from space: separating drivers and responses

Scientific/Technical/Management Section

1 Introduction

Arctic sea ice has undergone immense interannual variability as well as longer term declines in recent decades. The impact of sea ice loss on the radiative heating of the Arctic is a potential amplifier of Arctic warming and sea ice loss/variability (*Kay et al.*, 2012). Furthermore, radiative processes associated with Arctic sea ice loss directly impact the global energy budget (*Deser et al.*, 2015) and the large scale circulation of the atmosphere and ocean (*Hwang et al.*, 2011; *Francis and Vavrus*, 2012). Therefore, understanding how sea ice loss is connected to the radiative budget of the Arctic is of critical importance for forecasts of future sea ice decline, the persistence and predictability of anomalies (*Blanchard-Wrigglesworth et al.*, 2011) and the effect of sea ice decline on the global climate system.

Sea ice decline exposes the darker ocean surface and, thus, causes more solar radiation to be absorbed in the climate system. This effect is commonly termed the ice albedo feedback – a positive feedback whereby initial melting causes additional radiative input to the system which amplifies the initial ice loss. The magnitude of the ice albedo feedback differs substantial across global climate models (GCMs) due both to uncertainties in how much sea ice will retreat with warming and due to the radiative impact of the sea ice loss (*Qu and Hall*, 2005). Recent observations have improved our understanding of the Arctic surface energy budget (*Uttal et al.*, 2002) but there is very little observational work on the impact of sea ice anomalies on the top of atmosphere (TOA) radiative budget. Although surface energy budget changes are closely connected with sea ice loss, it can be argued that TOA changes are more relevant for understanding future climate change in the Arctic (and the global impact of those changes). The reason being, energy flux anomalies at the surface are often indicative of compensating changes in radiative heating of the surface versus the atmosphere that have little or no impact on the Arctic energy budget because of the rapid vertical adjustments of the coupled atmosphere/ocean/cryosphere system. For example, removing a bright cloud over a bright surface has little effect on the climate system since solar radiation is reflected by the system in both cases, but will dramatically change the surface energy budget. The TOA energy budget is closed with respect to radiative processes and tells the more revealing story about drivers and consequences of Arctic sea ice loss in the coupled climate system; is Arctic sea ice loss sustained by local radiative feedbacks or do changes in sea ice require changes in the input of energy into the Arctic via the atmospheric and oceanic circulation?

In order for changes in surface brightness to impact the TOA radiative budget, solar radiation must be transmitted downward through the atmosphere, reflected by the surface and then transmitted from the surface back to the TOA. Thus, the impact of melting ice on the Arctic energy budget depends not only on the changes in surface brightness but also on the climatological optical properties of the atmosphere (i.e. on solar reflectors such as clouds and aerosols and solar absorbers such as water vapor). Recent work (*Donohoe and Battisti*, 2011) has demonstrated that, in the global average, the impact of surface albedo on TOA albedo is reduced by a factor of three due to the solar opacity of the atmosphere. That work focused on the global climatology, but also suggested that the impact of Arctic surface albedo changes on the TOA radiation would be damped by a factor of five in the absence of concurrent cloud changes. The reason being, clouds are ubiquitous in the Arctic and, as a result, changes in surface brightness seen from the view of the TOA (i.e. the TOA energy budget) are masked by the cloud cover.

While the Arctic ice albedo feedback has been thoroughly studied in climate models using ensembles of forced simulations (*Bony et al.*, 2006) and radiative kernel techniques (*Soden and Held*, 2006) there have been very few observationally based studies on the ice albedo feedback (*Wang and Key*, 2005; *Kato et al.*, 2006). *Pistone et al.* (2014) used the interannual covariance between surface albedo anomalies and TOA radiation to deduce that sea ice decline in recent decades has resulted in more the 6 W m^{-2} additional solar radiation absorbed in the Arctic climate system. While novel in its use of the observations, this study assumed that the TOA radiation that co-varies with the surface albedo were caused by changes in the surface albedo – a logical connection but one that potentially confuses cause and effect. An alternative explanation is that radiative anomalies are either directly forcing sea ice loss or are responding to processes connected with the sea ice loss. For example, increases in downward solar radiation at the surface due to decreased cloud cover could initiate sea ice loss (*Kay et al.*, 2008; *Choi et al.*, 2014). Alternatively, sea ice loss may lead to decreased cloud cover by way of reduced stability in the boundary layer (*Schweiger et al.*, 2008). Either process could explain or contribute to the observed connection between TOA and surface anomalies. If that were the case, observational estimates of the role of the ice albedo feedback in the global climate system would have to be reevaluated. The *Pistone et al.* (2014) estimate of Arctic radiative changes associated with sea ice loss translates to a global mean positive radiative feedback of 25% of the forcing, suggesting a substantial (25%) amplification of future global temperature change by the Arctic ice albedo feedback which may be erroneous. Furthermore, the amplitude of the Arctic surface albedo feedback is the primary driver of model differences in the polar amplification of surface temperature changes (*Kay et al.*, 2012). Current observational estimates put the Arctic ice albedo feedback at the upper end of the model range and, thus suggest that future climate change will be strongly polar amplified. These observational estimates may be biased high if cloud processes indeed play a significant role in sea ice loss. Thus, future estimates of polar amplification and associated sea ice loss rely on understanding the radiative anomalies that result directly from sea ice loss versus those that are forcing or co-varying with sea ice extent.

1.1 Science questions

The overarching premise of this proposal is that the coupling between TOA radiation and sea ice retreat and its connection to cloud and surface radiative properties needs to be better understood in the observational record and appropriately represented in models. Currently available satellite products provide a unique opportunity to make substantial progress and we propose to answer the following questions:

- What are the mechanisms connecting TOA radiative anomalies with sea ice? Are the radiative anomalies caused by or are they forcing the sea ice anomalies?
- How do concomitant changes in the atmospheric optical properties (i.e. cloud changes associated with the sea ice loss) affect the connection between TOA and surface energy balance?

- What are the phase relationships between surface, atmosphere, and TOA changes? Ultimately, what processes drive Arctic ice loss and what processes respond to/damp the ice loss?
- What are the drivers of atmospheric variability that modify the relationship between TOA albedo changes and those at the surface?
- How are Arctic wide radiation budget changes connected to the global climate system; is the Arctic a passive responder to changes in the tropics and mid-latitudes or do changes in the Arctic drive far reaching climate changes?
- How does the current generation of climate models capture the radiative coupling between the TOA and the surface in the Arctic? How does their ability to do so affect predictions of future change and variability?

1.2 Approach

Nature does not afford controlled scientific experiments where a single variable can be changed in the absence of other changes and, thus, statistical relationships may be confused with casual physical mechanisms.

Our primary approach in the proposed work is to use a simple physical model of atmospheric radiative transfer to understand the relative contributions of surface and atmospheric processes to the Arctic radiative budget. This approach uses information about the radiative fluxes at the TOA and the surface – derived from satellite measurements – to glean the signatures of clouds and the surface on the TOA radiation. Preliminary results (shown in Section 2.2) suggest that a significant portion of the changes in the Arctic TOA radiation that occur when sea ice declines are not directly caused by the ice loss itself. Rather, much of the radiative anomalies associated with ice loss are a consequence of atmospheric constituents that co-vary with the ice loss. Therefore, previous work that relied on the co-variability of TOA radiation and surface albedo likely overestimated (by a factor of more than 2) the Arctic surface albedo feedback. A critical question to ask is: are the radiative anomalies we observe at the TOA driving the sea ice loss, a direct consequence of sea ice loss, or an indirect consequence of the ice loss via changes in clouds (or water vapor)? For example, ice loss is expected to warm and moisten the lower atmosphere resulting in low cloud thinning and high cloud thickening (*Schweiger et al.*, 2008). The net impact of such ice-loss-induced cloud changes on the TOA radiation is unclear.

An understanding of the root cause of Arctic sea ice variability is essential to backing out the direct impact of ice loss on TOA radiation from the co-varying radiative anomalies that either force or respond to the sea ice loss. For example, if ice anomalies are forced by anomalously clear skies leading to surface solar heating, that forcing would co-vary with and may mistakenly be identified as a result of the ice loss when, in reality, it was the forcing agent. Alternatively, if sea ice variability is triggered by anomalous atmospheric energy transport into the Arctic (remotely forced), the atmospheric energy flux is expected to result in a source of heating within the atmospheric column. The latter would affect the temperature, humidity and static stability of the atmospheric column and, thus, the cloud cover (fraction, height, optical thickness) and radiation (both SW and longwave) at the top of the atmosphere. Again, a portion of the TOA radiative anomalies that result from the processes that lead to sea ice variability would be mistakenly be identified as resulting from the sea ice variability itself. The aim of the proposed work is to achieve a better understanding of the connection between observed TOA radiative anomalies and sea ice loss. The broader goal is to understand the role of radiative processes in sustaining or damping Arctic sea ice anomalies and to compare the variability in Arctic radiation with that in the other processes –mainly the atmospheric energy transport into the Arctic and energy storage in the ocean and atmospheric column –that potentially contribute to sea ice retreat. Are sea ice anomalies a result of local radiative processes (feedbacks and forcing) or a consequence of changes in the energy input to the Arctic via the atmospheric energy transport and are the same mechanisms responsible for the interannual variability likely players in the response to global warming?

2 Methodology

The portion of incident solar radiation (insolation) that is not reflected back to space is absorbed within the climate system – either at the Earth's surface or within the atmospheric column. Therefore, the ratio of upwelling shortwave (SW) radiation at the TOA to insolation – the planetary albedo (α_P)– determines how much SW radiation is absorbed in the climate system. Over the Arctic, reflection off of clouds and reflection off the bright surfaces both contribute to α_P and the relative contributions of each are difficult to disentangle from radiation measurements at the TOA only (i.e. from satellites). However, simultaneous radiative measurements at the surface and TOA provide additional constraints since reflective clouds in the atmosphere will both reflect radiation to space and limit the transmission of radiation to the surface. Here, we propose to use simultaneous observational estimates of radiative fluxes at the TOA and surface to partition the satellite derived planetary albedo into surface and atmospheric contributions in order to derive a more comprehensive observationally based estimate of the Arctic surface albedo feedback.

Donohoe and Battisti (2011) recently developed a method for partitioning the observed climatological α_P into atmospheric and surface contributions using the CERES satellite data alongside the accompanying surface radiative flux products (*Kratz et al.*, 2010). In short, their method relies on a single layer atmosphere, isotropic SW radiation model which assumes that, independent of whether light is traveling upward or downward, a fixed fraction of the radiation incident on the atmosphere is absorbed and reflected by the atmospheric layer. For example, as light passes downward through the atmosphere, a fraction R is reflected back to space and a fraction A is absorbed within the column with the remainder (1-R-A) transmitted to the surface where it can be reflected by the surface albedo (α). The same processes is repeated for the upwelling radiation reflected by the surface and the reflections are continued indefinitely. The result is a set of predictive equations for the upward and downward SW fluxes at the TOA and surface given values of the fractional reflection (R) and absorption (A) of the single atmospheric layer. Given satellite based measurements of the radiative fluxes at the TOA and surface, one can solve the system of equations analytically and uniquely for A and R. One can then identify the contribution of atmospheric reflection ($\alpha_{P,ATMOS}$) versus surface reflection ($\alpha_{P,SURF}$) to the reflected SW radiation at the TOA. In order for the surface to contribute to α_P, the insolation must be transmitted through the atmosphere to the surface, reflect off the surface and then be transmitted back through the atmosphere to the TOA. Therefore, $\alpha_{P,SURF}$ is equal to α times the atmospheric SW transmissivity squared which is 0.34 in the global average and 0.2 over the Arctic. This method is simple to implement, physically based, compares well with comprehensive radiative transfer calculations (Section 3.1.2) and can be applied to observational data products and model output alike to allow for a comparison between observed and modeled processes. In the proposed work, we will apply this same methodology to the interannual and interseasonal variability of the Arctic planetary albedo over the CERES era (2000-2015). The end goal is to link sea ice variability with the surface contribution to planetary albedo to directly assess the ice albedo feedback.

2.1 Preliminary results: sea ice loss has very little direct impact on TOA radition

When sea ice area declines, α averaged over the Arctic domain (defined as poleward of 60°N) decreases (not shown) and the Arctic average α_P also decreases (c.f. the blue and red lines in Figure 1A). A one unit increase in Arctic averaged α is associated with 0.47 unit change in α_P (shown by the red regression slope in Figure 1). This matches the finding of *Pistone et al.* (2014) who interpreted this number to represent the actual impact of α changes on TOA radiation. However, the isotropic SW model suggest that the planetary albedo change that is directly due to change in surface albedo ($\alpha_{P,SURF}$) is significantly smaller in magnitude than the total change in α_P (the green line is Figure 1); the regression slope between $\alpha_{P,SURF}$ and α is 0.2 (dashed green line in Figure 1). This result suggests that looking at statistical correlations between α and α_P over the Arctic would overestimate the surface albedo feedback by a factor of 2.5. We note that, based on CERES climatology, less than 45% of the insolation makes it to the surface in the Arctic[*]. Therefore, in order for a one unit change in α to directly cause a 0.47 unit change in the α_P of the Arctic (as deduced from statistical correlations) more than all of the radiation reflected off the surface must be transmitted to space – an result that is not physically plausible.

We analyze the spatial pattern of α and α_P anomalies associated with an Arctic wide sea ice advance by defining the map of anomalies in a "typical" Arctic wide high α event. A "typical" pattern is defined by regressing a normalized index of the Arctic averaged α on the α anomaly at each grid point (we multiply by 2 to represent a 2σ event). It can be thought of as the average anomaly that occurs at each gridpoint when a 2σ basin wide α occurs – similar results are found from compositing around high versus low α events. The spatial pattern of α in a "typical" high α event features local maxima around the sea ice edge (contours in Figure 1C-E) with amplitudes of 60 W m^{-2} (α is multiplied by the climatological insolation to give units of W m^{-2}). In contrast, the associated α_P anomalies (contours in Figure 1C) are more spatially diffuse with nearly equal magnitude anomalies over the climatological sea ice edge and central Arctic. Moving from the ice edge North of the Canadian Arctic to the central Arctic, the α anomalies decrease by a factor of 5 but the α_P anomalies are nearly spatially invariant (c.f. the contours and colors in Figure 1C). Overall, there is a spatial mismatch in the pattern of α and α_P anomalies; the spatial pattern of α_P anomalies is more diffuse and spreads over the central Arctic and away from the ice edge. This suggests that there are changes in atmospheric reflection and/or absorption of SW radiation that are concurrent with the sea ice anomalies.

Indeed, the isotropic SW model ascribes the changes in α_P around the sea ice edge to $\alpha_{P,SURF}$ changes and the more spatially diffuse α_P anomalies over the central Arctic to $\alpha_{P,ATMOS}$ changes

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[*] The ratio of downwelling SW radiation at the surface to insolation is 0.45 in the CERES dataset. This includes contributions from multiple reflections off of the surface and clouds and, thus, 0.45 is an upper bound on the downwelling SW transmissivity of the Arctic

(c.f. the colors in Figures 1 D and E). As expected, the spatial pattern of $\alpha_{P,SURF}$ anomalies mimics that of α anomalies with reduced magnitudes (by a factor of 3-5) suggesting that the changes in $\alpha_{P,SURF}$ are being dictated by the surface brightness changes attenuated by the climatological atmospheric SW opacity. A "typical" Arctic wide α anomaly (2σ) is associated with an additional 4.2 W m^{-2} SW radiation reflected to space over Arctic, 1.5 W m^{-2} of which is due to $\alpha_{P,SURF}$ changes and 2.7 W m^{-2} of which is due to changes in $\alpha_{P,ATMOS}$. This analysis again suggests that if one were to merely look at regressions between the α and α_P over the observational record (as was done in the red line in Figure 1B and in *Pistone et al.* (2014)), the direct impact of sea ice anomalies on TOA radiation would be overestimated by a factor of 2-3. We further note that the α_P anomaly over the central Arctic is larger in magnitude than the α anomaly in that region (c.f. the magnitude of the colors and contours in Figure 1C). Even in the limit of a completely transparent atmosphere, the α anomalies can not cause such a large α_P anomaly. All evidence suggest that the α_P anomaly associated with sea ice loss is only partly a direct result of the α anomaly and that other important processes involving atmospheric constituents (i.e. clouds and water vapor) must be involved. We will identify these processes and thereby achieve a better understanding of the processes that drive sea ice loss.

3 Proposed work

The preliminary results reported in the previous section suggest that the surface albedo feedback of Arctic sea ice loss is highly attenuated by the atmospheric SW opacity and that previous observational estimates of the surface albedo feedback (*Pistone et al.*, 2014) may have confused concurrent changes in atmospheric properties with the direct impact of surface albedo on TOA radiation. This is an important finding because it suggests that these concurrent changes in atmospheric properties may have played a role in driving or modifying the sea ice losses. We propose to further investigate this finding by exploring the atmospheric conditions that lead to reduced cloud reflection when sea ice retreats, the consistency of the these findings between the CERES data set and other observations and the sensitivity of the conclusions reached to the assumptions made in the isotropic SW model. Most importantly, we wish to understand if the α_P anomalies associated with Arctic sea ice retreat are a result of the sea ice retreat –by way of changing cloud cover or atmospheric moisture content – or are byproduct of processes that force the ice retreat. Ultimately, this question is embedded in the larger question of what physical processes are responsible for the interannual and forced Arctic sea ice retreat and the associated polar amplification of Arctic surface temperature change (*Holland and Bitz*, 2003).

Based on the preliminary results we therefore formulate the following working hypothesis;

There are concomitant changes in atmospheric reflection and/or absorption when sea ice retreats that are either a result of the ice retreat or are emblematic of the large scale forcing that initiates the ice loss.

But where does this variation in atmospheric radiative properties come from? Is it connected to variability in the large scale circulation of the atmosphere or a local adjustment to surface variations? We begin by describing the proposed analysis to diagnose the nature of the cloud and atmospheric optical properties accompanying the sea ice loss including the methodological uncertainties associated with our application of the isotropic shortwave model to the CERES data (Section 3.1). Next, we propose analysis of the connection between sea ice variability and the en-

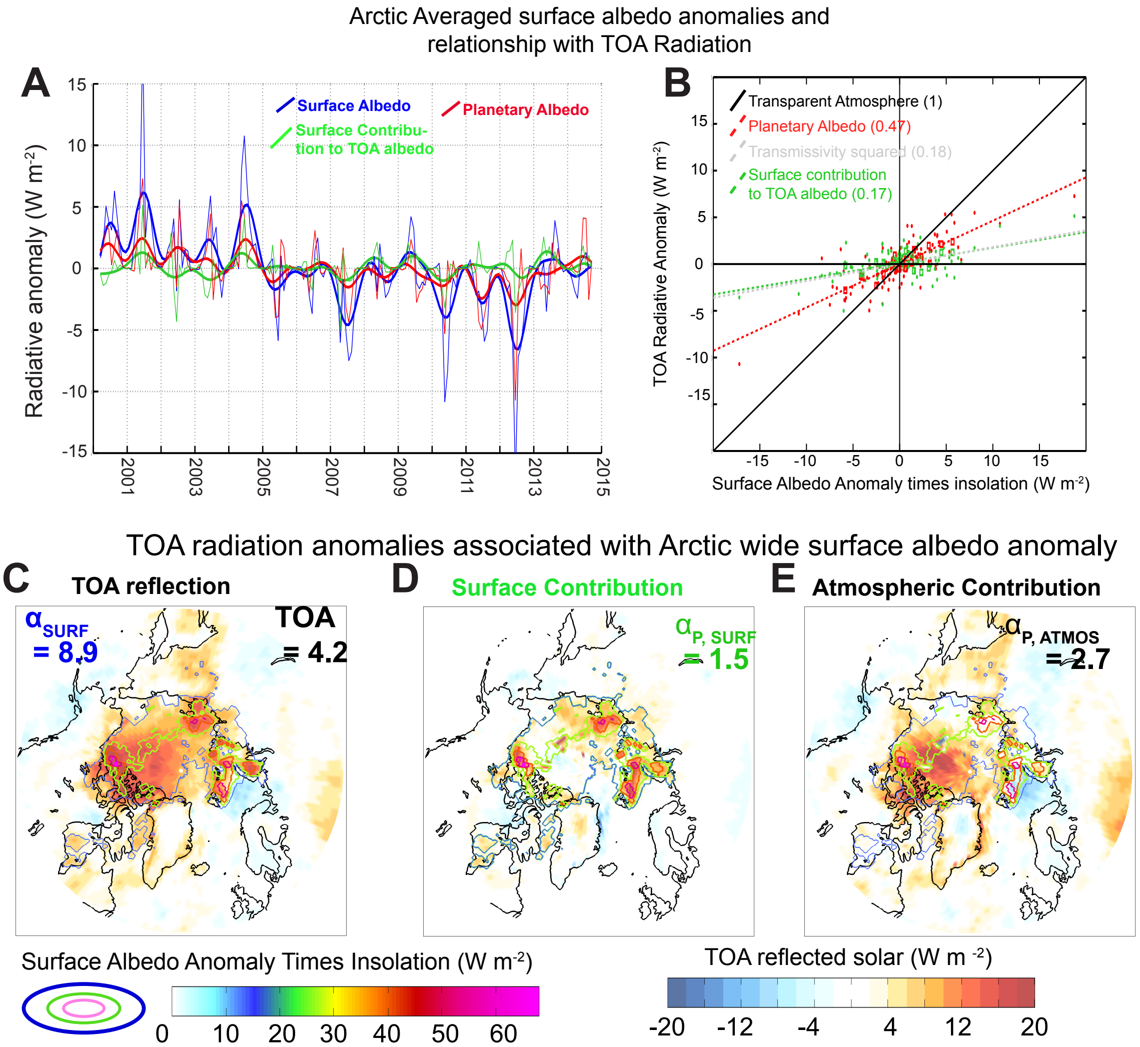

Figure 1: (A) Time series of anomaly in Arctic averaged (blue) surface albedo, (red) planetary albedo and (green) surface contribution to planetary albedo from CERES. All data are expressed as monthly albedo anomalies from climatology and then multiplied by the climatological insolation to account for solar weighting. Thin lines are monthly means and thick lines are low pass filtered with a 1 year cutoff period. (B) Scatter plots of Arctic averaged (red) α_P and (green) $\alpha_{P,SURF}$ versus α. Thin crosses are monthly mean anomalies, square boxes are low pass filtered results and dashed lines are linear best fits. The black line is the 1:1 relationship that would be expected if the atmosphere was completely transparent to SW radiation and the silver line is the atmospheric climatological atmospheric SW transmissivity squared – the relationship that would be expected if clouds did not vary above the α anomalies. (C-E) Spatial maps of (C) α_P, (D) $\alpha_{P,SURF}$ and (E) $\alpha_{P,ATMOS}$ associated with an Arctic wide α anomaly. The contours show the spatial map of the surface albedo map with contour interval of 15 W m^{-2} and the domain average values (in W m^{-2}) are given in the upper corners.

ergy transport into the Arctic by atmospheric motions (Section 3.2). Lastly, we discuss how we will use an ensemble of climate model simulations to analyze the physical processes that initiate, sustain and damp Arctic sea ice variability and if the same physical processes are responsible for the long term trends in Arctic sea ice loss due to external forcing (Section 3.3).

3.1 The connection between sea ice loss, cloud anomalies, and atmospheric optical properties

The isotropic SW model suggested that atmospheric reflection and/or absorption co-varies with Arctic sea ice decline. Here we look for signatures of that co-variance in the cloud and water vapor fields and assess the observational uncertainties on the relationship between sea ice retreat and TOA radiation.

3.1.1 Cloud changes accompanying sea ice anomalies

The multispectral Moderate Resolution Imaging Spectroradiometer (MODIS) is co-located with the CERES instrument on the AQUA and TERRA satellites and, thus, can be used to provide cloud observations alongside the CERES radiation data (*Platnick et al.*, 2003). We will analyze cloud fraction, cloud optical thickness, derived water path and cloud top pressure and the co-variance of these fields with sea ice and TOA radiation. The detection of cloud properties by MODIS over ice is known to be more problematic than over open ocean due to the similarity of thermal and SW optical properties of clouds and surface ice (*Liu et al.*, 2010). This is potentially problematic for our analysis since we aim to explicitly look at the co-variability of ice and clouds and this bias maybe confused for actual variability of the cloud fields. For this reason, we will also incorporate data from CloudSat radar and CALIPSO lidar in the synchronously flying A-train constellation of satellites (*Stephens*, 2008). Cloudsat Calipso data have limited spatial and temporal resolution and are only available since 2006 but provide an unprecedented vertical profile of cloud properties that is devoid of the contamination by changes in the surface brightness. *Kato et al.* (2011) recently developed a merged MODIS/CERES and CloudSat/Calipso product of cloud profiles based on a joint analysis of the different satellite products. We will compare the co-variability of sea-ice and clouds/atmospheric reflectance in this merged product over 2006-2014 period and compare with that in the MODIS product to determine if and how cloud detection in MODIS is biased by concurrent changes in surface brightness. Understanding and adjusting for this potential bias will allow us to analyze the co-variability of clouds and sea ice over the entire CERES era.

Additionally, we will analyze the relationship between sea ice, TOA radiation and cloud properties in the extended Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP-x) dataset (*Wang and Key*, 2005). This dataset covers the 1982-2011 period with further extensions to become available soon (J. Key pers. comm) and includes both TOA and surface radiative fluxes as well as cloud properties derived from the cloud and surface parameter retrieval (CASPR) system for polar AVHRR (*Key*, 2002). While the CERES data provides the most observationally constrained estimate of TOA radiation, we will analyze the APP-x data for consistency of our scientific findings and assess the potential for extending the observationally based calculation of the Arctic surface albedo feedback back to 1982 to provide a better context for the relative amplitudes of observed trends and natural variability of TOA radiation and sea ice.

3.1.2 Methodological uncertainties: accuracy of CERES surface albedo and isotropic SW model

As part of our investigation we will examine whether methodological problems may have contributed to the conclusion that TOA radiative anomalies associated with sea ice retreat are primarily due to changes in atmospheric as opposed to surface optical properties. Several possibilities exists: 1. The CERES product is underestimating the spatial extent of the surface albedo anomalies, especially over the central Arctic where melt ponds may exists, 2. The isotropic SW model is mis-attributing changes in α_P between changes in surface and atmospheric processes due to shortcomings of the isotropic and single layer assumptions. We believe neither of these shortcomings are effecting our preliminary conclusions based on comparison with the results of *Choi et al.* (2014) and *Kay et al.* (2008) and the performance of the isotropic model against a comprehensive radiative transfer model (discussed below). Nonetheless, we briefly explore the methodological uncertainties here.

Accuracy of CERES surface albedo

The CERES surface albedo is derived by first identifying the cloud scene from MODIS and then "tuning" the surface albedo (via a Lagrange Multiplier minimization technique) alongside atmospheric optical properties so that the TOA fluxes in the radiative transfer model (*Fu and Liou*, 1993) best match those observed by the CERES instrument for each cloud scene (*Rutan et al.*, 2006). Potential problems with the CERES α retrievals include: 1. Faulty cloud scene identification 2. Changes in the spectral shape of the surface albedo – which is prescribed from look up tables based on the initial scene identification and thereafter multiplied by a scalar (representative of the broadband α) in the "tuning" process. Despite these limitations, the CERES derived surface radiative budget agree with ground based measurements to within 2% (*Rutan et al.*, 2001). The goal of the proposed work is to evaluate the CERES Arctic sea ica albedo and its variability against alternative measurments of Arctic α.

We will compare the spatial pattern of albedo anomalies associated with sea ice retreat in the CERES data with that from the MODIS MCD43 (*Schaaf et al.*, 2002) product which is derived from measurements on the same satellite as the CERES instruments but provides additional spectral and angular dependencies of the surface albedo (*Lucht*, 1998). Additionally, *Rosel et al.* (2012) recently developed a (spectral unmixing) technique for melt pond detection from MODIS that we will use to assess if the CERES data adequately captures the spatial extent of surface darkening during a sea ice retreat event. Lastly, we will pursue the hypothesis that improper cloud scene identification by MODIS is leading to an underestimation of CERES α anomalies by comparing the CERES α anomalies to those derived using additional inputs of cloud vertical profiles from CALIPSO by comparison to the merged CERES-CALIPSO-MODIS product (*Kato et al.*, 2011) over the common time period (2006-2014) which includes the widespread sea ice retreat events of 2007 and 2012. Although MODIS cloud detection biases have been examined before (*Liu et al.*, 2010), here we will specifically focus on biases in CERES surface radiation products.

Validation of the isotropic SW model using radiative transfer calculations

The partitioning of SW radiative fluxes at the TOA into surface and atmospheric processes relies on the assumptions of the single layer isotropic model: A. The atmosphere can represented by a single layer and B. Atmospheric reflection and absorption are isotropic and can be represented by a single fraction representative of broadband optical properties. We emphasize that the preliminary conclusions found here – that a substantial portion of the TOA radiative anomalies associated with sea ice decline are not a direct consequence of the surface albedo feedback – are supported by findings that do not rely on the isotropic SW model including: 1. The spatial mismatch between the surface and TOA albedos in a "typical" ice retreat event and 2. The order 4-5 atmospheric attenuation of the impact of α anomalies to α_P expected from the mean state atmospheric opacity in the Arctic. Nonetheless, we will analyze the accuracy of the partitioning of α_P into atmospheric ($\alpha_{P,ATMOS}$) and surface ($\alpha_{P,SURF}$) contributions in the SW isotropic model by evaluation against an ensemble of experiments in a radiative transfer model. Specifically, we will input various atmospheric profiles representative of the Arctic (i.e. different cloud types, heights and cloud fractions) into the Streamer radiative transfer model (*Key and Schweiger*, 1998). For each atmospheric profile, we will vary the α from 0 to 1. We will then use the TOA and surface radiative fluxes from Streamer output to partition α_P into $\alpha_{P,ATMOS}$ and $\alpha_{P,SURF}$ via the isotropic model. If the isotropic model is working properly, all changes in TOA radiation that result from the imposed sweep across α in Streamer should be attributed to $\alpha_{P,SURF}$, since the atmospheric optical properties are fixed. These experiments will allow us to evaluate the isotropic SW model against the behavior of a more comprehensive radiative transfer model and assess the uncertainties of decomposing the observed α_P into $\alpha_{P,ATMOS}$ and $\alpha_{P,SURF}$ over the Arctic.

A similar evaluation of the isotropic model was performed by *Donohoe and Battisti* (2011). They found that the model performed very well globally and that the isotropic and single layer assumptions were consistent with the radiative transfer calculations. The Arctic climate system presents a unique challenge in SW radiative transfer because both the clouds and surface are highly reflective. As a result, radiative fluxes at the TOA and surface include contributions that have reflected back and forth between the surface and clouds. These interactions are explicitly included in the isotropic SW model which allows for an infinite number of reflections between the surface and clouds (by way of an analytic solution). Preliminary results using the above methodology suggests that the isotropic model is particularly well suited for the Arctic atmosphere; changes in α_P that result from α changes for a fixed atmospheric optical properties are primarily ($> 95\%$) attributed to $\alpha_{P,SURF}$. These preliminary results suggest that the isotropic SW model is an excellent tool for improving observational evaluations of the Arctic surface albedo feedback and improving our understanding of the root cause of sea ice retreat.

3.2 Atmospheric circulation changes associated with sea ice retreat

We have shown that the net radiative input into the Arctic varies by approximately 3 W m^{-2} from year-to-year due primarily to changes in atmospheric optical properties. It is unclear if the changes in cloudiness are a consequence of the ice retreat, forcing the ice retreat or if the statistical relationship between Arctic sea ice and TOA radiation is due to a common dependence on a third process such as changes in the atmospheric circulation. Here, we investigate the connection between sea ice retreat and the atmospheric circulation to ask: does the atmospheric circulation force Arctic sea ice retreat (and associated radiative anomalies) or respond to it? In the annual mean climatology, TOA radiation cools the Arctic by approximately 100 W m^{-2}. This energy loss is nearly balanced by energy input into the Arctic by the large scale atmospheric circulation (*Serreze et al.*, 2007) – commonly referred to as F_{WALL}. The ocean energy transport into the Arctic is an order of magnitude smaller. Sea ice retreat leads to radiative energy gain in the Arctic via the ice albedo feedback which, all else being equal, requires a smaller F_{WALL} into the Arctic. In contrast, an anomalously strong F_{WALL} heats the local atmosphere leading to surface heating and ice melt via enhanced downwelling longwave radiation at the surface. Thus, sea ice loss would phase lead and be associated with decreased F_{WALL} if it was forcing the atmospheric circulation and would phase lag and be associated with enhanced F_{WALL} if it were responding to atmospheric circulation. The goal of this piece of proposed analysis is to assess whether F_{WALL} forces or responds to sea ice loss and to assess the impact of the atmospheric circulation anomalies on the TOA radiation via its effect on the vertical structure of atmospheric temperature and cloudiness.

Essential questions to be asked are: How big is the interannual variability of F_{WALL} relative to the radiative anomalies induced by sea ice loss? At what vertical level do F_{WALL} anomalies heat the atmosphere? What is the impact of the atmospheric circulation anomalies on the Arctic cloud cover? Recently, *Donohoe and Battisti* (2013) developed a novel methodology for calculating the vertical structure of atmospheric energy fluxes from the observational reanalyses. Their method decomposes the atmospheric energy fluxes into components associated with the mass overturning circulation of the atmosphere, stationary eddies (associated northward flow at one longitude and 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 the F_{WALL} anomalies.

Our preliminary calculations of F_{WALL} using the methodology of *Donohoe and Battisti* (2013) on the NCEP reanalysis (*Kalnay et al.*, 1996) suggests two novel findings that begin to answer the questions posed above:

- The inter-annual variability of F_{WALL} (2σ) is approximately 7 W m^{-2} (Figure 2D and E) and exceeds that in the TOA radiation (3 W m^{-2}) substantially[†]. Thus, radiative processes alone can not drive the anomalies in F_{WALL} in the absence of concurrent changes in the energy input to the atmosphere via surface energy fluxes. This finding suggests that radiative processes can not be the primary driver of Arctic sea ice variability because, if the radiation was the primary driver, the anomalous radiative heating of the Arctic would be expected to warm the Arctic atmosphere leading to less F_{WALL} and an F_{WALL} that damps but *is smaller in magnitude* than the radiative anomaly. Rather, our findings suggest that the dominant Arctic energy balance at the interannual timescale is between atmospheric energy transport into Arctic balanced by energy exchange between the ocean and atmosphere. The cause and effect of that relationship and connection to sea ice loss is unclear and we hope to gain further insight in future work.

- Much ($\approx$40% of the energy transport into the Arctic occurs in the stratosphere (Figure 2A and B) as was previously suggested by *Overland and Turet* (1994). 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 component of F_{WALL} only may lead to new insights into the connection between sea ice and atmospheric circulation.

In the proposed work, we will perform similar calculations of F_{WALL} using the NASA Modern-Era Retrospective Analysis (MERRA– *Rienecker et al.*, 2011) and ERA-interim (*Dee et al.*, 2011) reanalysis to check for the consistency of the calculations between reanalyses and the robustness

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[†] Atmospheric energy storage is small but non-negligible (1.5 W m^{-2})

of our scientific conclusions and interpretations. Furthermore, we will look for signatures of the circulation on the large scale cloud fields, radiation and the phase relationship with sea ice retreat in order to separate cause and effect and isolate the mechanism responsible for sea ice retreat from those processes that respond to the ice loss.

3.3 GCM studies

While the proposed study is primarily observationally based, we will compare our observational findings on the impact of Arctic sea ice variability on TOA radiation and the physical processes responsible for sea ice decline with the same behavior in the suite of GCMs participating in the Coupled Model Intercomparison Project Phase 5 (*Taylor et al.*, 2012). We will analyze the internal variability of Arctic sea ice in pre-industrial (PI) simulations and the response of sea ice to anthropogenic forcing in strongly forced (instantaneous CO_2 quadrupling simulations– hereafter $4XCO_2$). Specifically, we will partition α_P in the models into $\alpha_{P,ATMOS}$ and $\alpha_{P,SURF}$ via the isotropic SW model and calculate the implied ice albedo feedback from the relationship between α and $\alpha_{P,SURF}$. We will then compare this calculation with the ice albedo feedback calculated from the co-variability of TOA radiation and surface albedo (in the models) to see if the atmospheric absorption and reflection co-vary with the Arctic sea ice in the models (as our preliminary findings in the observations suggests). We will further analyze if the relationship between sea ice retreat and TOA radiation at the interannual timescale is the same as the models' response to external forcing. That is, are the cloud changes associated with the sea ice retreat at the interannual timescale:

A. A consequence of the ice retreat? In this case, the same cloud changes are expected to apply to the long term response to external forcing. Or,

B. Part of and/or emblematic of the processes that force the interannual variability of sea ice? In this case, the cloud changes are associated with the processes that force the ice retreat and have a non-casual statistical relationship with the ice extent that should not be expected to apply to the long term response to anthropogenic forcing.

By comparing the relationship between sea ice retreat and TOA radiation in the simulated (unforced) interannual variability with that in the response to external forcing, we can assess how much of the TOA radiative anomalies are a consequence of the ice retreat versus that which is due to other processes (i.e the mechanisms that force the ice retreat) to yield a better understanding of the ice albedo feedback. Specifically, we will compare the relationship between Arctic sea ice retreat and TOA radiation – measured as the change in Arctic averaged α_P per unit change in α – in a "typical"[‡] unforced ice retreat event within the PI simulation (the regression between α and α_P anomalies) with that in the change in long term means between the $4XCO_2$ simulation and PI simulation (the forced response). The end goal is to remove the component of the TOA radiation that is associated with the processes that force the natural variability of sea ice from our assessment of the ice albedo feedback since these processes will not contribute to the long term response to external (i.e. anthropogenic) forcing. Ultimately, the goal of this analysis is to develop a technique for calculating the impact of sea ice loss on TOA radiation – the ice albedo feedback– from interannual variability alone. The reason being, the observational record features large interannual variability and a small trend and the end goal of this work is refine our observational calculation of

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[‡] "Typical" is defined by the regression of a normalized index of Arctic wide sea ice retreat onto the field being analyzed.

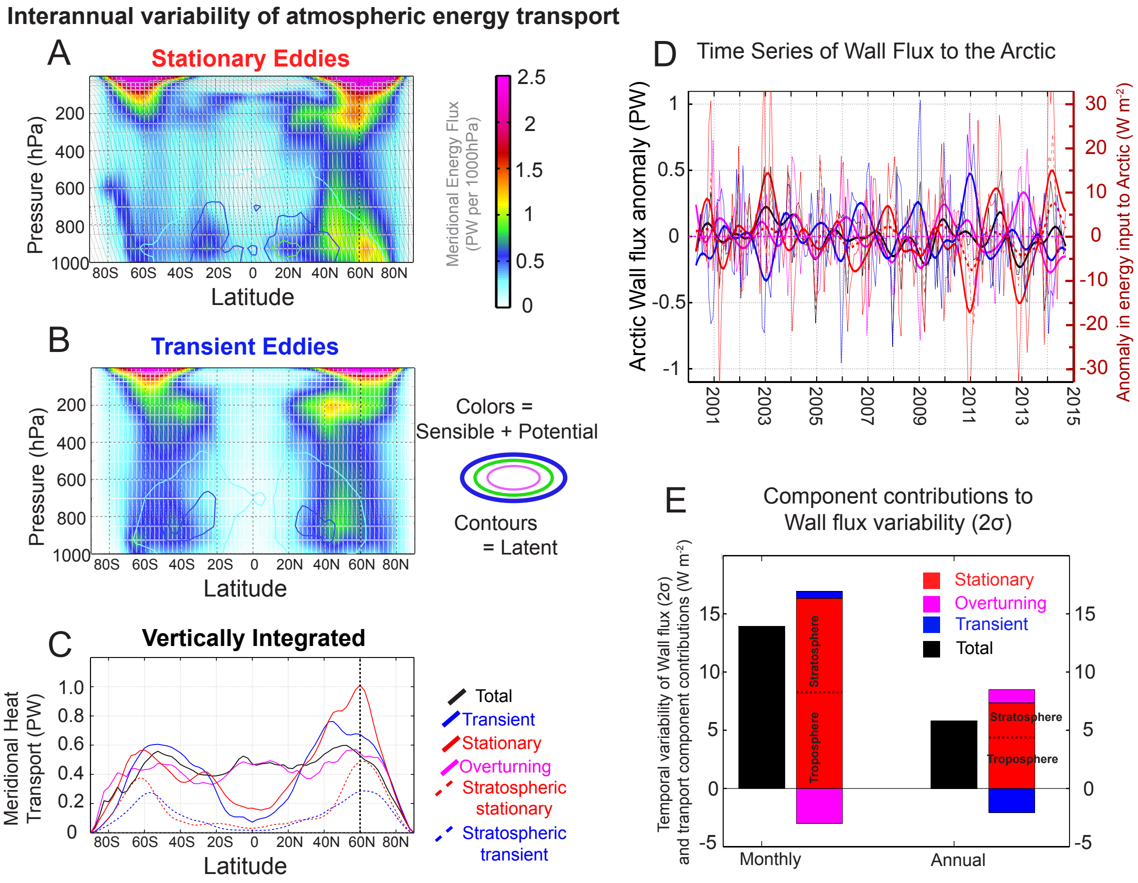

Figure 2: The vertical and latitudinal structure of interannual variations (2σ of monthly anomalies) of poleward atmospheric energy transport in the (A) stationary eddies and (B) transient eddies. The dry (potential plus sensible) energy transport is shown in colors and the contours are the moisture (latent) transport with the same colorbar to the right. The units are PW per 1000 hPa such that vertically averaging panels A and B gives the resultant vertically and zonally integrated atmospheric energy flux in PW (10^{15} W) shown in panel (C). 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). (D) Time series of anomalies in F_{WALL} into the Arctic (across 60°N) subdivided into the component circulations including the stratospheric circulation (dashed line). (E) The monthly (left) and interannual(right) variability of F_{WALL} (2σ) and the contributions from each circulation type defined as the regression of a normalized index of total F_{WALL} onto each component circulation.

the ice albedo feedback using the statistics and physical based models.

The combination of forced and unforced simulations will allow us to: 1. Determine if the relationship between Arctic sea ice and TOA radiation is the same for both forced and natural variability, 2. Assess if the physical mechanisms leading to interannual variability of sea ice are the same as those responsible for long term trends and 3. Give context to the relative amplitudes of trends versus internal variability of the Arctic energy budget (i.e. TOA radiation and F_{WALL}). Overall, the proposed GCM study will allow us to understand if the impact of sea ice retreat on TOA radiation seen over the observational period – in which the year-to-year variability is larger than the long term trend– should be expected to apply to the long term response of the Arctic to global warming.

4 Relevance to NASA Goals

The proposed work will *utilize space-based remote sensing data* primarily from CERES, MODIS and CloudSAT/CALIPSO to investigate the connection between Arctic sea ice loss and the top of the atmosphere radiation budget. By doing so we will help *determine the mechanisms controlling the sea ice cover, including the quantification of the connection between sea ice and the atmosphere*. By quantifying the roles of clouds and atmospheric transport in the atmosphere from remote sensing observations and comparing the results to GCMs, the proposed research will *help improve predictive models* and *elucidate connections to the global system.* The research directly addresses the US Arctic Research Plan (2013-2017) program priorities of *"developing an integrated understanding of Arctic Atmosphere processes, their impact on the surface energy budget"* to which NASA is tasked to contribute.

5 Working timeline

- **Year one–analysis of co-variability of sea ice and cloud fields and methodological uncertainties**
    1. Analysis of MODIS and CALIPSO cloud fields that co-vary with sea ice retreat and validity of extending results to longer time period with APP-x data
    2. Assess spatial extent of surface albedo anomalies in CERES versus other data sets
    3. Assess performance of isotropic SW model in Arctic climate system against radiative transfer calculations
- **Year two –Variability of F_{WALL} and relationship with TOA radiation and sea ice retreat**
    1. Perform atmospheric energy transport calculations with MERRA,NCEP and ERA reanalysis and check for consistency of the interannual variability between the different reanalyses
    2. Analyze co-variability of F_{WALL} with sea ice, TOA radiation and the vertical profile of atmospheric temperature and humidity. Further analyze lead/lag relationships and the impact the vertical structure of F_{WALL} has on the atmosphere and its link to surface climate, cloud fields and TOA radiation.

- **Year three – General circulation model studies**
  1. Apply isotropic SW model to CMIP5 pre-industrial simulations. Analyze the Arctic surface albedo feedback from $\alpha_{P,SURF}$ and compare to that from the co-variability of α and α_P: do clouds co-vary with ice retreat as was suggested by the observations?
  2. Look for root cause of natural sea ice variability. Assess the roles of atmospheric and ocean energy transport into the Arctic and radiative processes by use of lead lag analysis. Does the atmospheric circulation remotely force sea ice loss or does it respond to sea ice anomalies?
  3. Analyze mechanisms of long term sea-ice retreat in $4XCO_2$ simulations. Look at relative magnitudes of radiative feedbacks versus changes in atmospheric and oceanic circulation. Are the same mechanisms that force the interannual variability responsible for long term retreat of ice and is the implied ice albedo feedback equivalent to that deduced from inter-annual variability?

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