The relationships between Arctic sea ice and cloud-related variables in the ERA-Interim reanalysis and CCSM3

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Abstract

This study uses reanalysis data from ECMWF ERA-Interim and GCM output from the CCSM3 to investigate how sea ice and clouds interact locally (within individual grid boxes) and whether similar variability between the two datasets is captured. During autumn (October), the vertically integrated low cloud amount increases over increased sea ice in the reanalysis, but decreases in the GCM output. Closer inspection, however, reveals that both datasets have more low cloud cover over increased sea ice within the lower boundary layer (1000–925 hPa for the reanalysis and 1000–975 hPa for the GCM output), but they differ in their integrated response within the lower troposphere. These results highlight the differences between the datasets and show the importance of understanding where cloud changes occur, because clouds vary in their effect on the radiation budget as a function of height.

Keywords: Arctic sea ice, ECMWF ERA-Interim, Arctic clouds

1. Introduction

The polar regions, especially the Arctic, are expected to undergo the largest changes as our climate responds to increases in greenhouse gases. Polar sea ice is coupled closely to the atmospheric and surface energy budget, atmospheric circulation, and the hydrologic cycle. The coupling between sea ice and clouds is of particular importance, because clouds heavily influence the surface energy budget. This intimate relationship makes the Arctic a sensitive component of the earth system, and with global changes in climate and increases in greenhouse gases occurring, changes to the aforementioned processes may cause striking changes in the Arctic landscape.

Summer sea ice extent (September) has declined roughly 11% per decade, while winter sea ice extent (March) has declined roughly 3% per decade between 1979 and 2009 (Perovich and Richter-Menge 2009). The past four years (2007, 2008, 2009, 2010) have the lowest sea ice concentrations on record over the period 1979–2010, with the record minimum being observed in September 2007 (37% below the 1979–2006 average (Comiso and Nishio 2008)).

These observed declines in sea ice have been occurring at a faster pace than models predict when forced with increased greenhouse gas (GHG) concentrations (Stroeve et al 2007). IPCC AR4 models simulate an ice-free Arctic during the summer between 2050 and 2100, while other studies suggest an ice-free Arctic during the summer in roughly the next one to three decades, with the most extreme cases in 11 years (Wang and Overland 2009). Understanding the uncertainty amongst feedback mechanisms in the Arctic is paramount in clarifying the trajectory of future Arctic sea ice loss. One of the most uncertain processes is how clouds and their ‘accomplices’ (radiation, moisture advection, and water vapor) either enhance or slow the pace of sea ice loss in the Arctic.

The behavior of clouds remains the most uncertain quantity in our understanding of climate change (IPCC full report 2007, Corell et al 2004). These uncertainties involve the response of clouds to changes in large-scale circulation patterns and the effect cloud changes may have on surface radiation fluxes. Because ice edge variability seems to be closely tied to changes in downward emission of longwave radiation (Francis and Hunter 2006), it is important to establish an understanding of how clouds and sea ice interact in a less
ice covered Arctic, and what their influence is on the surface (Curry et al. 1993). The impact clouds have on radiation depends on factors such as cloud amount, phase, particle size, and vertical distributions with height (Randall and coauthors 1998, King et al. 2004). Over the course of the year, clouds tend to exert a warming influence, with some cooling briefly during the summer (Curry and Ebert 1992, Key et al. 1999). Satellite derived products have shown that changes in surface energy fluxes coincide well with respect to seasonal changes in clouds (Wang and Key 2003, 2005, Schweiger 2004, Liu et al. 2008). Likewise, modeling studies by Vavrus et al. (2008) show that under projected future greenhouse forcing, cloudiness is enhanced over the present-day sea ice pack and decreases over peripherally open water regions. Increases are largest during autumn, with the greatest increases occurring for low (below 700 hPa) and high (above 400 hPa) clouds. Because clouds warm the surface during most of the year, enhanced cloudiness may amplify future warming.

Recent work in understanding the relationship between clouds and sea ice has led to mixed results, particularly in autumn, when future sea ice declines are expected to be greatest. Schweiger et al. (2008), using the European Centre for Medium-Range Weather Forecasting (ECMWF) ERA-40 reanalysis from 1980–2001, found that cloud heights rose over decreased sea ice as a result of decreased static stability, leading to fewer low clouds but more mid-level clouds. Palm et al. (2008) found that very low cloud amount, below 500 m, declined over reduced sea ice cover. These results differ from Kay and Gettelman (2009) and Eastman and Warren (2010), who reported low cloud increases over enhanced open water. Expanding upon the investigation of the autumn response in Schweiger et al. (2008), our study uses the ECMWF ERA-Interim reanalysis for all 12 months and extends the analysis period through 2009. In this letter we focus mainly on autumn, particularly October, because it serves as the period of greatest predicted changes in cloud cover and as a transitional period for sea ice during the annual cycle. Also, in contrast to the integrated cloud fields used in Schweiger et al. (2008), we calculate cloud cover at specific pressure levels to more precisely establish where cloud changes occur. Another distinguishing feature of our study is that we analyze GCM simulations from the Community Climate System Model Version 3 (CCSM3) Modern (year 1990) to evaluate whether the same co-variability among sea ice and cloud-related variables exists between the reanalysis and climate model.

2. Methodology

We use the ECMWF ERA-Interim reanalysis dataset (1.5° × 1.5° horizontal resolution and 37 vertical levels) (Uppala et al. 2005). This product improves upon the ERA-40 reanalysis used in Schweiger et al. (2008), offering enhanced resolution, model physics, and radiative transfer model. The dataset spans 1989 to present (continuing in real time), however this study concentrates on the time period from January 1989–December 2009. Serving as our best option for internally consistent, observation-based information, this product also shows improvements over the NCEP reanalysis (Bromwich et al. 2006).

Monthly means of cloud cover, relative humidity, specific humidity, and temperature data were obtained at 14 levels, interpolated to pressure coordinates: 200, 300, 500, 650, 750, and 800–1000 by increments of 25 hPa. Vertically integrated low (below ~ 800 hPa), middle (~800–450 hPa), and high (>450 hPa) cloud cover were obtained, along with other cloud-related variables such as surface latent heat flux and boundary layer height. Sea ice concentration was combined with the other variables, before being regridded onto a 60 km, equal-area grid. Additionally, the NCAR CCSM3 Modern (1990) run was used (2.8° × 2.8° resolution and 26 levels) (Collins et al. 2006), which spanned 100 years, providing the same cloud-related variables as ERA-Interim.

In order to establish whether relationships between sea ice and clouds exist in the observationally constrained dataset (ERA-Interim) and whether co-variability exists with the modeled CCSM3 output, composites of clouds and their related variables are computed with respect to changes in sea ice concentration in individual grid boxes. The compositing methodologies used are outlined in Schweiger et al. (2008). Sea ice conditions are separated as those years that exhibit higher and lower sea ice concentrations than a specified threshold. For this experiment, high sea ice years are defined as those years in which sea ice concentration exceeded the mean plus one half standard deviation. Likewise, low sea ice years are defined as those years in which sea ice concentration fell below the mean minus one half standard deviation. High and low sea ice criteria are shown below:

\[
S_+(x, y) = \frac{1}{N_+} \sum_{k_+} V(x, y, k_+) \tag{1}
\]

\[
S_-(x, y) = \frac{1}{N_-} \sum_{k_-} V(x, y, k_-), \tag{2}
\]

where \(S_{\pm}\) is the set of data that satisfies high/low sea ice criteria at a given latitude (x) and longitude (y), \(N_{\pm}\) are the number of years in the dataset, \(k_{\pm}\) represents the number of years satisfying the high/low criteria, and V is the variable that is being composited (e.g. low cloud concentration). Lastly, the composite is completed as the difference between (1) and (2), thus allowing for an increase in signal. These composites are computed with individual grid boxes, allowing for insight into more direct relationships that may exist between sea ice concentration and cloud-related variables locally.

For this analysis, the spatial composites are computed poleward of 65° for low cloud cover, middle cloud cover, boundary layer height, surface latent heat flux, relative humidity (1000 hPa), and temperature (1000 hPa). Complementary plots include composites of vertical profiles of cloud cover, temperature, relative humidity, and vertical velocity.

3. Results

Spatial composites of sea ice concentration anomalies and total cloud cover for ERA-Interim and CCSM3’s Modern run are
Figure 1. Monthly spatial composited from ERA-Interim over the period 1989–2009. Shown are composites for sea ice concentration and total cloud cover with respect to sea ice anomalies. Composites are created as the difference between years which ice concentration exceeds and falls below one half standard deviation from the interannual ice concentration at an individual grid point. Areas with low ice concentration standard deviations are masked out (<0.001).

Figure 2. Same as figure 1 but for CCSM3 Modern run spanning 100 years.

Presented in figures 1 and 2. There is spatial similarity in the sea ice coverage between high ice years minus low ice years between the datasets, with regard to summer melt, autumn freeze up, and the wintertime distribution of ice pack. Total cloud cover generally increases over regions of largest sea ice increases in the ERA-Interim reanalysis, although the signal becomes noisy in the summer for both datasets. The total cloud composite for October, however, is significantly different between CCSM3 and ERA-Interim (figure 1 versus figure 2). Both datasets show enhanced variability of sea ice along the periphery during October, but whereas total cloud amount increases over higher sea ice cover in ERA-Interim, cloudiness
Figure 3. Composite plots from ERA-Interim during October 1989–2009 for high–low ice years. Shown are composites for sea ice concentration (CI), low cloud cover (LCC), middle cloud cover (MCC), relative humidity at 1000 mb (RH), temperature at 1000 mb (temp), latent heat flux (LHF), and boundary layer height (BLH).

3.1. ERA-Interim October

To diagnose ERA-Interim’s relationship between sea ice concentration and cloud amount during October, the spatial composites for this month were extended to include low cloud cover, middle cloud cover, relative humidity at 1000 hPa, temperature at 1000 hPa, latent heat flux, and boundary layer height. During October, sea ice freeze up is apparent along the periphery of the Arctic, and the ice pack growth expands towards the continental coastlines during high ice years (figure 3). Similar to the response of total cloudiness, there is increased low cloud cover over increased sea ice; specifically, Arctic-wide (65°N–90°N) sea ice concentration is 25% higher and low cloud cover increases by an average of 5%. Middle cloud cover tends to decrease over increased sea ice, similar to ERA-40, although the signal is not as robust. Indicative of freeze up, temperature decreases over higher sea ice concentration approximately 3.4 K Arctic-wide, while upward latent heat flux decreases 9.8 W m$^{-2}$. Boundary layer heights likewise decrease, falling on average 140 m Arctic-wide, with decreases in some locations upwards of 250 m. Despite the reduced evaporation, relative humidity increases 3.6% region-wide, suggesting that the temperature effect outweighs the reduced moisture availability.

Cross sectional composites (figure 4) were computed at (74°N, 130°–230°E), where the strongest sea ice–cloud relationships occurred (i.e., low cloud cover increases over increased sea ice during October). Although integrated low cloud cover increases over enhanced sea ice in the spatial composites, the cross section reveals that this increase only occurs near the surface (1000–950 hPa). A sharp dipole is evident, as cloud increases near the surface transition to cloud decreases throughout the remaining atmospheric layer. Clouds increase during high ice years by 29% at 1000 hPa and 26% at 975 hPa, but decrease by a maximum of 2.4% at 900 hPa, representing an extremely sharp gradient of cloud cover anomalies near the surface. Correspondingly, relative humidity also increases near the surface, where temperature decreases the most, coinciding with the layer of low cloud increases. Similar to cloud cover, relative humidity anomalies vary strongly, reaching a maximum increase of 11.9% at 1000 hPa but a decrease of 1.15% at 950 hPa. Temperature falls through the atmospheric column during high ice years, with a maximum decrease of 6.1 K at 1000 hPa.

Because ERA-Interim defines the low cloud layer as 1000–800 hPa, an atmospheric profile within this layer was taken at 74°N, 190°E to determine the relationship of other variables with the low cloud anomalies. This location was used because it contained especially strong cloud and relative humidity increases near the surface and sharp temperature decreases. Depicted in figure 5 are the profiles of temperature, specific humidity, vertical velocity, relative humidity, and cloud cover during both high and low ice years. During high ice years, temperature and specific humidity are lower throughout the column, representing diminishing moisture
Fig. 4. Cross section composites for temperature, relative humidity, and cloud concentration from ERA-Interim at 74°N, 130°–230°E for October (dotted line in spatial composites of sea ice concentration and low cloud concentration). Highlighted are the ERA-Interim model integrated low cloud cover depth (1000–800 mb) and 190°E highlighted for cross section in this figure.

Fig. 5. Composites of temperature, specific humidity, vertical velocity (negative = rising motion), relative humidity, and concentration at 74°N, 190°E for ERA-Interim during October. Composited for low (red) and high (blue) ice years are plotted.

flux from the ocean as the surface ocean cools and sea ice forms. Over higher sea ice there is enhanced sinking motion, corresponding well with the pronounced decreases in boundary layer height during high ice years. Although specific humidity decreases during high ice years, relative humidity increases from 1000 to 950 hPa. Therefore, the contribution from decreased temperatures, which reduce the moisture-holding capacity, outweighs the influence of decreased specific humidity. During high ice years cloud concentration ranges from 45% to 50% between 1000 and 950 hPa, whereas cloud amount during low ice years is only 10% at 1000 hPa. Thus, the cloud cover increases near the surface dominate the integrated low cloud cover signal, corresponding to the highly positive signal in the low cloud spatial composite.

3.2. CCSM3 Modern run October

Our analysis of October was extended to further understand relationships between sea ice and clouds in the GCM (figure 6). Over increased sea ice there is good spatial agreement with ERA-Interim in terms of temperature, latent heat flux, boundary layer height and relative humidity, although the magnitudes differ between datasets. During high ice years, relative humidity increases Arctic-wide 1.2% in CCSM3, (3.6% in ERA-Interim), while temperature and upward latent heat flux decrease by 4 K and 6 W m \(^{-2}\) in CCSM3 (by 3.4 K and 9.8 W m \(^{-2}\) in ERA-Interim). A striking difference occurs between the two datasets for boundary layer height. Although both show decreases over increased sea ice, the
average magnitude is much less in CCSM3 (−60 m) than in ERA-Interim (−140 m). Even more noticeable and contrary to 
ERA-Interim, vertically integrated low cloud cover decreases 
over increased sea ice Arctic-wide. For example, although 
regionally averaged sea ice concentrations are similar between 
CCSM3’s Modern run (increase 22% during high ice years) 
and ERA-Interim (increase 25%), the vertically integrated 
low cloud cover response is opposite. Whereas low cloud 
cover increases 5% in ERA-Interim during high ice years, it 
decreases by a greater magnitude of 8% in CCSM3 Modern. 
The cross sectional composites (figure 7) performed along 
the same axis as ERA-Interim illustrate these differences. The 
temperature and relative humidity composite shows a similar 
response as ERA-Interim near the surface, as temperature 
decreases and relative humidity increases, although the 
magnitude and depth of these changes is not as great. Relative 
humidity increases 4.2% at 1000 hPa during high ice years, 
which is less than the 11.9% increase in ERA-Interim, but 
shifts to a maximum decrease of 1.1% at 950 hPa. The cooling 
maximizes at 6.2 K at 1000 hPa, which is similar to the 
6.1 K maximum decrease in ERA-Interim. More importantly 
both datasets display a dipole response, as cloud increases 
are confined to the surface, juxtaposed by cloud decreases aloft. 
These near-surface cloud increases in CCSM3 are 25–50 hPa 
shallower than in ERA-Interim, however, representing only a 
15% increase at 1000 hPa (ERA-Interim was 29%), while the 
cloud cover decreases consistently above the lower boundary 
layer (11.8% at 925 hPa). As a result of the weaker and 
shallower cloud increases, the integrated low cloud anomalies 
are negative in CCSM3. 
Profile plots (figure 8) indicate lower temperature 
and specific humidity during high ice years throughout 
the atmospheric column. During these years, there is 
slightly enhanced upward vertical velocity at the surface that 
trends toward sinking motion around 950 hPa, while rising 
motion is apparent throughout the column during low ice 
years. Although relative humidity increases during high 

ice years near the surface, differences with low ice years 
are small, corresponding to the decreased magnitude of the 
positive relative humidity signal in CCSM3’s cross sectional 
composites. This difference also is mirrored in the cloud cover 
profile plots: cloud amounts are greater during high ice years 
near the surface but become greater during low ice years above 
950 hPa.

3.3. Comparison of ERA-Interim and CCSM3
3.3.1. Modern run during October. Shown in figure 9 are 
profile plots taken at 74°N, 190°E during October, comparing 
high and low ice years for both ERA-Interim and CCSM3. 
Temperature during both high and low sea ice years exhibits 
a similar pattern, but ERA-Interim has a slightly higher surface 
temperature followed by more rapid cooling with height than 
CCSM3. From the surface up to 800 hPa, however, specific 
humidity is higher in CCSM3: 0.2 g kg⁻¹ more in high 

ice years and 0.5 g kg⁻¹ in low ice years. In both high 
and low ice years, relative humidity is higher in CCSM3 
than ERA-Interim, but during low ice years the difference 
between the datasets is greater (10% difference in relative 
humidity at 1000 hPa). Because higher relative humidity in 
CCSM3 coincides with greater specific humidity and 
higher temperature than in ERA-Interim, the increased specific 
humidity in CCSM3 has to account for the higher relative 
humidity values. Increases in relative humidity, however, do
not necessarily indicate increased cloud cover. In the spatial composites (figures 3 and 6), there is a sharp decrease in low cloud cover during high ice years for CCSM3 but an increase in ERA-Interim. The plots in figure 9 show that the differences in cloud concentration between high and low ice years are much greater in ERA-Interim than CCSM3. Values for CCSM3 are similar between high and low ice years, with low ice years being slightly greater between 950 and 925 hPa. Values for ERA-Interim, however, show that cloud cover is much greater during high ice years than low ice years (35% increase at the surface), probably related to the low relative humidity during low ice years in ERA-Interim. Regardless, this brings into question the inter-model differences in the formation of low clouds. which will be elaborated on in section 4.

4. Discussion and conclusions
Although sea ice cover is predicted to further decline in the future, less is known about how this change will affect the interaction of sea ice and clouds. Clouds have a large impact on the surface radiation budget of the Arctic and thus serve as an important player in affecting the trajectory sea ice will
Figure 9. Comparison of composites of temperature, specific humidity, vertical velocity, relative humidity, and cloud concentration at 74°N, 190°E between ERA-Interim (black) and CCSM3 Modern run (green) during October. Composite for low and high ice years are plotted.

Results from the cross sectional composites in both data sets correspond well with the satellite measurements of Palm et al (2008), who found that autumn clouds increase within 500 m of the surface over sea ice (as compared with open water) but quickly decrease above this point. In ERA-Interim and CCSM3 Modern, the atmospheric levels of low cloud increase over positive sea ice anomalies correspond roughly to thicknesses of 500 m and 200 m respectively. These results during October have important implications for radiative transfer within the Arctic: if cloud increases occur within the lower boundary layer, radiative impacts may be significantly different than if the same cloud increases occur higher in the lower troposphere.

Kay and Gettelman (2009) present analysis from CloudSat and CALIOP during 2006–8, a period of the lowest sea ice concentrations on record. Composites showed that cloud
fraction increased over increased open water below 2 km, related to decreased static stability. One caveat however, is that Kay and Gettelman (2009) excluded data below 720 m because of difficulties from contamination and detection. This is the very layer where results of this study and Palm et al (2008) indicate the largest cloud increases occur over ice. Similar to Kay and Gettelman (2009), Eastman and Warren (2010) showed that total low cloud cover increases over reduced sea ice, based on synoptic observations from land-based weather stations, drifting stations, and ships over the period 1979–2007, but their data were unable to resolve cloud variations within this layer.

Differences in the integrated low cloud response over enhanced sea ice between ERA-Interim and CCSM3 must be occurring due to differences in model physics. Although low cloud formation is dictated by relative humidity threshold criteria in both ERA-Interim (80%) and CCSM3 (90%), the reanalysis and GCM differ in how cloud fraction is calculated once this threshold is met. Outlined in Collins et al (2006) for CCSM3, cloud formation is governed by relative humidity values which exceed a relative humidity threshold. In CCSM3, the integrated low cloud depth extends from 1000 to 750 mb, 50 mb greater than ERA-Interim. In order for cloud formation within the low cloud depth, the relative humidity must meet or exceed 90% in CCSM3. Rather than varying with height, the relative humidity threshold in CCSM3 remains constant throughout the layer. Once the relative humidity threshold is met, cloud formation is determined by:

$$\text{Cloud fraction} = \left( \frac{\text{RH} - \text{RH}_{\text{crit}}}{1 - \text{RH}_{\text{crit}}} \right)^2 \quad (3)$$

Although beyond the scope of this project, ERA-Interim defines low cloud amount differently than CCSM3. Rather than making cloud formation a diagnostic function of relative humidity, ERA-Interim first uses a relative humidity threshold as a means to establish cloud formation. If this threshold— which varies in the vertical as a function of pressure—is met, then ERA-Interim calculates the cloud formation in a more complex manner than CCSM3. Instead of using relative humidity to calculate cloud fraction, ERA-Interim calculates new cloud formation as a function of how the saturation specific humidity varies with respect to the environmental specific humidity and also accounts for ambient cloud fraction present within the grid box.

Although boundary layer height composites agree spatially, the magnitudes of boundary layer height decreases over increased sea ice are over 50 m greater for ERA-Interim. A factor that may explain differences in the dipole structure are the differences in the vertical resolution of ERA-Interim and CCSM3. ERA-Interim has 37 levels in the vertical, as opposed to 26 in CCSM3, which are both interpolated to pressure coordinates. The vertical resolution for the integrated low cloud layer for ERA-Interim (1000–800 mb) is given by the midpoint values in hybrid sigma coordinates at: 998, 995, 991, 983, 973, 959, 941, 919, 893, 863, and 829 (11 layers). For CCSM3, the vertical resolution for the integrated low cloud layer (1000–750 mb) is given by the midpoint values in hybrid sigma coordinates at: 992, 970, 929, 867, and 787 (5 layers). Perhaps the dearth of levels in CCSM3 can explain a portion of the discrepancy between the two datasets, because boundary layer processes may be missed without sufficient resolution. This may also contribute to the difference in boundary layer height anomalies between the two models during October when ERA-Interim had heights that were 140 m lower in high ice years, compared with 60 m in CCSM3. In terms of cloud cover, increases during October were shown to be within the lower boundary layer in both datasets. Because ERA-Interim has more resolved layers in the atmosphere, particularly at lower levels (<800 mb), the changes in cloud cover could be captured with better resolution, possibly resulting in differences in the depth of surface cloud increases over higher sea ice concentrations.

The analysis of the CCSM3 Modern run is consistent with an analysis performed on this model’s 2 × CO2 run (not shown), which produced increased low cloud cover over areas of decreased sea ice. This result indicates that the modern relationship between sea ice and clouds in CCSM3 remains consistent into the future, and it is also consistent with other GCM studies (Vavrus et al 2009), which suggest a cloudier Arctic associated with widespread sea ice loss under greenhouse warming. Determining the resulting cloud feedback on an annual-mean basis, however, is complicated by the opposing seasonal changes in cloud radiative forcing in a cloudier climate, such that increases during October (and throughout polar night) are mitigated by decreases during summer.

One of the looming questions surrounding the interaction between sea ice and clouds is causality. Local changes in sea ice can drive changes in clouds and vice versa, although remote forcing (e.g., moisture or heat advection) can also drive changes in both sea ice and clouds. Although the model accounts for remote and local processes, the analysis performed only explicitly accounts for local processes, however, as it was only applied on a grid box basis. Also, results presented here can only suggest that sea ice changes are associated with changes in the overlying cloud and cloud-related variables, although Karlsson and Svensson (2011) demonstrate that non-cloud processes play a major role in intermodal differences in the surface temperature of sea ice. Future work evaluating differences between ERA-Interim and CCSM3 in terms of cloud formation, vertical resolution, and sea ice parameterizations is needed to provide a more complete understanding of how sea ice and clouds interact, both on local and remotely forced scales.

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