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A cloudier Arctic expected with diminishing sea ice

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[1] Arctic sea ice cover has decreased dramatically over the last three decades. Global climate models under-predicted this decline, most likely a result of the misrepresentation of one or more processes that influence sea ice. The cloud feedback is the primary source of uncertainty in model simulations, especially in the polar regions. A better understanding of the interaction between sea ice and clouds, and specifically the impact of decreased sea ice on cloud cover, will provide valuable insight into the Arctic climate system and may ultimately help in improving climate model parameterizations. In this study, an equilibrium feedback assessment is employed to quantify the relationship between changes in sea ice and clouds, using satellite-derived sea ice concentration and cloud cover over the period 2000–2010. Results show that a 1% decrease in sea ice concentration leads to a 0.36–0.47% increase in cloud cover, suggesting that a further decline in sea ice cover will result in an even cloudier Arctic.
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1. Introduction

[2] Arctic sea ice has been shrinking for the past three decades during all seasons of the year, but especially in summer and autumn [*Deser and Teng*, 2008; *Serreze et al.*, 2007; *Stroeve et al.*, 2007]. Climate model simulations captured the general downward trend in Arctic sea ice extent but with considerable differences in magnitude, which suggests the important roles of both greenhouse gas loading and natural variability in determining this trend [*Serreze et al.*, 2007; *Stroeve et al.*, 2007; *Zhang and Walsh*, 2006]. The model-predicted decrease in Arctic sea ice is slower than that observed from passive microwave data [*Stroeve et al.*, 2007], implying that some processes controlling Arctic sea ice are not well represented in climate models. The cloud feedback is the primary source of uncertainty in model simulations, especially in the polar regions [*Solomon et al.*, 2007], where limitations in our understanding of cloud processes and their interactions with other processes have hindered the study of climate sensitivity and future climate projection. Clouds are a key factor in the radiative components of the surface energy budget, and therefore have a significant influence on sea ice melt and growth [*Intrieri et al.*, 2002; *Francis et al.*, 2005, 2009]. *Wang and Key* [2003] observed a trend in the radiative effect of Arctic clouds in the 1980's and 1990's, such that changes in cloud cover resulted in increased cooling during summer and decreased warming during winter, possibly suppressing Arctic warming to some degree. Taking this one step further, *Liu et al.* [2008, 2009] quantified the effects of trends in cloud cover and sea ice on the surface temperature.

[3] Changes in sea ice, in turn, are very likely to cause changes in cloud cover and other cloud properties. *Vavrus et al.* [2011] found that areas of increased total cloud cover were collocated with declining ice concentration over the Arctic Ocean in autumn during rapid sea ice loss events in the 21st century, as projected by the Community Climate System Model (CCSM3). *Vavrus et al.* [2009] reported 7–9% greater cloudiness over the region from North America to Siberia where more than a 30% ice concentration reduction appears between late 20th century and late 21st century from 20 global climate models. *Schweiger et al.* [2008] showed the association of fewer low-level clouds and more mid-level clouds over lower ice concentrations in satellite observations and reanalysis products. A similar finding using ERA-Interim Reanalysis was recently reported by *Cuzzone and Vavrus* [2011]. *Kay and Gettelman* [2009] investigated the physical controls of Arctic cloud by analyzing the interannual variability of Arctic clouds from satellite lidar and other atmospheric observations from 2006 to 2008. They found no cloud response to sea ice loss in summer, but an increase in low-level clouds over newly open water in autumn. Using satellite lidar data, *Palm et al.* [2010] reported a 6%–7% increase in cloud fraction in October from 2003 to 2007, associated with a 6%–7% decrease in sea ice concentration. These model projects and empirical case studies suggest the importance of cloud-sea ice interaction in the changing Arctic climate, and in turn emphasize the need to further quantify the feedback of sea ice changes on cloud cover using longer observations with more advanced analysis tools.

[4] This paper provides observational assessment of the degree to which cloud cover responds to changes in Arctic sea ice. The equilibrium feedback assessment (EFA) method is used with daily satellite observations of cloud cover and sea ice concentration over the period 2000 to 2010. The magnitude of the sea ice feedback on cloud cover and the percentage of cloud cover variance due to sea ice changes are quantified. Our assessment offers an observational benchmark for the sea ice feedback on cloud cover in model simulations. This study quantifies the strength of the ice cover feedback on the cloud cover on a broad scale.

2. Data and Method

[5] Daily sea ice concentration was obtained using the NASA Team algorithm [*Cavalieri et al.*, 1999; *Meier et al.*,

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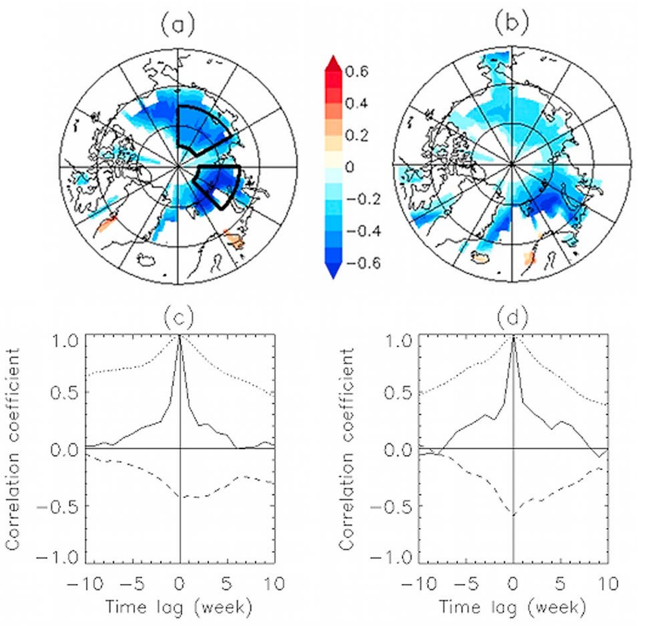

Figure 1. Correlation coefficients of weekly anomalies of sea ice concentration and cloud cover (a) from July to November, and (b) from January to December 2000–2010. Only those significant at the 90% confidence level are shown. Autocorrelation of weekly anomalies of sea ice concentration (dotted line), cloud cover (solid line), and correlation of sea ice concentration and cloud cover with lead-lag (dashed line) over (c) region 1 (120–180E, 75–85N) and (d) region 2 (45–90E, 75–85N) using data from July to November 2000–2010. Positive lags mean the sea ice time series leads the cloud cover time series.

2006] with brightness temperature data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) -F8, -F11 and -F13 Special Sensor Microwave/Imager (SSM/I), gridded to 25 × 25 km resolution. Daily cloud cover was from the Terra satellite Moderate Resolution Imaging Spectroradiometer (MODIS) Daily Global Product at 1° × 1° resolution on equal-angle grids. *Ackerman et al.* [1998] describe the cloud detection algorithm in detail, and *Frey et al.* [2008] improve the algorithm in the polar regions based on work by *Liu et al.* [2004]. The daily sea ice concentration and cloud cover data used here cover the period from March 2000 to March 2010. Both daily data sets were binned into 3° × 3° grids and for different subregions, and converted to weekly anomalies by removing the annual cycle and linear trend.

[6] Instantaneous and lead-lag correlations of weekly sea ice concentration and cloud cover anomalies were calculated to evaluate the sea ice-cloud interactions at each grid point for the Arctic, both year-round and from July to November. The summer season is important because the changes in sea ice extent and concentration are rapid, with substantial melting in the first half of the season and refreezing in the latter half. The minimum ice extent generally occurs in September. To further quantify the response of cloud cover to changes in sea ice concentration, we compute the feedback coefficient of sea ice concentration on cloud cover using the equilibrium feedback assessment.

[7] The EFA has been employed to derive the feedback coefficient of land vegetation on the atmosphere by *Liu et al.* [2006] and *Notaro et al.* [2006], as well as the sea surface temperature (SST) feedback on the atmosphere [*Frankignoul et al.*, 1998; *Frankignoul and Kestenare*, 2002; *Zhong et al.*, 2011]. In this work, we examine the impact of changes in sea ice concentration on cloud cover over the Arctic Ocean.

[8] Following *Liu et al.* [2006] and *Notaro et al.* [2006], the response of cloud cover to changes in sea ice concentration can be represented as:

$$C(t + dt_c) = \lambda_C I(t) + N(t + dt_c), \qquad (1)$$

where dt_c is the characteristic timescale of cloud processes, $C(t + dt_c)$ is the cloud cover at time $t + dt_c$, $\lambda_c I(t)$ is the cloud response to a change in sea ice concentration $I(t)$ after time dt_c, and λ_c is the feedback (or response) coefficient (or parameter) of sea ice concentration changes on (to) cloud cover; and $N(t + dt_c)$ is the climate noise independent of sea ice variability. The feedback coefficient can be calculated as the ratio of the lagged covariance between C and I to the lagged covariance of I:

$$\lambda_C = \frac{\mathrm{cov}[C(t), I(t-\tau)]}{\mathrm{cov}[I(t), I(t-\tau)]}, \qquad (2)$$

where $\tau > dt_c$ is the time lag.

[9] A Monte Carlo bootstrap approach was used to test the statistical significance of the feedback coefficient. The calculation of (2) was repeated 1000 times with a shuffled time series of cloud cover [*Czaja and Frankignoul*, 2002; *Notaro et al.*, 2006], and the significance level of the feedback coefficient was then determined as the percentage of the 1000 values smaller than the feedback coefficient in magnitude.

[10] The fraction of the cloud cover variance due to the effect of sea ice concentration was calculated as the ratio of cloud cover variance induced by sea ice feedback, $\sigma^2(\lambda_c I)$, to total cloud cover variance, $\sigma^2(C)$.

3. Results

[11] From July to November, mean Arctic sea ice concentration is largest (exceeding 90%) north of Greenland and the Canadian Archipelago, and it decreases gradually toward the Pacific sector of the Arctic, with minima over the Chukchi, Laptev, and Kara Seas (less than 80%). In contrast, the standard deviation of the sea ice concentration is larger over the outskirts of the Arctic sea ice, especially over the Kara, Laptev, and Chukchi Seas (not shown). The standard deviation of the cloud cover is more homogeneous over the Arctic Ocean, with slightly larger values on the Pacific side than on the Atlantic side. Annual mean sea ice concentration and its standard deviation resemble their counterparts from July to November but with a larger mean and less variability. The standard deviation of the annual mean cloud cover is more spatially homogeneous than cloud cover standard deviation from July to November.

[12] Figures 1a and 1b show instantaneous correlations of weekly cloud cover and sea ice concentration, significant at the 90% confidence level. From July to November, significant negative correlations are found over most of the Arctic Ocean exhibiting large sea ice variability, with the strongest correlations over the Barents, Kara, Beaufort, and Chukchi

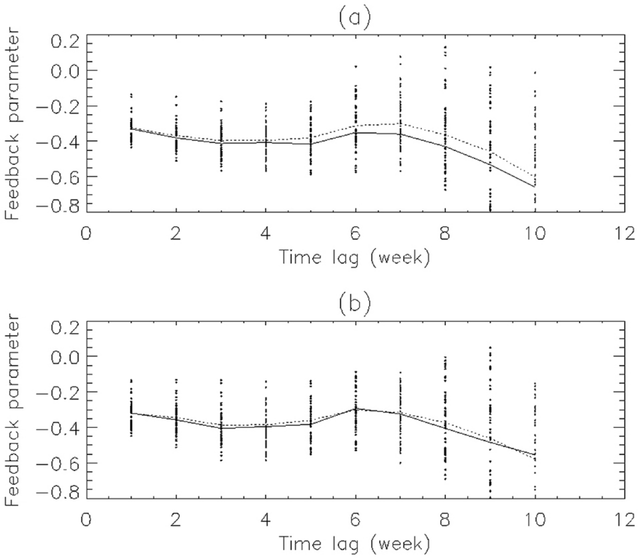

Figure 2. Feedback coefficient of sea ice concentration on cloud cover as a function of time lag over region 1 (120–180E, 75–85N) for (a) July to November, and (b) for January to December. Each point represents a feedback coefficient in 3 × 3 degree longitude/latitude box inside this region; solid line represents the feedback coefficient using mean weekly anomalies; dotted line is the averaged feedback coefficient of all feedback coefficients of each 3 × 3 degree longitude/latitude box.

Seas. These results suggest that increased cloud cover over the Arctic Ocean tends to be associated with a smaller sea ice concentration (more open water). This finding is consistent with the findings of *Palm et al.* [2010]. The mean correlations from January to December are spatially similar to those from July to November but with a smaller magnitude.

[13] Over the two Arctic subregions exhibiting significant instantaneous correlations of sea ice concentration and cloud cover (region 1: 120−180E, 75−85N, the northern portions of the Laptev and East Siberian Seas; region 2: 45−90E, 75−85N, the northern portions of the Barents and Kara Seas), autocorrelations of sea ice concentration decay with a much slower time lag than those of cloud cover, reflecting a substantially longer memory in sea ice (Figures 1c and 1d). Decorrelation time, as a measure of the memory time, is calculated as $(1 + \alpha_1)/(1 - \alpha_1)$, where α_1 is the one-week autocorrelation [*Notaro et al.*, 2006]. The decorrelation time of sea ice concentration is longer than 10 weeks for both January – December and July – November time periods; that of cloud cover is shorter than two weeks. The peaks of cloud cover autocorrelations with lead/lag longer than two weeks imply a possible impact from other climate agents of longer memory, like sea ice.

[14] Lead/lag correlations (Figures 1c and 1d) show that cloud cover and sea ice concentration are significantly negatively correlated for a lead/lag shorter than 5 weeks, with instantaneous correlations larger for region 2. The relatively symmetric decay of correlations with lead/lag for region 2 implies two-way sea ice-cloud interactions with a positive climate feedback: an increased cloud cover reduces sea ice, which in turn further increases cloud cover. The decay of correlations as sea ice leads cloud cover (positive lags in Figures 1c and 1d) is slower than the decay of correlations as cloud cover leads sea ice over both region 1 and 2, with slower decay over region 1. This asymmetric decay implies that the influence of sea ice on cloud is stronger than that of cloud on sea ice.

[15] The feedback coefficient for the effect of sea ice concentration changes on cloud cover is calculated over the Arctic and in the subregions with relatively large sea ice variability, i.e., where standard deviation of sea ice concentration is greater than 6%. Theoretically, the feedback coefficient is independent of time lag [*Liu et al.*, 2006]. In practice, the feedback coefficient is not reliable when the time lag is smaller than the characteristic timescale of the faster process, or when the time lag is too large, due to the sample error. As a result, the feedback coefficient is conventionally calculated as the weighted average of the feedback coefficients with time lags larger than the decorrelation time, two weeks for cloud cover in this study.

[16] As shown in Figure 2 (solid line), the negative feedback coefficient obtained with the area-averaged cloud cover and sea ice concentration time series over region 1 first increases modestly in magnitude with lag before leveling off between lags 3 and 5; it drops at lags 6 and 7, and then increases rapidly for the increasing sample error with increasing lag. Therefore, the feedback coefficient is robust with regard to the lag of estimation as long as the lag is not too long (<8 weeks). Also shown in Figure 2 is the mean feedback coefficient (dotted line) derived as the average of gridded feedback coefficients over region 1, which closely approximates that obtained with area-averaged cloud and sea ice time series. This implies that the feedback is insensitive to the spatial scale, and the feedback occurs predominantly locally within a 3° × 3° area. The gridded feedback coefficients also show the least variability at lags 3, 4 and 5, with values between −0.5 and −0.2.

[17] Figure 3 shows the feedback coefficients as the weighted averages of lags 3, 4 and 5 with a weighting of 1.0, 0.5, and 0.25 respectively. Only are those significant at the 90% confidence level shown. We see mostly negative values over the Arctic Ocean, with the averages between −0.36% and −0.47% (units: percent cloud cover per unit change in sea ice concentration) over multiple subregions from July to November (Table 1); i.e., for a 1% decrease in sea ice concentration, cloud cover increases by approximately 0.4%. For the January to December period, there is a 0.27–0.45% cloud cover increase corresponding to a 1% decrease in sea

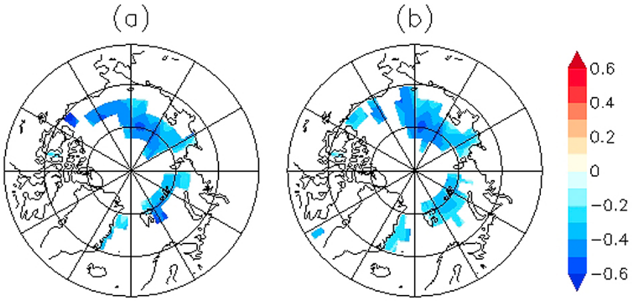

Figure 3. Feedback coefficient of sea ice concentration on cloud cover (a) from July to November, and (b) from January to December. Only those significant at the 90% confidence level are shown.

Table 1. Averaged Feedback Coefficients, and Percentage of the Variance of Cloud Cover Explained by the Feedback of Sea Ice Concentration Changes on Cloud Cover in Percentage (in Parentheses) for Different Regions From July to November, and From January to December Before (Line 1) and After (Line 2) Cloud Amount Adjustment Based on Sea Ice Concentration

Feedback Coefficient	July to November	January to December
Beaufort Sea	−0.47 (27)	−0.33 (7)
	−0.39 (22)	−0.26 (5)
Chukchi Sea	−0.39 (22)	−0.37 (9)
	−0.24 (10)	−0.21 (3)
Central Arctic	−0.45 (28)	−0.45 (10)
	−0.29 (16)	−0.31 (5)
Laptev Sea	−0.36 (34)	−0.33 (9)
	−0.24 (20)	−0.23 (5)
Barents Sea	−0.36 (34)	−0.27 (26)
	−0.23 (19)	−0.16 (8)
Pacific Section	−0.41(28)	−0.36 (8)
	−0.29 (18)	−0.25 (4)
Overall	−0.37 (29)	−0.33 (11)
	−0.24 (16)	−0.21 (6)

ice concentration. The negative feedback coefficients suggest a positive feedback between sea ice and cloud cover; that is, lower sea ice concentration (or more open water) favors increased cloud cover possibly through stronger surface evaporation [*Francis et al.*, 2009]; the increased cloud cover, in turn, tends to trap (emit) more longwave radiation and thus warm the surface resulting in further sea ice shrinkage.

[18] The sea ice feedback on the cloud cover explains 22%–34% of the total variance in cloud cover over these subregions from July to November. For the January to December interval, 7%–26% of the total cloud cover variance is attributable to sea ice variability. While the explained variance implies that cloud cover responds to changes in sea ice, other processes, such as large-scale heat and moisture advection, also control cloud cover.

4. Discussion and Conclusions

[19] In this study the equilibrium feedback assessment (EFA) is employed to assess the Arctic sea ice feedback on cloud cover, or the response of cloud cover to changes in sea ice concentration. A lead-lag correlation analysis illustrates some qualitative features, but EFA provides a quantitative assessment of the interaction between these two components of the Arctic climate system. This study quantifies the strength of the ice cover feedback on the cloud cover. *Vavrus et al.* [2011] were unable to determine the lead-lag relationship between sea ice and cloud cover during rapid ice loss events because only instantaneous correlations were used in that modeling study. *Palm et al.* [2010] investigated the sea ice extent influence on cloud fraction through an analysis of corresponding trends of Arctic sea ice extent and cloud fraction in October from 2003 to 2007, but did not otherwise take into account the covariance between the two parameters. Note that the EFA does not explicitly account for nonlinearity, multi-variable interactions or non-local effects. In reality, the sea ice-cloud interactions may involve non-linear [*Curry et al.*, 1996], non-local [*Liu et al.*, 2007] processes and complex interactions with a third or more climate processes [*Chen et al.*, 2011; *Francis et al.*, 2009].

[20] This work provides an observational assessment of the sea ice feedback on cloud cover based on satellite-derived daily sea ice concentration and cloud cover. Over areas of the Arctic with large sea ice variability, a 1% decrease in sea ice concentration is associated with a 0.36–0.47% increase of cloud cover from July to November. Furthermore, 22%–34% of the cloud cover variance can be explained by sea ice variability. The mean results from January to December indicate a relatively weaker sea ice effect on cloud cover in other seasons. The results can be used as an observational benchmark in evaluating sea ice-cloud interactions in the Arctic from model simulations.

[21] Some issues remain with cloud detection over polar regions, where MODIS detects less cloud than active satellite lidar/radar sensors over ice [*Liu et al.*, 2010]. This cloud detection dependence is likely to introduce a negative correlation between changes in sea ice and cloud cover, which will affect the assessment of feedback. To quantify this effect, our analysis was repeated after the MODIS cloud amount was adjusted based on the sea ice concentration [*Liu et al.*, 2010]. The updated feedback coefficients at the 90% confidence level and higher are still negative, though the absolute magnitude is smaller than that without the adjustment (Table 1). The percentages of cloud cover variance explained by the sea ice feedback are also smaller than those before the cloud amount adjustment, However, the reduction in magnitude does not impact the conclusions of this study.

[22] This study demonstrates that decreases in sea ice concentration lead to increases in cloud cover. If Arctic sea ice extent continues to decline over the coming decades as projected by climate models, and even become seasonally ice free [*Wang and Overland*, 2009; *Zhang and Walsh*, 2006], a cloudier Arctic can be expected.

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