Sensitivity of Surface Cloud Radiative Forcing to Arctic Cloud Properties

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Introduction

The majority of cloud radiative forcing studies to date conclude that on a global-level, clouds have a net cooling effect on the climate system (e.g., Ramanathan et al. 1989). In contrast, observations and model results of cloud forcing in the Arctic show that, with the exception of a short period during summer, clouds warm the surface because their thermal insulating effect outweighs their solar reflective capability (Curry and Ebert 1992). The difference between high-latitude versus low-latitude cloud forcing stems mainly from the reduced solar flux at large zenith angles for a substantial part of the year, the low levels of atmospheric moisture, and the similarity between the albedos of clouds and those of surfaces covered with snow and ice (Curry et al. 1996).

A common approach for quantifying the radiative relationships between clouds and the radiation budget is to determine cloud forcing (Ramanathan et al. 1989), which provides an estimate of how much a cloud changes the surface radiative fluxes relative to clear skies. In this paper, we present the variability of surface cloud radiative forcing to various cloud properties using cloud and flux measurements from a yearlong field program in the Arctic.

Methodology

This research utilizes Arctic observations obtained over the year-long Surface Heat Budget of the Arctic Ocean (SHEBA) field program conducted from October 1997 to October 1998 on a multi-year ice floe (Uttal et al. 2002). The SHEBA measurements used as part of this study include shortwave (SW) and longwave (LW) fluxes from a radiometer set (Fairall et al. 1998), cloud fraction, base height and occurrence of liquid water from a depolarization lidar (Alvarez et al. 1998), liquid water paths retrieved from a microwave radiometer (Han et al. 2001), and atmospheric temperature profiles from radiosondes.

The SHEBA measurement dataset has already been processed to produce an annual cycle of cloud macrophysical properties (Intrieri et al. 2002a) and the surface cloud radiative forcing (CRF) components (Intrieri et al. 2002b). In this study, we present the variability of surface CRF to variations in cloud fraction, cloud base temperature, phase and integrated cloud water path using SHEBA observations. Although, observationally it is impossible to hold all cloud properties constant and just vary one, the cloud data were analyzed in a manner to produce dominant relationships.

Results

Cloud Fraction Sensitivity

The presence of clouds, by definition, is one of the dominant factors in CRF (e.g., cloud forcing under clear skies = 0). Therefore, as expected, there exists a strong relationship between the surface Longwave Cloud Radiative Forcing (LWCRF) and cloud amount over the annual cycle as shown in Figure 1. Here, 20-day averages of cloud amount were used to calculate the LWCRF sensitivity, yielding a value of 0.7 W m^{-2} per percent cloud occurrence. The strong relationship between the LW radiation at the surface to cloud amount suggests that an increase in cloudiness will substantially increase the amount of LW radiative warming at the Arctic surface.

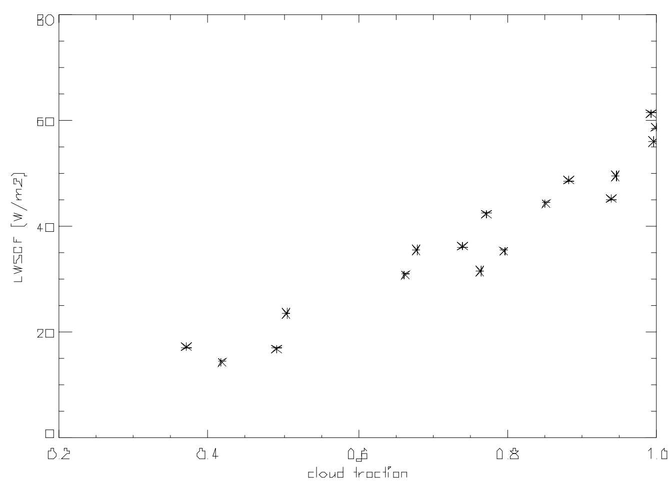

Figure 1. 20-day averages of LW surface cloud forcing versus cloud fraction for the SHEBA year.

The SWCRF variations to cloud fraction are complicated over the course of the year because it is also a function of the highly varying solar zenith angles and surface albedos. However, there is a general trend that is negatively correlated, with increasing cloud cover, corresponding to a decrease in daily SWCRF values (i.e., the negative magnitude increases). This negative correlation is, in essence, the cloud albedo effect yielding a value of approximately -0.3 W m^{-2} per percent cloud fraction.

During spring and summer, the LW radiative forcing component outweighed the SW forcing by 2 to 1 quantifying the long-held observation that snowmelt is enhanced under cloudy skies versus clear skies. This has significant implications on the ice-albedo feedback mechanism, which may be even stronger than previously predicted.

We surmise that most of the variability in the SWCRF and LWCRF (~10-20 W m^{-2}) associated with cloud fraction is attributed to combinations in variability of cloud phase, cloud base height, and microphysical properties, which are each discussed below.

Cloud Phase Sensitivity

Clouds containing liquid water phase were observed to occur throughout the SHEBA year at altitudes as high as 6.5 km and at temperatures as low as -34°C. During winter, the lidar and radiometer observations revealed that clouds containing liquid water phase, no matter how thin or transient, substantially increased the infrared (IR) fluxes measured at the surface. This strong influence is due to the fact that water droplets are more numerous per unit volume, are highly efficient emitters in contrast to ice and that wintertime water clouds often reside near the inversion layer at temperatures much warmer than the surface.

Figure 2a is a histogram of the LWCRF values determined from cloud scenes containing liquid and those containing no liquid. Also plotted is the distribution of LWCRF for clear skies. Note that although there are some cases of ice clouds that act to warm the surface and water clouds that have little surface warming effect, the majority of samples indicate that water clouds impart between a 40-65 W m^{-2} forcing, while ice clouds have a relatively negligible influence and are often radiatively similar to clear skies.

Coupling the two facts that liquid water occurred in ~40% of the observed clouds during winter and that the sensitivity of cloud forcing to phase is significantly large suggests water clouds are the most responsible cloud type warming the Arctic surface during winter. Thus, it is imperative to parameterize phase properly when modeling Arctic clouds and their radiation interaction with the surface (Bretherton et al. 2001).

We see similar results for the summer LWCRF with liquid water clouds imparting a strong surface warming effect with cloud forcing values mostly between 40 and 75 W m^{-2} (Figure 2b). Water clouds also display a more important role than ice clouds in summer (albeit of the opposite sign) by reflecting the incoming solar radiation and thus cooling the Arctic surface with SWCRF values between -5 and -75 W m^{-2} with a peak around -15 W m^{-2} (Figure 2c). We note here again that the summer is predominantly cloudy in the Arctic (~95% cloud occurrence) with the majority of cloud scenes containing liquid phase, so that even if high ice clouds did contribute to the cloud forcing their relative contribution at the surface is low.

Cloud Microphysical Properties

Based on our findings that clouds containing liquid water phase are a major component in cloud forcing, we wanted to further understand how the amount of cloud liquid water influenced the surface forcing. For this, we analyzed both the yearlong LWP retrievals from the microwave radiometer (Figure 3a) and the LWP results from the radiative transfer model runs (Figure 3b). The observations and model display a similar overall sensitivity trend in the LW with increasing LWP corresponding to increasing CRF. Note that for both the observations and the model results there is a greater sensitivity between 0 and 30 g m^{-2} and an essentially flat response between 30 and 200 g m^{-2}. In this latter high water content

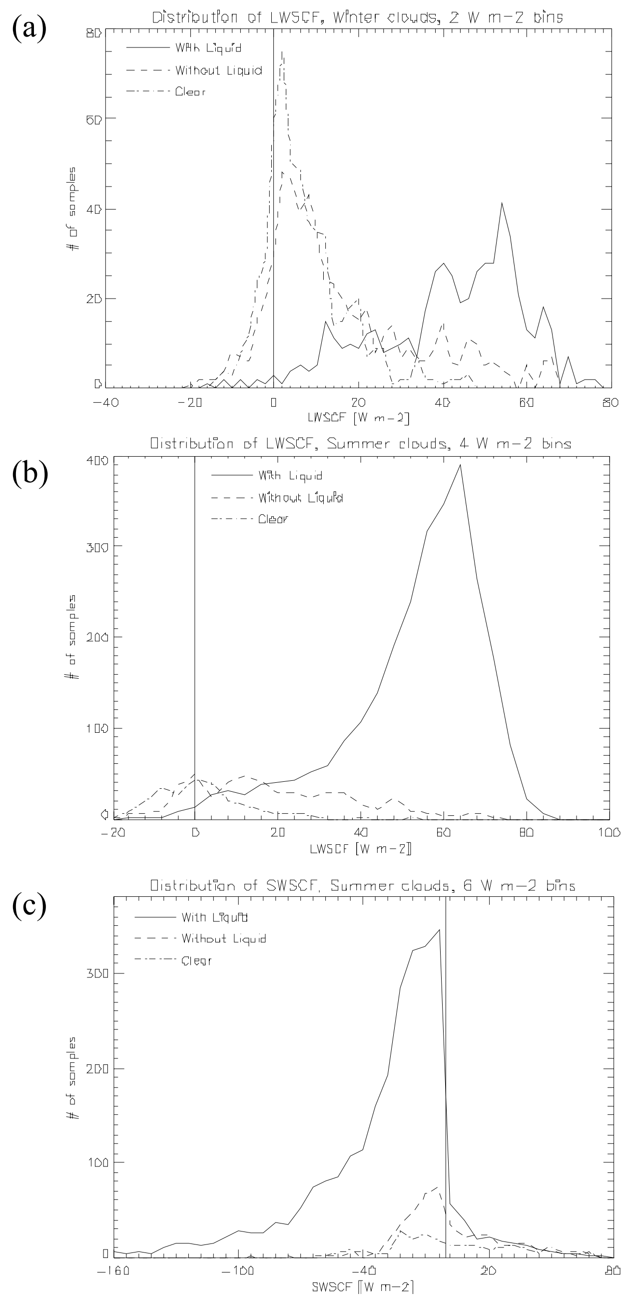

Figure 2. Histogram of cloud forcing under clouds containing liquid water, ice and clear skies for (a) LW winter, (b) LW summer, and (c) SW summer.

regime, the LWCRF sensitivity coefficient during winter and summer is essentially zero indicating that adding more liquid water mass to a cloud after a certain point will not increase surface fluxes. At LWP's greater than 30 g m^{-2} liquid clouds are essentially blackbody emitters.

In order to provide additional information into the low cloud water regime, we relied on model results instead of microwave radiometer measurements since LWP observations less than 25 g m^{-2} are suspect

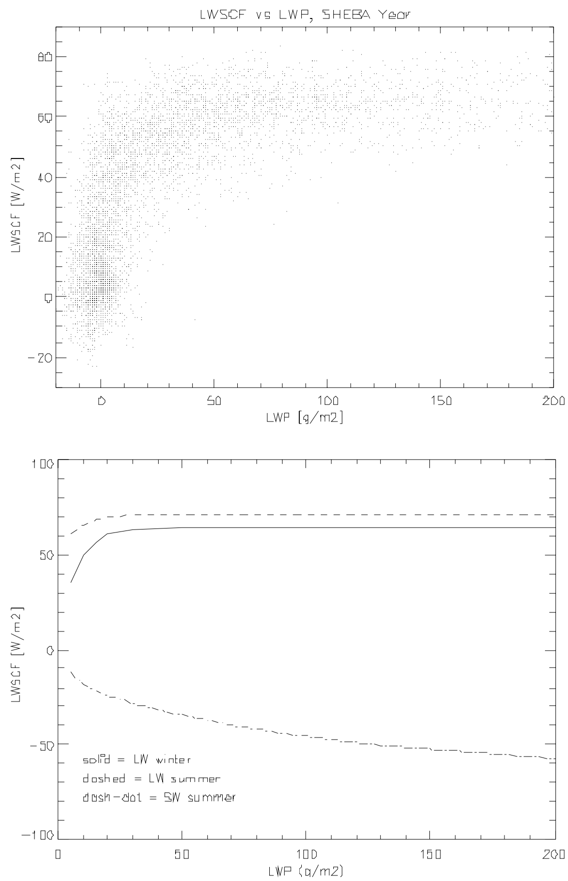

Figure 3. LWP from microwave radiometer retrievals (top) and model results (bottom).

due to high noise levels (Westwater, personal communication). Model calculated LW cloud forcings indicate that there is a greater sensitivity between 5 and 25 g m^{-2} in both winter and summer seasons with increasing LWP's corresponding to a gain in energy at the surface. The winter variability is slightly larger than in summer with values of approximately 1.5 W m^{-2} and 0.66 W m^{-2} per g m^{-2}, respectively.

The summer SWCRF variability to increasing LWP is much greater, and of the opposite sign, than the summer LWCRF with -0.75 W m^{-2} per g m^{-2}. This is as expected since the more opaque the cloud is to incoming radiation the greater the reflection and the larger the forcing difference will be. The combined summertime LW and SW radiative effects indicate that after a cloud becomes optically thick, the decreasing SW effect will dominate the variability in radiative forcing, since the LWCRF levels off.

The sensitivity of LWCRF to effective radius (not shown) from the model results is approximately zero during both winter and summer. By contrast the sensitivity of SWCRF in summer is much greater (2 W m^{-2} per micrometer) with increasing cloud droplet sizes corresponding to lesser cooling effects. This is consistent with prior model results (Zhang et al. 1996; Francis1999) showing that smaller droplets reflect SW radiation more efficiently than larger droplets. Smaller droplets are more numerous for an equivalent cloud volume, thus allowing radiation to be scattered back to space before it becomes absorbed in-cloud or transmitted to the surface.

Cloud Height/Temperature Sensitivity

Radiosonde temperatures were interpolated to the lowest cloud-base heights, determined from lidar observations, to obtain cloud-base temperatures. Because there were only two soundings per day in winter and up to four daily in the summer, the cloud-base temperatures have some scatter associated with interpolation. However, in general we found good seasonal association between cloud base height and temperature, which is discussed, in detail in Shupe and Intrieri (2002). In Figure 4, the wintertime LWCRF is plotted as a function of cloud base temperature for the lowest cloud (water or ice phase) detected. Even though there is a large spread in values, increasing cloud base temperatures correspond to increasing positive LWCRF's. The warmest winter clouds, residing near the inversion between -10 and -25°C, provide the greatest contribution to surface warming and forcing. The scattering of points between -40 and -60°C, contributing between 0-15 W m^{-2}, are most likely associated with either high, thin ice clouds, infrequent occurrences of diamond dust (observed between -40 and -43°C), or instrument mismatches. Because of the Arctic inversion layer, changing cloud height will have a significant impact on the surface cloud forcing through the cloud-base temperature during winter. However, cloud height and the temperature inversions are closely linked. The LWCRF variability is approximately 2 W m^{-2} per degree C, translating to the fact that a cloud residing in a layer that is 5°C warmer will increase the surface forcing by approximately 10 W m^{-2}.

Discussion and Summary

An annual cycle of Arctic cloud and surface flux observations from SHEBA show that cloud radiative forcing at the surface is most highly sensitive to cloud fraction and phase and to a lesser degree and more seasonally on cloud base temperature and microphysical properties. Cloud fraction governs the sign and magnitude of the net effect on the surface by increasing the LWCRF throughout the annual cycle and decreasing (i.e., increasing the negative magnitude) the SWCRF during summer. The dominant cloud property affecting the amount of surface warming in winter and the degree to which clouds shade the surface from incoming solar radiation in summer is cloud phase. Thus, it is critical to correctly prescribe the phase in order to model the surface radiation.

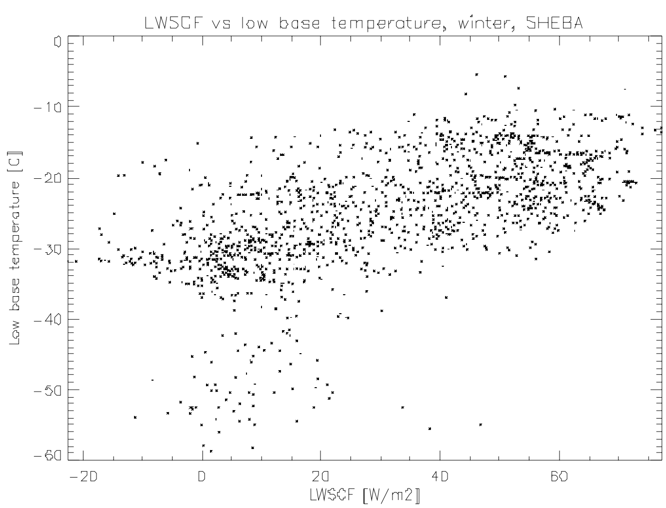

Figure 4. Surface cloud forcing versus cloud base temperature (C).

Winter observations show that even a small amount of cloud water (sometimes with LWP's less than ~30 g m^{-2} which is beneath the detectability threshold of the microwave radiometer, but distinguishable by the depolarization lidar) near the inversion, imparts a significant radiative influence on the surface as compared to clear skies.

In summer, the water clouds both reflect incoming solar radiation and emit IR. The LW radiative forcing component outweighs the SW forcing by 2 to 1 quantifying the long-held indication that snowmelt is enhanced under cloudy skies versus clear skies. This has significant implications on the ice-albedo feedback mechanism, which may be even stronger than previously predicted. For only a short period, at the height of the melt season, clouds have greater albedos than the underlying surface and cool the surface relative to clear skies.

Given the logistical challenges and measurement difficulties in cold remote regions, it is important to prioritize which cloud properties are most critical to observe. From this analysis, it is obvious that cloud amount be accurately documented, but it is also imperative that clouds in liquid phase be categorized as well throughout all the seasons. At present, there is only the depolarization lidar dataset from SHEBA documenting the occurrence and height of Arctic cloud liquid water layers. Obtaining additional measurements should be of high priority so that liquid water cloud climatologies can be built especially in winter and spring and in as many different Polar Regions as possible. Additionally, our data show that thin liquid water clouds are often present and affect the surface radiation throughout the year, yet these clouds are not adequately quantified since they are below the current noise level in microwave radiometer retrievals. Therefore, in order to fully understand the surface impact of these low LWP clouds in the Arctic, more sensitive LWP observations are necessary. The SHEBA observations show that 40% of the time the lidar observed liquid clouds where the LWP was below the noise levels (below 25 g m^{-2}) for the microwave radiometer LWP retrievals.

Understanding the differences between the radiation in the Arctic Ocean region versus the polar coastal zones will be explored in an extension of this study by comparing the SHEBA data analysis with long-term measurements currently being obtained at the Department of Energy North Slope of Alaska (NSA) site near Barrow, Alaska. At present, there are no depolarization lidar observations to categorize liquid water phase and height at the NSA; however, this is a planned addition to the site by 2004. Notwithstanding the omission of this very important cloud parameter, the NSA observations will allow us to compare the cloud forcing from an oceanic region to a site located at a more southerly location and with different albedos.

Acknowledgments

The authors would like to thank everyone involved in the SHEBA project especially C. Fairall, W. Eberhard, T. Uttal, R. Alvarez, S. Sandberg, J. Otten, the crew of the *C.C.G.C Des Groselliers,* and the entire SHEBA Project Office staff. Microwave radiometer data were obtained from the U.S. Department of Energy's Atmospheric Radiation Measurement Program. This work was supported by NASA FIRE.ACE Program under Contract No. L64205D, the NSF SHEBA Program under Agreement No. OPP-9701730, the NASA EOS Validation Program under Contract No. S-97895-F, and by the Biological and Environmental Research Program (BER), U.S. Department of Energy, Interagency Agreement No. DE-AI03-02ER63325.

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