6.7 THE NSA/SHEBA CLOUD & RADIATION COMPARISON STUDY

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1. INTRODUCTION

Clouds play an especially important and amplified role at high latitudes because the polar surface is characterized by high albedos and the polar atmosphere is much drier than lower latitudes. Arctic clouds also strongly influence the yearly sea-ice cycle of melting and formation so any potential feedback from clouds, in a changing climate scenario, can be substantially important. Changes in surface temperature, sea-ice concentration, atmospheric stability, etc. will undoubtedly affect the properties of clouds, and a change in cloud properties will, in turn, affect the radiation at the sea-ice surface. However, neither this cloud-radiation feedback mechanism, nor it's relation to the ice-albedo feedback, both of which are critical components in a changing climate scenario at high latitudes, are well understood.

In this study, we utilize Arctic datasets from two distinctly different Arctic locations to a) create a baseline of data in a region where measurements are generally lacking, b) investigate the differences between coastal Alaskan and Arctic Ocean region clouds, and c) determine the respective influences of clouds on the surface radiation budget. The cloud and radiation datasets were obtained at the DOE's Atmospheric Radiation Measurement (ARM) North Slope of Alaska (NSA) facility in Barrow, Alaska, from 1998 to 2003, and the Surface Heat Budget of the Arctic Ocean (SHEBA) program, in the Western Arctic Ocean region during 1997-1998. Similar cloud and radiation observations obtained in both locations by lidar, radar, and radiometers allow for a comparison of cloud occurrence and physical properties between these two distinctly different regions and were used to produce annual cycles of cloud occurrence and height, surface broadband fluxes, surface albedo, and cloud radiative forcing.

2. INSTRUMENT AND ANALYSIS INFORMATION

The instrumentation from the SHEBA field program and the NSA facility used as part of this study were similar and included cloud occurrence from lidar, ceilometer and radar, upwelling and downwelling shortwave (SW) and longwave (LW) fluxes from upward and downward looking broadband hemispheric radiometers and temperature and humidity profiles from atmospheric soundings. Although, the soundings at SHEBA and NSA provide identical information, the frequency of the soundings was much greater during SHEBA (2-4 per day/everyday) versus those obtained at NSA (once per day on weekdays only). For additional information on SHEBA instruments please refer to Intrieri et al. (2002a) and Persson et al. (2002). For additional information on the NSA site and instrument specifications refer to www.arm.gov.

Annual cycles of surface shortwave and longwave fluxes and surface cloud radiative forcing (SCF), defined as the difference between the all-sky and clear-sky net surface radiative fluxes, have already been documented for SHEBA (Intrieri et al. 2002b). Cloud forcing provides an estimate of how much a cloud changes the surface radiative fluxes relative to clear skies, and has become a common means for quantifying the radiative relationships between clouds and the radiation budget (Ramanathan et al. 1989). Definitions for the LW, SW and total SCF's, are given as:

$$CFLW = F(Ac) - F(0) \quad (1)$$

$$CFSW = Q(Ac) - Q(0) \quad (2)$$

$$SCF = CFLW + CFSW \quad (3)$$

Where, Ac is the cloud fraction and F and Q are the net surface LW and SW fluxes, respectively. Positive forcing values indicate that clouds impart a warming effect at the surface relative to clear skies (i.e., a greenhouse effect) and negative forcing values indicate that clouds impart a cooling effect relative to clear skies (i.e., the albedo effect). Cloud forcing at the surface is calculated using ground-based measurements of broadband fluxes for the all-sky values and modeled fluxes for the clear-sky values since clear skies occur so infrequently in the Arctic. In order to derive the SHEBA and NSA surface cloud forcing values, modeled clear-sky radiation results were calculated using the Santa Barbara DISORT Atmospheric Radiative Transfer code (SBDART: Richiazzi et al. 1998). The NSA fluxes and SCF's were calculated and processed in the same way as the SHEBA dataset for consistency. (Note: In Intrieri et al. 2002b the Total SCF's contained a turbulent flux component –sensible plus latent heat contributions over the annual cycle. However, in order to compare most closely with the NSA forcing values only the LW and SW fluxes were used in the SHEBA calculations for this study).

Measurements used for input into the SBDART model included temperature and relative humidity profiles from radiosondes and surface albedo from the SW radiometers. Interpolating atmospheric conditions between sounding times can introduce errors given that weather can change significantly and weather systems can pass through undetected in that amount of time. This is especially an issue in the NSA dataset since the

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soundings were less frequent. The surface albedo, a critical parameter in cloud forcing calculations, was calculated from the upward and downward looking SW radiometer hourly averaged flux values at both SHEBA and NSA. These measurements are therefore most representative of the local areas within view of the radiometers.

3. SHEBA AND NSA SURFACE CLOUD FORCING

3.1 *Total Cloud Forcing Annual Cycle*

The annual cycle of 20-day average total SCF (CFLW + CFSW) at SHEBA (Fig. 1, top panel – solid bold line) shows that clouds induced surface warming throughout most of the year with only a short period of surface cooling in the middle of summer, when cloud shading effects overwhelmed cloud greenhouse effects. At NSA, the annual trend is the same, (warming in winter, spring and fall), but the summer cooling effect is much stronger and lasts much longer. The total SCF at NSA falls below 0 Wm^{-2}, dipping down to ~-100 Wm^{-2}, for 3 months (from early June to mid September) while at SHEBA, the total SCF only fell below 0 Wm^{-2}, dipping to -5 Wm^{-2}, for the month of July. The seasonal averages for the total SCF at SHEBA are 30 Wm^{-2} for fall, winter and spring and -10 Wm^{-2} for summer (defined as the time period when the SCF is negative). At NSA, the seasonal averages (averaged over all six years) are 37 Wm^{-2} for fall, winter and spring and -60 Wm^{-2} during summer (defined same as above).

The greatest year-to-year variability at NSA is noted during the spring and summer melt season between day 130 and 230 (May through August) and the least amount of year-to-year variability is observed during the fall freeze-up. The yearly variability of the total SCF at NSA between the six years of data is ~30 Wm^{-2} during winter, spring and fall; however, during early summer, the variability is greater, varying by as much as ~80 Wm^{-2} between 1998 and 2002. The variability of the total SCF is greatest during the early summer season due to 1) fluctuations in the timing of the melt season onset and 2) local weather-related events that produce extended periods of clear skies and fluctuations in cloud amount and precipitation (which affect albedo). By the same reasoning, the data suggest that the fall season shows a much more consistent cloud, temperature and weather patterns between each NSA year, translating to greater consistency in cloud forcing. Fig. 2 illustrates 20-day averages of cloud fraction from NSA and SHEBA. Note the more consistent values between day 250 and 320 (September through November) with cloud fractions varying only between 90 and 100% whereas between day 150 and 250 (June through August) the fractions fluctuate between 70 and 100%.

In general, the annual cycle of NSA total cloud forcing reveals several points: 1) cloud amounts are fairly consistent and did not change substantially in the Barrow region during the fall, winter and spring seasons over the six year analysis period, 2) late spring and summer are most variable since late spring season weather-related disturbances vary the onset of the melt season, and 3) cloud's in the Barrow region have fairly consistent boundaries by which they affect the surface radiation (<50 Wm^{-2} in fall, winter and spring and > -150 Wm^{-2} in summer). In order to understand the specific differences between the two regional annual cycles, including the inter-annual melt season onset variability and smaller-scale anomalous events at NSA, we discuss the individual LW and SW components below.

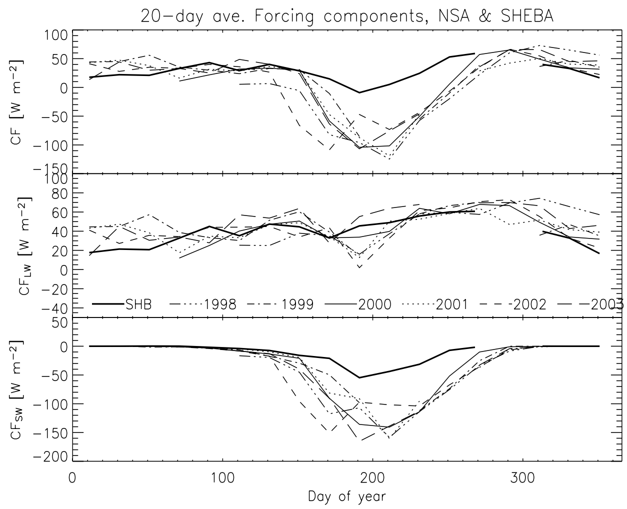

Fig. 1. Annual cycle of 20-day average a) Total, b) LW, and c) SW surface cloud forcing for SHEBA (bold line) plus six years of NSA data. All values in Wm^{-2}.

3.1 *Longwave Cloud Forcing Annual Cycle*

Cloud and radiation study results from SHEBA (Shupe and Intrieri 2004) showed that LW Cloud Forcing (CFLW) is a function of cloud temperature, height, and emissivity (which is a function of cloud microphysical properties). The trend and magnitude of the cloud LW warming effect on the surface during the entire annual cycle is similar at both SHEBA and NSA, with clouds warming the surface in the LW between 10 and 70 Wm^{-2} throughout the year (Fig. 1, middle panel). This general warming is predominantly due to the fact that clouds are optically thicker (i.e. stronger emitters) than the clear atmosphere. The warming is accentuated by the frequent occurrence of temperature inversions that often cause clouds to emit at temperatures warmer than the surface. In winter, surface temperatures are much warmer under cloudy skies than during clear conditions (Persson et al. 2002) and in all seasons clouds containing liquid water are efficient emitters in the longwave, becoming essentially black at LWP's greater than 30 gm^{-2}. The average LWCF during SHEBA was ~38 Wm^{-2} while at NSA the 6-year average was ~45 Wm^{-2}. The differences in the magnitudes of the CFLW between the two regions are attributed to the atmospheric temperature structure as well as the relative amount of clouds observed between the two sites. In general, NSA had greater cloud occurrence values in all seasons except for summer than was observed at SHEBA (Fig. 2). For example, in early winter at SHEBA (bold line between days 0 and 50) there were substantially less clouds present than at NSA so the forcing values are smaller. During mid-summer (~Day 200), for all years except 2003, NSA was less cloudy than SHEBA, so the LW forcing values are accordingly lower during that period at NSA. By the same logic, there is a fall season (September-November: ~days 240 and 310) CFLW maximum present in all of the measurement years which coincides with the cloudiness occurrence maximum values in both locations.

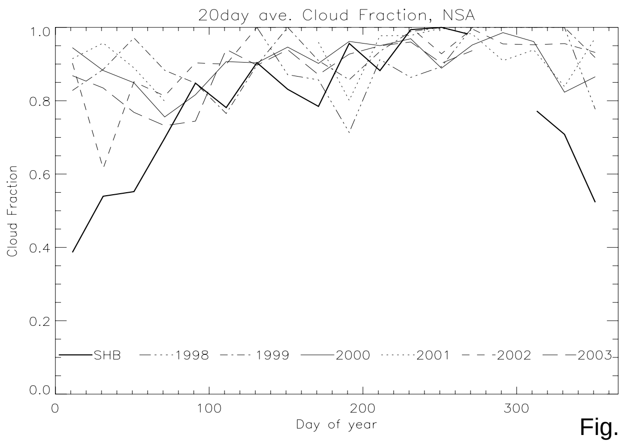

Fig. 2. 20-day averages of cloud fraction for SHEBA (solid line) and six years of data from NSA.

3.3 *Shortwave Cloud Forcing Annual Cycle*

Cloud and radiation results from SHEBA (Shupe and Intrieri 2004) showed that SW Cloud Forcing (CFSW) is a function of cloud transmittance (i.e., cloud microphysical properties), surface albedo, and the solar zenith angle. The CFSW cloud cooling effect (i.e., the SW shading effect of clouds) in summer is significantly stronger at NSA than at SHEBA (Fig. 1, bottom panel). At SHEBA, the 20-day average CFSW values dipped to ~ -50 W m^{-2} in July (centered around day 190). At NSA, the 20-day average CFSW values typically were two to three times greater than the SHEBA values, dipping to more negative values between -100 to -150 W m^{-2}.

This amplified shortwave radiative effect during summer at NSA is directly related to the much lower surface albedos (Fig. 3) as well as the somewhat higher insolation values and sun angles. Generally speaking, the snow/ice surface never fully melted away at SHEBA. For practical purposes, the radiometers at SHEBA were sited on a multi-year ice floe so that the instrumentation wouldn't need to be relocated due to melting. In this manner, the albedos calculated at the singular radiometer point near the tower were somewhat higher with typical albedos being 0.10-0.15 greater than the average albedos determined from a 200 m line which included meltponds and leads (see Fig. 5, Intrieri et al. 2002b). A direct comparison between the radiometers and 200 m line albedo measurements can be seen in Fig. 19 of Persson et al. (2002).

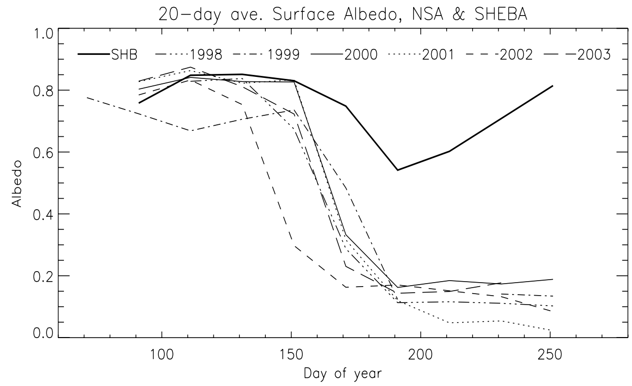

Fig. 3. Annual cycles of albedo for SHEBA (solid line) and six years of data from NSA.

Taking into account the lower line-averaged values at SHEBA produced lower total cloud forcing values, dipping below 0 W m^{-2} between early June to mid-August and a minimum value of ~-50 W m^{-2} (see Fig. 11, Intrieri et al. 2002b). However, even at these lower SHEBA albedo values, the NSA SW and total cloud forcing are still twice as large. The reason boils down to the fact that at NSA the snow fully melts away to reveal bare dirt and tundra. At SHEBA, the minimum albedo values were 0.50 for the point measurement and 0.38 for the line-averaged measurement, while at NSA these values are typically ~0.15. Together, these data indicate that the surface albedo is the major source of CFSW difference between SHEBA and NSA.

Solar Zenith Angle (SZA) also contributes to the differences observed between the CFSW at SHEBA and NSA. The SZA determines the potential amount of solar radiation available at the surface and the length of time that the sun is above the horizon. Since the SHEBA drift site was ~1000 km North of Barrow, the minimum summer SZA was 54° compared to a minimum SZA of 50° at Barrow. Thus, at SHEBA the annual maximum insolation was about 650 W m^{-2}, while the NSA maximum is nearly 750 W m^{-2}. Shupe and Intrieri (2004) found that at SHEBA the SWCF was always less than 25%, but typically around 3-10%, of the total insolation. Therefore, a small, but significant, portion of the CFSW difference between SHEBA and NSA can be directly attributed to SZA.

As stated above, some of the year to year variability at the NSA site is directly related to the onset of the melt season and its impact on surface albedo. On average, the melting begins to occur around June 9 to19 (day 160-170) but was observed as early as May 27 (day 147) in 2002 and as late as June 28 (day 179) in 1999. After melt has fully occurred the variability in the observed CFSW is often due to extended periods of clear skies present over Barrow Alaska (Fig. 1, bottom panel; e.g. ~day 190 during 1998, 2001, 2002) when the forcing values effectively increase because forcing under clear skies is zero. In spite of the variable spring melt onset, there appears to be little variability in the timing of the fall transition back to a snow covered surface indicating that once snow falls, it remains cold enough to keep the surface albedo high.

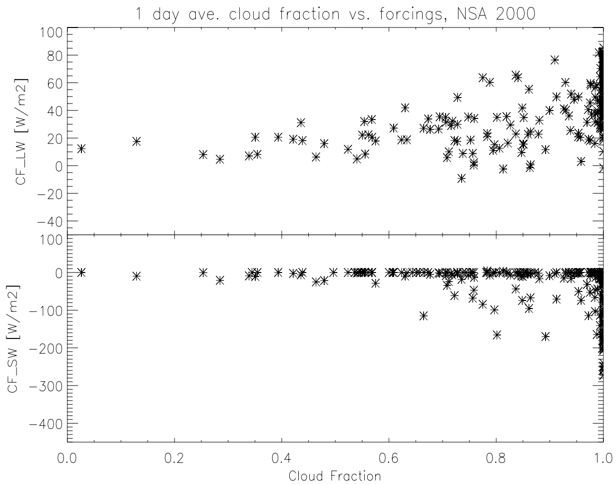

Fig. 4 . Scatter plot of CFLW (top) and CFSW (bottom) versus cloud fraction amount for NSA, 2002.

3.4 ***Sensitivity of Cloud Forcing***

We examined the sensitivity of the cloud occurrence to the cloud forcing for both the LW and the SW forcing values. By definition, cloud forcing under clear skies is equal to zero and under 100% overcast skies the forcing is at its maximum. At SHEBA, we found that the sensitivity of CFSW to cloud fraction ranged between 0.0 and -1.0 W m^{-2} per percent cloudiness (Shupe and Intrieri 2004) whereas at NSA values approached twice that to around -2.0 W m^{-2} per percent cloudiness under overcast sky conditions (Fig. 4). At SHEBA, the CFLW and cloud fraction were positively correlated and the sensitivity was about 0.65 W m^{-2} per percent cloudiness. At NSA the sensitivity is slightly higher at about 0.75 W m^{-2} per percent cloudiness (Fig. 4).

4. SUMMARY AND FUTURE WORK

Cloud and radiation data from two distinctly different Arctic areas are analyzed to study the differences between coastal Alaskan and open Arctic Ocean region clouds and their respective influence on the surface radiation budget. Radar, lidar, radiometer, and sounding measurements from both locations were used to produce annual cycles of cloud properties, atmospheric temperature and humidity, surface longwave and shortwave broadband fluxes, surface albedo, and cloud radiative forcing.

In summary, the warming effect trend of clouds on the surface during winter is similar at both SHEBA and NSA, mostly due to the ever-present inversion and similar atmospheric temperatures. Variability can be attributed to differences in cloud occurrence amount. During summer, the shading effect of clouds at Barrow is much greater than at SHEBA because of the significantly lower surface albedos and higher insolation values. Generally, both regions revealed a similar annual trend of cloud occurrence fraction with minimum values in winter (60-75%) and maximum values during spring, summer and fall (80-100%). However, the annual average cloud occurrence fraction for SHEBA was lower (76%) than the 6-year average cloud occurrence at NSA (92%). Both Arctic areas also showed similar annual cycle trends of cloud forcing with clouds warming the surface through most of the year and a period of surface cooling during the summer, when cloud shading effects overwhelm cloud radiative warming effects. The greatest difference between the two regions was observed in the magnitude of the cloud cooling effect (i.e., shortwave cloud forcing), which was significantly stronger at NSA and lasted for a longer period of time than at SHEBA. This is predominantly due to the longer and stronger melt season at NSA (i.e., albedo values that are much lower coupled with sun angles that are somewhat higher) than the melt season observed over the ice pack at SHEBA.

Further studies are planned with this dataset to assess the statistics in more detail in order to quantitatively understand the differences between the two sites and to extend the dataset forward in time to create and examine the evolving climate forcing record.

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