16.7 THE INFLUENCE OF ARCTIC SEA ICE EXTENT ON POLAR CLOUD FRACTION AND VERTICAL STRUCTURE AND IMPLICATIONS FOR REGIONAL CLIMATE

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1. INTRODUCTION

In recent years, much attention has been given to the Arctic because of its well known sensitivity to climate change. Evidence of change has been seen at an accelerating rate over the last decade or more. Surface temperatures, albeit scarce in the Arctic, show a 1-2 degree C increase over the last 20 years (Rigor et al., 2000). During this period, Arctic sea ice extent has decreased by roughly 15 to 20 percent (Serreze et al., 2007). The decrease in sea ice and subsequent increase in open water will have two immediate effects: 1) increase the surface fluxes of heat and moisture from the ocean to the atmosphere and 2) markedly decrease the surface albedo. The first effect will tend to cool the ocean and moisten and warm the atmosphere with possible changes to cloud properties such as coverage, vertical structure, phase, and optical depth. The second effect will allow more solar radiation to be absorbed at the surface, thereby heating the ocean. If cloud properties change in response to more open water in the Arctic, it could have implications for regional climate.

Prior work on Arctic cloud changes has often led to conflicting conclusions. Schweiger et al.(2008) used passive observations from TOVS and the 40 year ECMWF Re-Analysis (ERA-40). They found that sea ice retreat was linked to a decrease in low-level cloud amount and a simultaneous increase in mid level clouds. Wang and Key (2003) and Schweiger (2004) used AVHRR derived cloud datasets to conclude that the springtime cloudiness is increasing with time while Comiso (2003) used a separate AVHRR data set and found springtime cloudiness is decreasing. Part of the ambiguity in these results may be attributable to the passive cloud detection techniques employed. It is very difficult to obtain accurate cloud detection over ice from passive instruments. Active remote sensors such as lidars are not affected by problems that can often hamper passive cloud retrievals such as the underlying surface albedo, lack of sunlight and atmospheric temperature inversions.

This study utilizes satellite lidar data from ICESat and CALIPSO to ascertain changes in Arctic clouds since 2003. Emphasis is placed on cloud fraction, vertical structure and optical thickness over ice free versus ice covered areas. The overall radiative effect of clouds will depend on their fractional coverage, height, geometric and optical thickness, vertical structure and water phase. Additionally, we will use these findings to infer what effect the reduced ice cover in the Arctic has on the radiative balance and Polar climate

2. SATELLITE DATA SETS

The Ice, Cloud and land Elevation satellite (ICESat) was launched in 2003 to study the mass balance of the earth's major ice sheets using high precision altimetry (Schutz et al.., 2005). Onboard ICESat is the Geoscience Laser Altimeter System (GLAS) comprised of the altimeter channel and two atmospheric lidar channels (1064 and 532 nm) used to detect clouds and aerosols (Spinhirne et al, 2005). Though designed to obtain measurements continuously for a period of 3 years, laser problems encountered shortly after launch required a modified observation approach consisting of month-long measurement periods executed three times per year. The ICESat cloud data set utilized here is known as GLA09 and is publicly available at the National Snow and Ice Data Center (NSIDC). We used the version 28 4 second cloud heights derived from the 1064 nm channel which was more stable in laser energy than the 532 nm channel. Though ICESat continues to operate, we do not use the cloud data past October of 2007 (ICESat observation period known as L3I), because of low laser energy.

CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) is a dual wavelength atmospheric lidar similar to GLAS and has been in continuous operation since June of 2006 (Winker et al., 2007). The cloud data set

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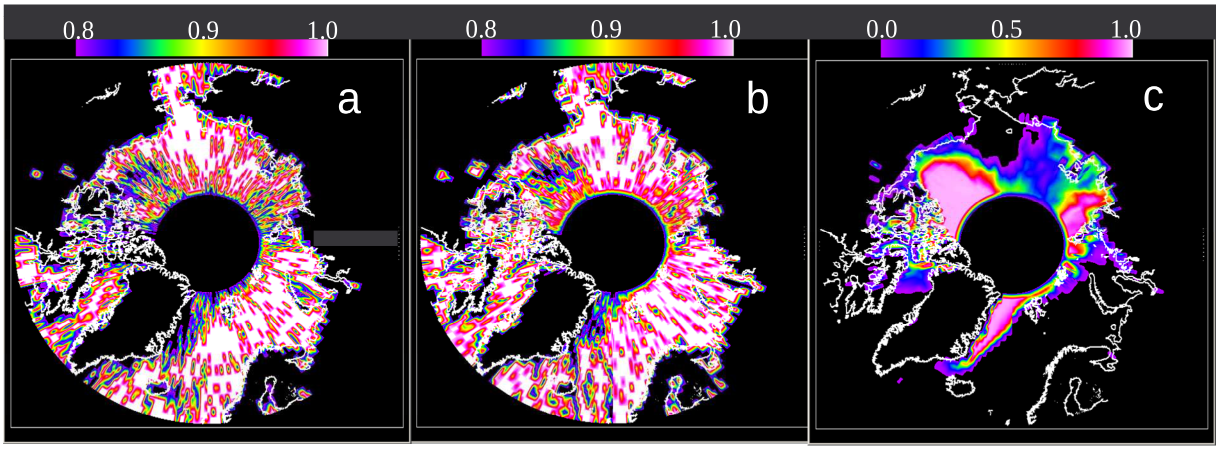

Figure 1. ICESat (a) and CALIPSO (b) cloud fraction over water and sea ice for the period October 2 to November 5, 2007 and the AMSR-E measured sea ice fraction (c) for the month of October, 2007. The overall cloud fraction for the region shown is 93.5% for CALIPSO and 94% for ICESat. Note that ICESat obtains measurements to 86° N and AMSR-E to the pole, while CALIPSO only to 82° N. The ICESat and AMSR-E data above 82° N are masked out to ensure the cloud and sea ice observations of the three satellites covered the same area.

used in this study is from version 2 of the level 2B data obtained from the NASA Langley Data Center. The cloud heights were derived from the 532 nm channel of CALIPSO. We used only the 5 km and 20 km cloud resolutions in compiling the CALIPSO cloud statistics. There is a period from June, 2006 to November of 2008 that gives limited (4) opportunities to compare the CALIPSO cloud retrievals to those of GLAS. We will explore this more in section 3.

Sea ice coverage is derived from the Advanced Microwave Scanning Radiometer (AMSR-E) on the EOS Aqua satellite launched in May, 2002. The instrument provides daily coverage of the entire Arctic Ocean at a spatial resolution of 12.5 km. In this analysis, we use the AMSR-E monthly average sea ice amount.

3. CLOUD FRACTION

This study seeks to determine trends and relationships between sea ice coverage and Arctic cloud properties. As such, we limit our analysis of clouds to areas north of 60° N and to areas over ocean and sea ice. The land/ocean mask available in both the GLAS and CALIPSO data products is used to segregate the cloud data so that only cloud data over water or ice is considered in the analysis. An example of cloud fraction retrieval over the study area is shown in Figure 1. Displayed are the cloud fraction obtained from ICESat and CALIPSO for the period October 2 to November 5, 2007 and the sea ice fraction for the month of October, 2007. Immediately obvious are two things: 1) ICESat and CALIPSO are measuring nearly the same cloud distribution and amount and 2) there is a high anti-correlation between cloud fraction and sea ice amount. Though cloudiness is very high over the entire Arctic, it is generally 10 to 15 percent greater over areas with little or no sea ice (less than 20 percent ice coverage) than it is over regions with high sea ice concentration (greater than 80 percent). In areas of open water, cloudiness is often near 100 percent. This observation is consistent with increased surface fluxes in areas of open water.

While there are of course other factors that regulate cloud formation and amount, the surface boundary condition has a large influence. Also, the averaging period of one month used here helps to remove the high frequency variability of cloudiness due to the synoptic scale weather systems leaving mainly the influence of the surface boundary condition. Occasionally, however, large scale weather patterns may persist for periods longer than a month as they did over the Arctic in the summer of 2007 when anomalously low cloud fraction was observed over much of the Arctic by CALIPSO and other satellites during June and July. Kay et al. 2008 suggest that this low cloud amount allowed an increased amount of solar energy to warm the surface and helped to contribute to the record sea ice melt during the late summer of 2007.

Utilizing the entire data record of ICESat and CALIPSO, a 63 month-long history (though not continuous) of cloud fraction over the Arctic can be constructed. Figure 2 shows the average cloud

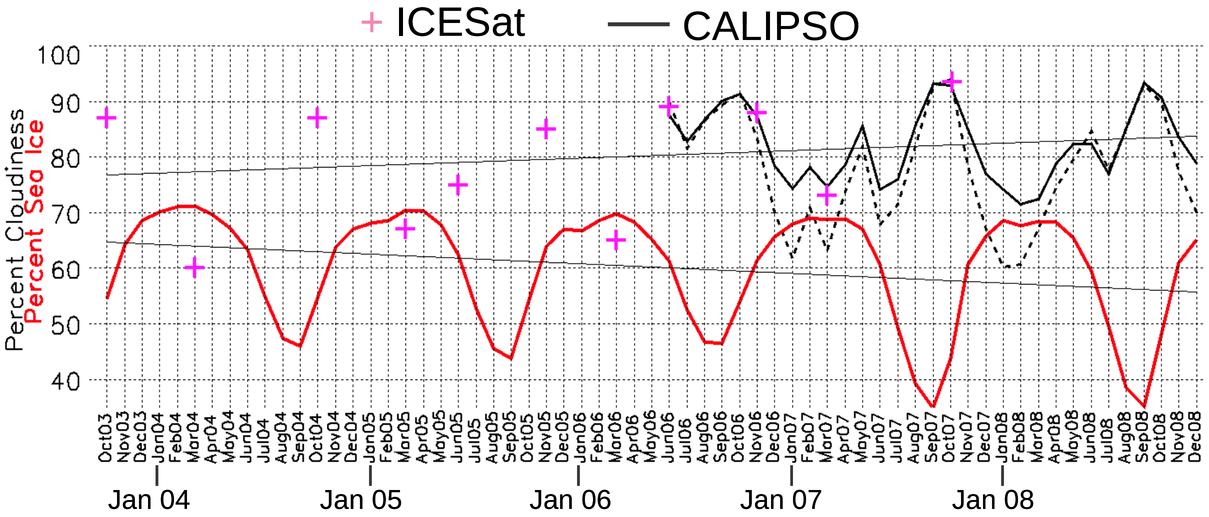

Figure 2. Average cloud percent for the region shown in Figure 1 from ICESat observations periods (each about 33 days long) beginning in October, 2003 and ending in October of 2007 (pink crosses) and from monthly average CALIPSO measurements (solid black line) from June, 2006 to December, 2008. The dashed black line is CALIPSO cloud percent but only for longitudes between 90° and 270° and north of 70° N. The red line is the average monthly AMSR-E ice coverage for the same area. Upper and lower thin black lines are trends estimated from the cloud fraction and sea ice data, respectively.

Fraction obtained from all ICESat observation periods since October, 2003 and ending in October, 2007 (pink crosses). Also plotted is the monthly average cloud fraction derived from CALIPSO measurements (solid black line) and the AMSR-E derived sea ice coverage (solid red line). Readily visible is the yearly cycle in sea ice amount and the high anti-correlation between sea ice amount and cloud fraction. Note that there are four ICESat observation periods for which exist corresponding CALIPSO measurements and that the agreement in cloud amount between the instruments is very high. Also shown in Figure 2 is the linear least square fit to the cloud fraction data points (both ICESat and CALIPSO) (upper thin, straight black line). The slope of this line indicates that cloud fraction has increased by about 7 percent over the observational period, or about 14 percent per decade. The linear least square fit to all the sea ice data points is also shown in Figure 2 (lower thin, straight black line) and indicates a roughly 7 to 8 percent decrease in sea ice over the 5 year period. While this rate of decrease is somewhat larger than other published figures (5 to 10 percent per decade) it may not be unreasonable considering the accelerating rate of decline in the last 2 to 3 years.

The dashed black line in Figure 2 denotes the CALIPSO cloud fraction for the sub-region bounded by 90° to 270° longitude and north of 70° latitude. There are two things to note about the cloudiness in this region. 1) The wintertime minimum in cloudiness is considerably lower than for the whole Arctic region, while the summer and fall maximum in cloudiness is about the same. 2) June and July of 2007 experienced lower cloud fraction in the sub-region than the Arctic region as a whole, though the latter region cloud amount was considerably less than the values for June and July of either 2006 or 2008. It is in this sub-region that a large amount of melting occurred during the late summer of 2007. Kay et al. 2008 attribute this melting at least in part to the anomalously low cloud amount over the region in June and July caused mainly by a stationary high pressure area with widespread subsidence. This allowed a higher than normal amount of solar radiation to reach the surface. Initially, most of the sunlight will be reflected from the ice, but as the ice melts and water ponds form, the albedo decreases allowing more of the incoming solar radiation to be absorbed. The more the ice melts, the more shortwave radiation is absorbed and the melting accelerates. If, however, clouds form in response to the increased open water, this process would be disrupted because the clouds will reflect much of the shortwave radiation. In June and July, 2007 cloud cover was low, but note that the cloud amount in the sub-region increased dramatically in August and September, 2007 from about 70% in July to 93% in September, due at least in part to the increase in open water during

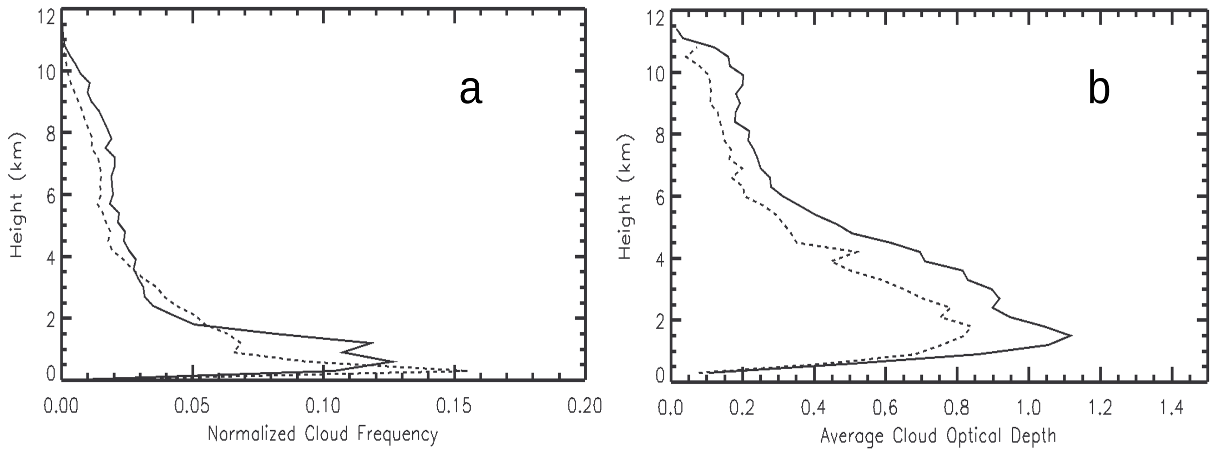

Figure 3.ICESat measured cloud frequency as a function of height normalized by the total number of cloud observations (a) for clouds that occur over water (solid line) and for clouds that occur over ice (dashed line) and the average cloud optical depth (b) segregated in the same manner. The observations are from October ICESat observation periods of 2003 through 2007.

August and September. Of course, a full analysis of the cause must include an examination of the synoptic scale meteorological conditions present during this period.

Another interesting thing to note from Figure 2 is the marked increase in wintertime cloudiness during the period shown. ICESat data from 2006 and earlier show an average March cloudiness of about 65%, while after this time the ICESat and CALIPSO measurements indicate cloudiness has increased to about 73%. Might increased cloud cover in winter months be related to the decreasing winter sea ice coverage even though that rate at which wintertime sea ice is decreasing is much less than for summer? Further, if winter cloud amounts are increasing, it follows that it would keep winter Arctic temperatures warmer through increased trapping of longwave radiation. This, in turn, would tend to lessen the maximum thickness that wintertime ice can obtain, leaving it more susceptible to melting the following summer.

4. VERTICAL DISTRIBUTION OF CLOUDS

In addition to cloud amount, the vertical distribution and properties of clouds are also very important in determining the affect they have on radiative balance and regional climate. Fortunately, lidars are ideal tools for retrieving cloud vertical structure, phase (if depolarization channel is present as for CALIPSO), and optical depth. Figure 3 shows the vertical structure (frequency distribution) and optical depth of Arctic clouds as derived from the five October ICESat observations from 2003 through 2007. The cloud retrievals have been segregated into those that occur over areas with ice concentration greater than 80% (dashed line) and those that occur over regions where the ice concentration is less than 20% (solid line). For the cloud frequency plot (Figure 3a), they have also been normalized by the number of clouds detected in each segregated population. Note that when shown in this way, the curves do not show the true number of clouds relative to each other, but rather how the clouds in each population are distributed vertically. There are distinct differences in the cloud vertical frequency and optical depth of the two populations. The vertical distribution of clouds over water peaks somewhat higher in the atmosphere at a lower frequency of occurrence than for the clouds over ice. However, the frequency distribution of clouds over water below 2 km is broader, indicating more clouds between about 800 and 1800 m altitude. This is most likely due to a de-stabilization of the lower troposphere and deepening of the boundary layer caused by increased surface fluxes over the open water. This observation is somewhat contrary to the conclusion of Schweiger et al. (2008) who found a decrease in clouds below 800 hPa (roughly 2 km) and an increase in cloud amount between 800 and 450 hPa (roughly 2 to 6 km) as ice cover retreated. The conclusion from our analysis indicates that over open water the number of very low clouds (less than 500 m) decreased, while the number of clouds between 500 m and 2 km increased significantly. The difference between our analysis and the findings of Schweiger et al. could be due to the limitations of assigning height values to clouds via passive remote sensing. In addition, our results in Figure 3 indicate less clouds over water between 2 and 4 km, but that above 4 km there is a slightly higher frequency of clouds over water than over ice.

In addition to the changes in cloud vertical distribution, Figure 3b indicates that there is a 20 to 30 percent increase in the optical depth of the clouds over open water above 1 km altitude. This is difficult to explain, but further analysis indicates that the increased optical depth is due mainly to the fact that clouds are geometrically thicker, on average, over water than over ice. The average backscatter does not differ significantly between the two groups. This geometric thickness difference decreases as clouds become lower and thus the optical depths converge below about 1 km.

5. CONSEQUENCES OF CLOUD CHANGES ON RADIATIVE BALANCE AND CLIMATE

Our observations indicate that as sea ice retreats, polar cloud fraction will continue to rise. In general, with more cloudiness we expect a decrease of down-welling shortwave radiation and an increase of down-welling longwave radiation. The net down-welling radiation in sunlit conditions is expected to be decreased because for most sunlit conditions, the shortwave component is larger than the longwave. Less down-welling radiation could slow down the melting of sea ice in summer months. Note that because of the lack of sunlight for a large part of the year, and low solar zenith angle in late spring and summer, longwave radiation dominates the radiation budget of the Arctic.

Our results also suggest that the vertical distribution of clouds may change in response to sea ice melt with an increased fraction of the clouds below 2 km, especially between 800 and 1800 m. Also, cloud geometrical and optical thickness tend to higher values over open water or low sea ice concentration areas. In addition to cloud fraction, these observed cloud property changes will have effects on the radiation balance of the Arctic. Increases in low cloud cover tend to have a cooling effect during summer months and a warming effect in winter months. The effect is not clear for late spring and early fall months when the Arctic is sunlit, but the solar elevation is low. The total effect of cloud changes on radiative balance in the Arctic is complicated and needs further study including observations and modeling.

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