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

During the last 20 to 30 years, and especially during the last decade, noticeable changes to the Arctic environment have taken place. Surface temperatures have increased by roughly 2 degrees Celsius [1] and Arctic sea ice has decreased substantially in both extent and thickness [2]. These changes are a concern because most climate models predict that the effects of global warming will be the greatest in the polar regions of the earth. Decreasing Arctic sea ice has many consequences but among them are increased surface fluxes of heat and moisture from the ocean to the atmosphere. Additionally, the decreased surface albedo of open water will dramatically increase the amount of solar radiation absorbed by the ocean. These combined effects will certainly have implications for regional climate and possibly impact the weather or climate of areas far from the Arctic. A number of studies, both theoretical [3] and observational [4] have found connections between arctic sea ice extent and general circulation and precipitation patterns. However, a more immediate result of increased surface fluxes associated with more open water in the Arctic is the formation of more clouds. The total cloud fraction, optical depth and vertical distribution may change as Arctic sea ice gives way to open ocean. There have been a number of studies examining the trend of arctic cloudiness over the last few decades, but often, prior work on Arctic cloud changes has led to conflicting conclusions. Schweiger et al., [5] 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 [6] used AVHRR derived cloud datasets to conclude that the springtime cloudiness is increasing with time while Comiso [7] 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 and to examine how cloud properties differ over sea ice versus over

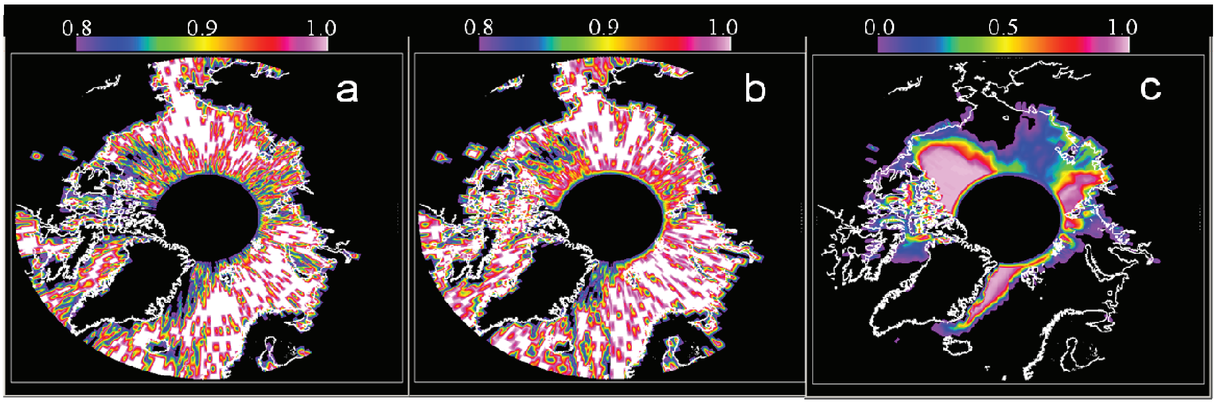

Figure 1. ICESat (a) and CALIPSO (b) cloud fraction over water and sea ice for the period 10/02 to 11/05, 2007 and the AMSR-E measured sea ice fraction (c) for the month of October, 2007. The cloud fraction for the region shown is 93.5% for CALIPSO and 94% for ICESat. Note that ICESat obtains measurements 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.

open water.

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. 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 [8]. The ICESat cloud data set utilized here is known as GLA09 and is publicly available at the National Snow and Ice Data Center (NSIDC). 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 [9]. The cloud data set 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. 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. ARCTIC CLOUD FRACTION

We limit our analysis of clouds to areas north of 60 N and to areas over ocean and sea ice (the study area). 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 ice). 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. 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 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 (normalized) 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 observation 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 of this period.

4. SUMMARY AND CONCLUSIONS

We conclude from these observations that overall cloud fraction will continue to rise in the Arctic as the sea ice retreats in areal extent and thickness. In general, with more cloudiness we expect a decrease of down-welling shortwave radiation and an increase of down-welling longwave radiation. Less down-welling radiation could slow down the melting of sea ice in summer months. However, in winter the increased cloud cover could decrease the radiative cooling and slow down the freezing process, resulting in less thick ice at the end of winter. 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 (not shown) also suggest that the vertical distribution of clouds may change in response to sea ice melt with an increased fraction of the

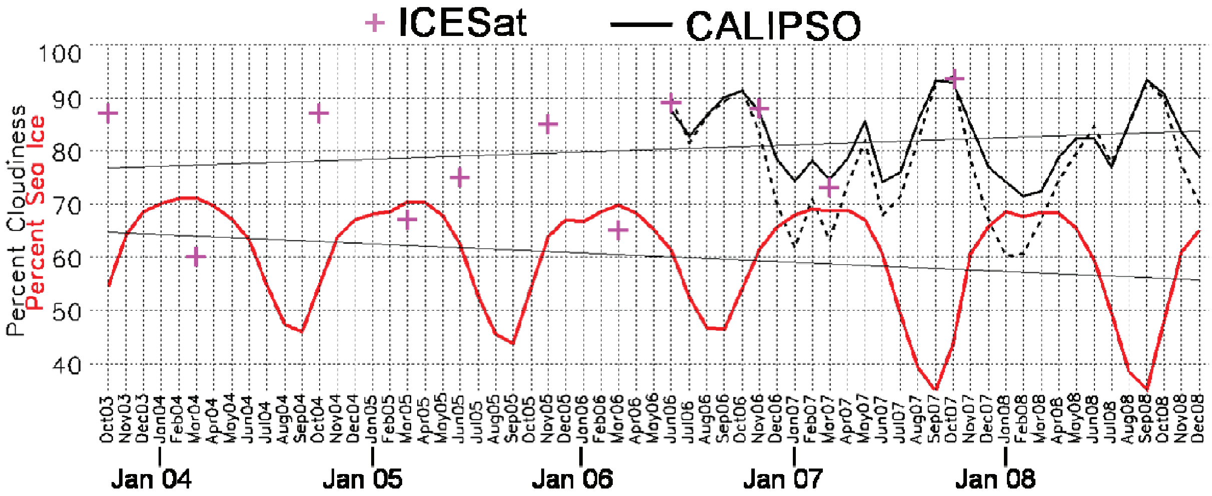

Figure 2. Average cloud percent for the region shown in Figure 1 from ICESat observations periods (each about 33 days long) beginning in October, 2003 and ending in October of 2007 (pink crosses) and from monthly average CALIPSO measurements (solid black line) from June, 2006 to December, 2008. The dashed 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.

clouds below 2 km, especially between 800 and 1800 m. This observation is consistent with the hypothesis of increased surface fluxes destabilizing the lower troposphere and creating a warmer, moister and deeper boundary layer over open water. Modeling studies have also shown both an increase in boundary layer height and higher surface fluxes associated with sea ice retreat [4]. Further results and implications for climate will be presented.

5. REFERENCES

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