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Antarctica cloud cover for October 2003 from GLAS satellite lidar profiling

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[1] Bright surfaces and low surface temperature limit the study of Antarctica cloud cover by passive techniques. Starting in 2003 the Geoscience Laser Altimeter System (GLAS) provides the first measurements of polar clouds by satellite lidar. From the GLAS data the presence and height of all clouds are detected, and in the case of transmissive clouds that predominate in the Antarctica, the thickness is also found. Initial results for October 2003 data are summarized. There are two basic cloud types profiled: stratus below 3 km and cirrus form clouds with cloud top altitude and thickness tending at 12 km and 1.3 km. Zonal average cloud fraction varies from over 93 % for ocean and coastal regions to a consistent average of 40% over the East Antarctic plateau and 60–90% over West Antarctica. Differences between the zonal average GLAS and MODIS cloud fractions are as much as 40% over the continent.
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1. Introduction

[2] Clouds play two fundamental and critically significant roles in the climate of Antarctica: they are the source of precipitation, and they perturb and control the overall radiation balance. The role of Antarctic clouds partly contrasts with other regions of the globe. The dynamical forcing due to latent heat release is much less of a factor for circulation, but cloud related precipitation maintains the ice mass of the continent and thus affects global sea level. For radiation, Antarctica clouds have a much smaller top of the atmosphere effect but largely control the surface radiation budget [*Yamanouchi and Charlock*, 1997]. The important influence of clouds on Antarctica's climate and global change issues gives rise to a need to observe and understand their distribution and characteristics. A comprehensive view of the cloud distribution is best provided, as else where, from satellite sensors. But as is well known, polar regions present a most difficult challenge for passive remote sensing techniques. The strong short wave reflectance of snow and ice combined with low thermal brightness temperatures of the surface obscure cloud presence and limit the accuracy of passive cloud retrievals for polar regions, particularly in central Antarctica. Large differences exist between estimates from different sensors and algorithms [*Pavolonis and Key*, 2003]. A very important climate issue is change in Antarctic cloud cover [*Dutton et al.*, 1991]. But cloud variability is given little study, most likely due to the inadequacy of existing satellite and surface based measurements.

[3] Satellite lidar measurements can provide a nearly unambiguous measurement of the distribution of polar clouds. Active lidar remote sensing of clouds is not affected by cold temperatures, and high surface albedo only effects solar background noise. The Geoscience Laser Altimeter System (GLAS) satellite lidar launched on the Ice, Cloud and land Elevation Satellite (ICESat) in 2003 was specifically designed to accomplish high accuracy profiling of all global clouds [*Spinhirne et al.*, 2005; *Zwally et al.*, 2002]. Observations of tropospheric clouds in Antarctica were a particular interest given the relative lack of knowledge of their distribution. In addition polar stratospheric clouds (PSC) were to be profiled. A secondary application was a need to detect and remove biases in the GLAS surface elevation estimates due to forward scattering [*Duda et al.*, 2001; *Mahesh et al.*, 2002]. A GLAS instrument requirement was to detect clouds down to total scattering cross sections of 10^{-5} m^{-1}, the equivalent of an optical thickness of 0.01 for a 1 km layer. The GLAS on orbit results show the required levels of performance were achieved when the laser transmitters functioned within planned limits. (Some later data are with degraded performance due to technical problems with the lasers (J. Abshire et al., Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Abshire et al., submitted manuscript, 2005).)

[4] The initial measurements with the fully operating GLAS instrument were begun in late September 2003 through mid November 2003. Processing of these data for the fall 2003 period has now produced probably the most accurate observational result for the coverage and height distribution of Antarctic cloud cover. In this paper we give an initial description of these results and contrast them with other satellite retrievals.

2. Observation Results

[5] GLAS is a non-scanning lidar nominally operating in a nadir-viewing mode with wavelengths of 532 nm and 1064 nm [*Spinhirne et al.*, 2005]. The laser pulse rate of 40 Hz, yields vertical cloud profiles beneath the satellite at approximately ~172 m spacing along a given orbit track. Though limited to along track coverage, the data profiles are a direct measurement of the height distribution up to the limit of signal attenuation at a resolution of 76.8 m in the vertical. *Spinhirne et al.* [2005] lists the GLAS data prod-

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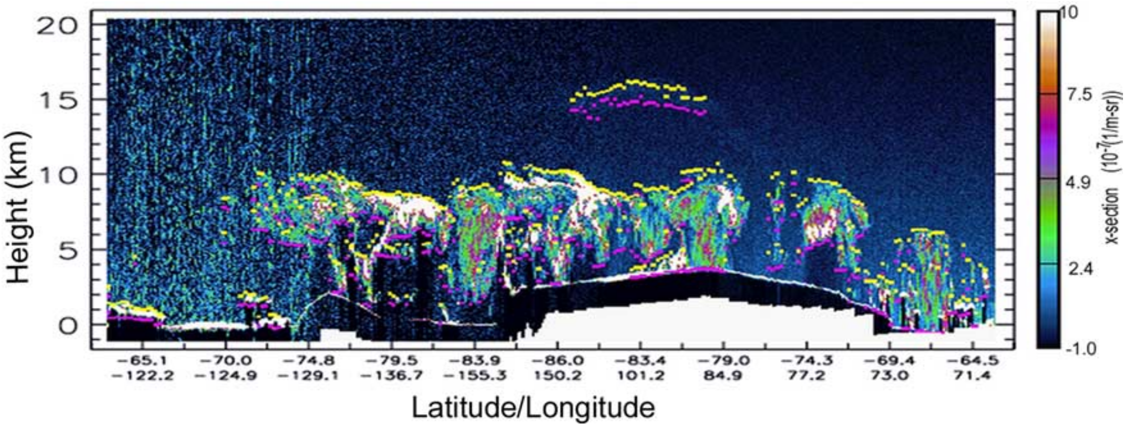

Figure 1. GLAS atmospheric calibrated attenuated backscatter cross section, from GLA07(Global Backscatter Data Product) and cloud height from GLA09 (Global Cloud Heights for Multi-layered Clouds Product), for a single 14 minute orbit track (repeat number 57) over Antarctica at 15:50 UTC October 1 2003. The derived cloud boundaries are shown as yellow dots for the cloud top and purple dots for the cloud bottom. Where there is a sufficiently large separation, multiple layers are detected.

ucts derived from the lidar signals. An example of the GLAS return signal strength as a function of height and distance for one orbit (ICEsat repeat track 57) across Antarctica is shown in Figure 1. The result is from the more sensitive 532 nm cloud channel. The plotted parameters are from the GLA07 and GLA09 products: the calibrated, attenuated backscatter cross section and derived cloud boundaries respectively. The figure shows signals from ~39,000 laser pulses. The effect of pulse averaging increases the detail visible, and similarly pulse averaging is applied in data analysis. The increased noise evident on the left side of the figure is caused by the solar brightness in this region. Cloud heights in GLA09 are obtained, as shown in Figure 1, from sensitive detection of the presence of cloud edges and include both top and bottom boundaries for sufficiently thin and multi layered clouds [*Palm et al.*, 2002; *Hart et al.*, 2005]. The very thin Type I PSC detected near the center of the image illustrates the sensitivity of the measurement.

[6] The clouds shown in Figure 1 are typical of GLAS 532 nm channel lidar data collected over Antarctica. There are in general three types of clouds present: upper troposphere ice clouds; dense surface clouds; and PSC's. The bulk of the clouds below 10 km are ice crystal clouds, which may be considered cirrus and in Figure 1 are associated with a cyclonic storm moving from the Weddell Sea region. In some areas these extend to the surface. Dense clouds are present near to the surface in some regions. Near the coast these are stratus. Over the plateau regions these surface clouds can appear in the figure as a thickening of the signal return from the surface and are thus a layer of low vertical thickness. These are possibly blowing-snow [*Mahesh et al.*, 2003] and are not currently detected as clouds in the data processing. Improved detection and classification of such low layers is being developed. The third cloud type is PSC's. *Palm et al.* [2005] describe a more dramatic case of PSC associated with a cyclonic storm.

[7] We present here the initial result from the first month the GLAS lidar was fully operating, October 2003. From the multiple orbit tracks over the continent in this first month, statistics can be assembled on the frequency of coverage and the height distribution of the cloud cover. Figures 2 and 3 show the frequency of occurrence of all clouds and the zonal average cloud top height frequency for latitudes south of 60°. For the frequency of occurrence there are two distinct regimes. For oceanic, coastal and large areas of West Antarctica, low stratus type clouds dominate cloud cover with the frequency of occurrence varying generally between 60 and 100%. Over most of East Antarctica cloud cover varies between 60% to completely clear with cloud cover generally decreasing with increasing surface altitude. The predominate cloud type over the continent is cirrus clouds which exist below the effective tropopause height of

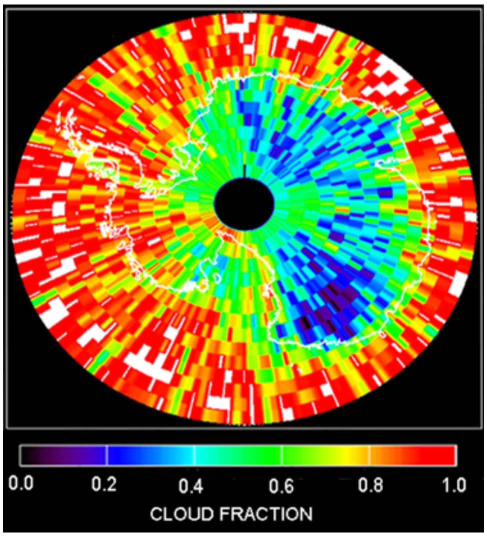

Figure 2. Fractional cloud cover over Antarctica as detected by GLAS for October 2003 averaged into 1° grid boxes. The value in each box represents the fraction of the total number of 5 Hz average laser profiles within the box for the month where a cloud is detected at any level. A 5 Hz profile corresponds to approximately a 1.4 km track horizontal resolution.

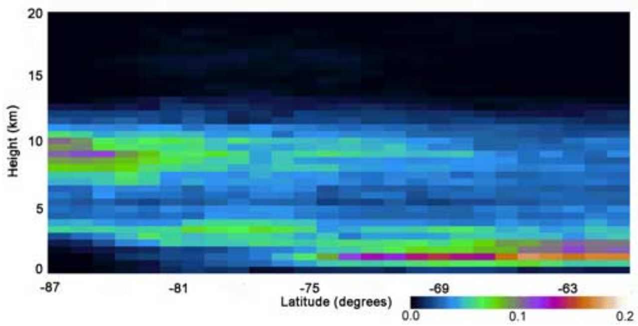

Figure 3. The zonal average vertical distribution of cloud top height over Antarctica for October within 1° degree (latitude) by 0.5 km (vertical) boxes. Only the top of the highest layer has been used. The value in each box represents the occurrence of the cloud height level for each latitude band divided by the total number of incident clouds detected.

10 to 12 km. PSC's are observed in this time period extending to 20 km [*Palm et al.*, 2005] but are too few to significantly affect the overall cloud frequencies.

[8] In general the GLAS cloud cover results are in the range of other observations reported for October by ground based observers [*Hahn et al.*, 1995] and some other satellite retrievals [*Lubin and Harper*, 1996; *Pavolonis and Key*, 2003]. More generally the passive satellite retrievals are known to disagree in significant amounts for cloud coverage. The International Satellite Cloud Climatology Product data underestimate cloud cover in Antarctica relative to other data sets. Any of the retrievals based on AVHRR data will have known limitations and be much more uncertain for the height distribution of the cloudiness. More recently improved observations and cloud retrievals from the MODIS satellite instruments on TERRA and AQUA were to improve accuracies. *Mahesh et al.* [2004] compare GLAS and MODIS cloud detection at high latitudes on a pixel-to-pixel basis from orbit crossings. They use a dataset from February–March 2003 when only the less sensitive 1064 nm cloud channel of GLAS was operating. Even with these data, there was still considerable disagreement the two cloud retrievals, primarily for night-time where the passive short wave techniques can not be used.

[9] Cloud retrievals between sensors may also be compared through monthly averages. There are sampling differences between nadir only measurements of the active lidar and wide swath width passive sensing. However over the course of one month there are over 480 ICESat orbits evenly distributed with respect to longitude. For monthly longitudinal means, inaccuracies due to sampling variance are expected to be minor. Averaged cloud frequencies from the GLAS GLA09 cloud product for one degree latitude bins are shown in Figure 4. Also shown are the MODIS cloud fractions as obtained from the standard MODIS data product distribution system. Since the MODIS data product was only available for sunlit conditions, only results from the AQUA satellite crossing in late afternoon are used. For the best comparison to GLAS, only lidar passes acquired just after sunset are used. As is shown in Figure 2, for the east and west hemisphere of the Antarctica continent, the cloud cover characteristics are very different. Thus in Figure 4, the averages for the two hemispheres are plotted separately. For the ocean at 60°S the cloud fraction is the same in both hemispheres, and is very high at 93%. For East Antarctica, GLAS shows that the cloud fraction is almost constant south of latitude 72.5°S approximately corresponding to the edge of the high plateau. The MODIS average fraction is less constant there, and with an increasing positive bias – 0.6–0.7 rather than 0.4. (The large increase in the MODIS fraction toward 90° is likely related to a retrieval problem for the large off nadir angles.) For the region of West Antarctica, average cloud cover decreases gradually to the south but in this case GLAS gives higher cloud cover. The ICESat orbit limit is 86°S, hence the data stop at that latitude.

[10] Another aspect of the GLAS lidar measurement is the presence, or not, of a return pulse from the surface. The lack of a surface return is an indication of large cloud optical thickness. For a clear atmosphere and high surface reflectivity as from snow, on the order of a thousand detectable photons will reach the GLAS 532 detector; whereas a surface pulse is detectable through only a few received photons. Although there is a complicated relation involving multiple scattering, the lack of a surface return is a clear indication of optical thickness of four or higher. Over Antarctica, the GLAS data show the fraction of blocked surface return to be near constant south of 73° at 25% and 43% for East and West Antarctica respectively, with blocking increasing to 90% over the ocean at 60°S. When either the surface or a lower cloud layer is detected, then the lidar profile shows the thickness of the cloud layer. For almost all of the higher clouds shown in Figure 3, a lower layer or surface is detected. The GLAS results show the zonal average thickness is fairly uniform with respect to latitude and longitude with values ranging between 1100 m and 1400 m.

3. Summary

[11] Satellite lidar sensing of clouds has the advantage of direct and unambiguous detection and height measurement. For polar regions, the cloud measurement is basically unaffected by a high albedo surface and cold temperatures, issues which affect passive cloud sensors. The initial data from the GLAS instrument provide the most accurate measurement of the coverage and height distribution of clouds in the Antarctic region to date, sufficient to define inaccuracies of passive measurements. The GLAS profiles

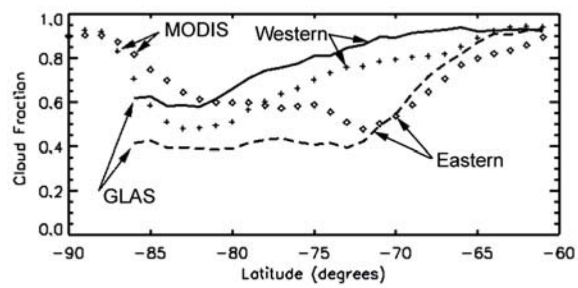

Figure 4. Average cloud fraction (1° latitude bins) derived from GLAS and MODIS observations over Antarctica for October 2003, for the eastern and western hemispheres separately.

reflect two basic cloud types in the Antarctic region: low stratus and higher cirrus form clouds including PSC's. For zonal averaged values of October 2003 data we find discrepancies in cloud fraction with the MODIS cloud product to be significant, and over much of Antarctica to be as high as 40%.

[12] We have established the essential role of satellite lidar measurements to accurately understand the distribution of Antarctica cloud cover for climate change studies. Beyond the results presented here, there is a GLAS retrieval and data product for the optical thickness of cirrus. If the intended GLAS mission lifetime (3–5 years) were realized, a very significant understanding of the change and effects of cloud cover in Antarctica will have been possible. However, the GLAS instrument has unfortunately experienced multiple technical problems (Abshire et al., submitted manuscript, 2005). The high quality 532 nm data as presented here is only available through mid-February, 2004. There are five additional months of data and continuing with only the 1064 nm data, or that plus degraded 532 nm data, available. Most of the cloud cover (apart from PSC's) and height distribution results can be provided from these data with additional work, but with somewhat lower accuracy. Our initial view of the GLAS Antarctica cloud observations presented here will be followed by a more thorough analysis including the data beyond 2003.

[13] **Acknowledgment.** We thank NASA's ICESat Science Project and the NSIDC for distribution of the ICESat data, see http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat.

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