Antarctica Cloud Cover for October 2003 from GLAS Satellite Lidar Profiling

J. D. Spinhirne, S. P. Palm and W. D. Hart

Seeing clouds in polar regions has been a problem for the imagers used on satellites. Both clouds and snow and ice are white, which makes clouds over snow hard to see. And for thermal infrared imaging both the surface and the clouds cold. The Geoscience Laser Altimeter System (GLAS) launched in 2003 gives an entirely new way to see clouds from space. Pulses of laser light scatter from clouds giving a signal that is separated in time from the signal from the surface. The scattering from clouds is thus a sensitive and direct measure of the presence and height of clouds. The GLAS instrument orbits over Antarctica 16 time a day. All of the cloud observations for October 2003 were summarized and compared to the results from the MODIS imager for the same month. There are two basic cloud types that are observed, low stratus with tops below 3 km and high cirrus form clouds with cloud top altitude and thickness tending at 12 km and 1.3 km respectively. The average cloud cover varies from over 93 % for ocean and coastal regions to an average of 40% over the East Antarctic plateau and 60-90% over West Antarctica. When the GLAS monthly average cloud fractions are compared to the MODIS cloud fraction data product, differences in the amount of cloud cover are as much as 40% over the continent. The results will be used to improve the way clouds are detected from the imager observations. These measurements give a much improved understanding of distribution of clouds over Antarctica and may show how they are changing as a result of global warming.

Antarctica Cloud Cover for October 2003 from GLAS Satellite Lidar Profiling

J. D. Spinhirne, S. P. Palm* and W. D. Hart*

Laboratory for Atmospheres/613.1, NASA Goddard Space Flight Center, Greenbelt, MD 20771

Bright surfaces and low surface temperature limit passive satellite measurement of Antarctica cloud cover. Starting in 2003 the Geoscience Laser Altimeter System (GLAS) provides the first accurate measurement of the coverage and height distribution of polar clouds by satellite lidar measurements. 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 with tops below 3 km and cirrus form clouds with cloud top altitude and thickness tending at 12 km and 1.3 km respectively. 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. The GLAS monthly average cloud factions are compared to the MODIS cloud fraction data product. Differences in the active and satellite average cloud fractions are as much as 40% over the continent.

*Affiliation: Science Systems Applications Inc.

Paper for GRL submittal
May 2005

1. Introduction

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 Antarctica 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 affect global ocean 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 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 know, polar regions are the most difficult challenge for passive cloud observation and retrieval techniques. The strong short wave reflectance of snow and ice and low thermal brightness temperatures of the surface both obscure cloud presence and accentuate limitation of passive retrievals. The accuracy of all passive cloud retrieval for polar regions and, in particular central Antarctica, are in question. Large differences exist between different sensors and retrievals [Pavolonis and Key, 2003]. A very important climate issue is change of Antarctic clouds [Dutton et al., 1991]. In terms of understanding and predicting climate change impacts it is likely of greater importance than measurement the height change of the ice sheets. But cloud variability is given little study, most like due to the inadequacy of existing satellite and surface based measurements.

Satellite lidar measurements are an approach that can provide a nearly unambiguous measurement of the distribution of polar clouds. Active lidar remote sensing of clouds are not affected by cold temperatures and high surface albedo only effects solar background noise. The Geoscience Laser Altimeter System (GLAS) satellite lidar launched in 2003 was specifically designed to accomplish high accuracy profiling of all global clouds [Spinhirne et al., 2005]. Antarctic cloud observations were a particular interest given the relative lack of knowledge of their distribution and also because of a need to detect and remove biases for the GLAS surface altitude measurements from to cloud scattering [Zwally et al.,2002; Duda et al., 2001; Mahesh et al., 2002]. In addition polar stratospheric clouds (PSC) were to be profiled. The GLAS measurements were required to detect clouds down to total scattering cross sections of 10-5 m-1, the equivalent of a optical thickness of 0.01 for a 1 km layer. The on orbit results show the required level of performance, except for the brightest solar background levels (due to uncorrected problems with the instrument as launched).

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

2. Observation results

The GLAS instrument is a non-scanning instrument nominally operating in a nadir-viewing mode. Cloud vertical profiles are obtained on a given orbit track below the satellite. Though limited in horizontal 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 and, given the laser pulse rate of 40 Hz, approximately 175m along the track. An example of GLAS return signal strength as a function of height and distance for one orbit across Antarctica is shown in Fig. 1. Within the image are the signals from 39 thousand laser pulses. The effect of pulse averaging increases the detail visible, and similarly pulse averaging is applied in data analysis. Spinhirne et al. [2005] lists the GLAS data products derived from the lidar signals. The results shown in Fig. 1 are from the GLA07 and GLA09 products, the calibrated, attenuated backscatter cross section and derived cloud boundaries respectively. The increased noise evident on the right side of the GLA07 image is caused by the solar brightness in this region. Cloud heights in GLA09 are obtained from sensitive detection of the presence of cloud edges and includes both top and bottom boundaries, as shown in Fig. 1, for sufficiently thin and multi layered clouds. The very thin type I PSC (polar stratospheric cloud) detected near the center of the image illustrates the sensitivity of the measurement.

The clouds shown in Fig. 1 are typical of data from Antarctica. The result is from the more sensitive 532 nm cloud channel. There are in general three types of clouds. The bulk of the clouds below 10 km are ice crystal clouds which may be considered cirrus and in this case associated with a cyclonic storm moving from the Weddell Sea region. In some areas these reach to the surface. Also very close to the surface are regions of dense cloud. Near the coast these are stratus. But for the plateau regions many of the latter show as a thickening of the signal return from the surface and thus a low vertical thickness layer at the ground. These are possibly blowing snow and are not currently detected as clouds in the data processing. Detection and classification of such low layers require further study. The third cloud type are PSC's (Palm et al. [2005] describe in detail a more dramatic case of PSC associated with a cyclonic storm).

From the multiple orbit tracks over the continent in one month, statistics can be assembled on the frequency of coverage and the height distribution of the cloud cover. We present here the initial result from the first month the GLAS lidar was fully operating, October 2003. In Fig. 2 and 3 are shown the frequency of occurrence of all clouds and the zonal average cloud top height frequency for latitudes south of 60 degrees. For the frequency of occurrence there are two regimes. For oceanic, coastal and large areas of west Antarctic, cloud are dominated by low stratus type clouds with the frequency of occurrence varying generally between 60 and 100%. Over most of east Antarctica cloud cover varies between 40% to completely clear with a general correlation between surface altitude and decreased cloud cover. The predominate cloud type over the continent is the cirrus clouds existing below the effective tropopause height of 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 affect the overall cloud frequencies.

In general the cloud coverage results are in the range of other observations reported for October by ground based observers [Hahn et al., 1995] and some 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 ISCCP data underestimate cloud cover in Antarctica relative to other data sets. Any of the retrievals based on AVHRR data will have know 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 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 data set from February – March 2003 when only the less sensitive 1064 nm cloud channel of GLAS was operating. Even then there were considerable disagreement of the two cloud retrievals, primarily for nighttime where the passive short wave techniques can not be used.

Another means for comparison of cloud retrievals is to use monthly means. There are of course sampling differences between nadir only measurement of the active lidar and wide swath width passive sensing. However in a month there are over 480 orbits that are evenly distributed with respect to longitude. For monthly longitudal means, inaccuracies due to sampling variance are expected to be minor. In Fig. 4 are shown the mean cloud frequencies from the GLAS GLA09 cloud product for one degree bins as in Fig.2. 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 Acqua satellite crossing in late afternoon are used. For the best comparison to GLAS, only lidar passes just after sunset are used.

As is shown in Fig. 2, for the east and west hemisphere of the Antarctica continent, the cloud cover characteristics is very different. Thus in Fig. 4 the average for the two hemispheres are shown separately. For the ocean at 60° S the cloud fraction is the same and very high at 93%. For East Antarctica GLAS shows that the cloud fraction is almost constant south of a latitude corresponding to the edge of the high plateau. The MODIS average fraction 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 giving higher cloud cover.

Another direct measurement from the lidar is whether or not a pulse return from the surface is present below clouds, an indication of large optical thickness. For a clear atmosphere and the highest snow reflection, 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 four or greater. For the Antarctica region the GLAS data shows the fraction of blocked surface return to be near constant south of 73° at 25% and 43% for east and west Antarctica respectively and 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 Fig. 3, a lower layer or surface is detected. Interestingly the zonal average thickness is fairly uniform with respect to latitude and longitude with a value between 1100 m and 1400 m.

3. Summary

Satellite lidar sensing of clouds has the advantage of direct and unambiguous detection and height measurement. For polar regions, the cloud measurement is essentially unaffected by a high albedo surface and cold temperatures as is the case for passive cloud sensors. The initial data from the GLAS instrument gives the most accurate measurement of the coverage and height distribution of clouds in the Antarctica region. There are two basic cloud types in the Antarctic region in the profile, low stratus and higher cirrus form clouds. The results from October 2003 shown in this paper are sufficient to define inaccuracies of passive measurements. 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 as high as 40%.

We have established the essential role of satellite lidar measurements in order 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 and experimentally the potential to retrieve the size of ice crystals. With a data set of three to five yeas of the full GLAS data, as intended, a very significant understanding of the change and effects of cloud cover in Antarctica was possible. Unfortunately the GLAS instrument was launched with multiple technical problems. The high quality 532 nm data as presented here will only be available for one other month. There are six 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 and height distribution results can be provided from these data with additional work, but with less accuracy and not for PSC's. The additional cloud processing is especially import for cloud clearing of the GLAS ice sheet altimetry if results are to approach within an order of magnitude of the stated requirements. All GLAS data products are openly available for further research (http://nsidc.org/daac/icesat/).

References:

Duda, D. P. J. D. Spinhirne, E. W. Eloranta, Atmospheric multiple scattering effects on GLAS altimetry – Part I: Calculations of single pulse bias, *IEEE Trans. Geosci. Remote Sensing*, 39, p. 92-101, 2001.

Dutton, E. G., D. W. Nelson and B. G. Mindonca, Recent interannual variations in solar radiation, cloudiness and surface temperature at the South Pole, J. Climate, 4, 848-858, 1991.

Hahn, C. J., S. G. Warren and J. London, The effect of moonlight on observations of cloud cover at night and application to cloud climatology, J. Climate, 8, 1429-1446, 1995.

Hart, W. D., J. D. Spinhirne, S. P. Palm, and D. Hlavka, Height Distribution Between Cloud And Aerosol Layers From the GLAS Space Borne Lidar in the Indian Ocean Region, *Geophys. Res. Let.*, in submission, 2005.

Lubin, D. and D. A. Harper, Cloud radiative properties over the South Pole from AVHRR infrared data, *J. Climate*, 9, p. 3405-3418, 1996.

Mahesh, A., R. Eager, J. R. Campbell and J. D. Spinhirne, Blowing Snow Over the Antarctic Plateau, J. Geophys. Res., 108(D22), p. 4707-4718, 2003.

Mahesh, A., J. D. Spinhirne, D. Duda, and E. Eloranta, Analysis of Expected Errors in Antarctic Altitude Measurements: Atmospheric Multiple Scattering Effects on GLAS Altimetry Part II, *IEEE Trans. Geosci. Remote Sensing*, 40, 2353-2362, 2002.

Mahesh A., M. A. Gray, S. P. Palm, W. D. Hart and J. D. Spinhirne, Passive and active detection of clouds: Comparisons between MODIS and GLAS observations, *Geophys. Res. Let*,, 31, 4108-4113, 2004.

Palm, S. P., M. Fromm and J. D. Spinhirne, Observations of Antarcitic Polar Stratospheric Clouds by the Geoscience Laser Altimeter System (GLAS), , *Geophys. Res. Let.*, in submission, 2005.

Pavolonis, M. J. , and J. R. Key, Antarctic cloud radiative forcing at the surface estimated from the AVHRR Polar Pathfinder and ISCCP D1 datasets, *J. Appl. Meteor.*, 42 p. 827-840, 2003.

Spinhirne, J. D., S. P. Palm, W. D. Hart, D. L. Hlavka and E. J. Welton, Cloud and Aerosol Measurements from the GLAS Space Borne Lidar: Initial Results, *Geophys. Res. Let.*, in submission, 2005.

Palm, S. P., J. D. Spinhirne, W. D. Hart and D. L. Hlavka, Algorithm Theoretical Basis Document for the Geoscience Laser Altimeter System, Atmospheric Data Products, NASA internal document, at http://www.csr.utexas.edu/glas/.

Yamanouchi, T., and T. P. Charlock, Effects of clouds, ice sheet, and sea ice on the Earth radiation budget in the Antarctic, *J. Geophys. Res.*, 102 P. 6953-6970, 1997.

Zwally H. J., B. Schutz, W. Adbalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Herring, B. Minster, K. Quinn, S. Palm, J. Spinhirne, R. Thomas, J Ice, Cloud and land Elevation Satellite's laser measurements of polar ice, atmosphere, ocean and land, *Geodyn.*, 34, 405-445, 2002

Figure 1 GLAS atmospheric calibrated attenuated backscatter, GLA07, signal data product and cloud boundary data product, GLA09, for a single 14 minute orbit track 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 layer are detected.

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

Figure 3 The zonal average distribution of cloud top height over Antarctica for October within 1 degree by 0.5 km spatial areas. 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 ratioed to total number of incidents clouds detected.

Figure 4. The east and western hemisphere zonal average cloud fraction for GLAS and MODIS observation in October 2003.

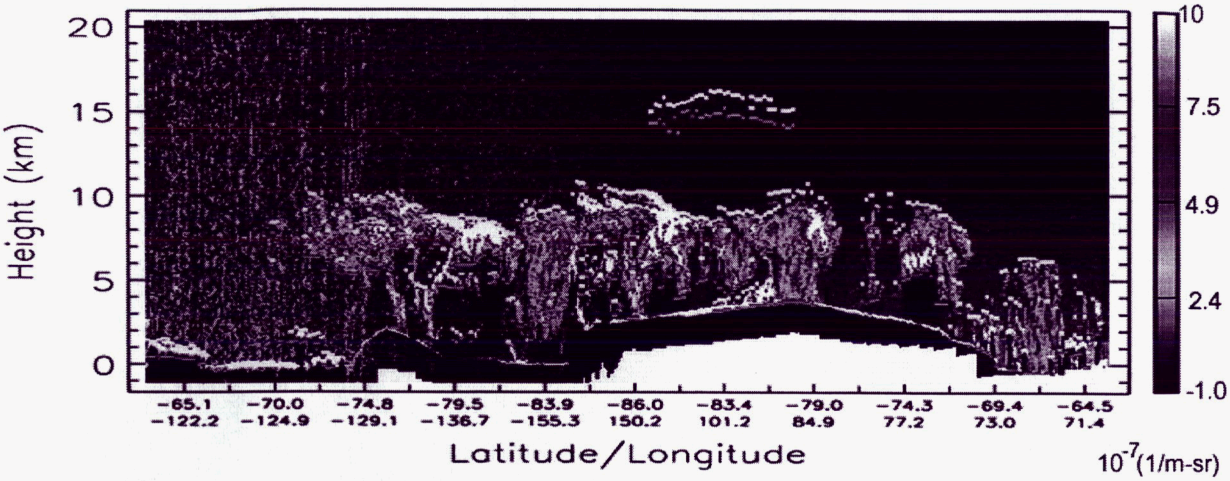

Figure 1

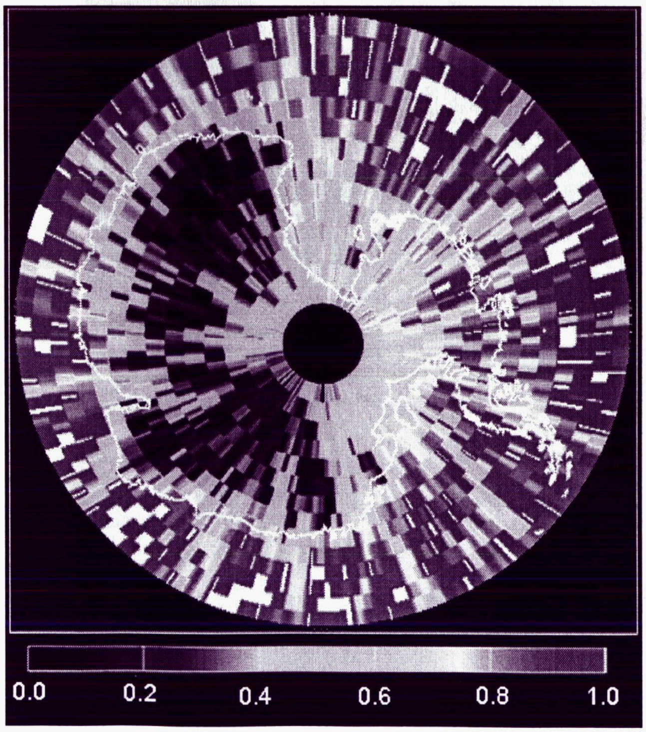

Figure 2

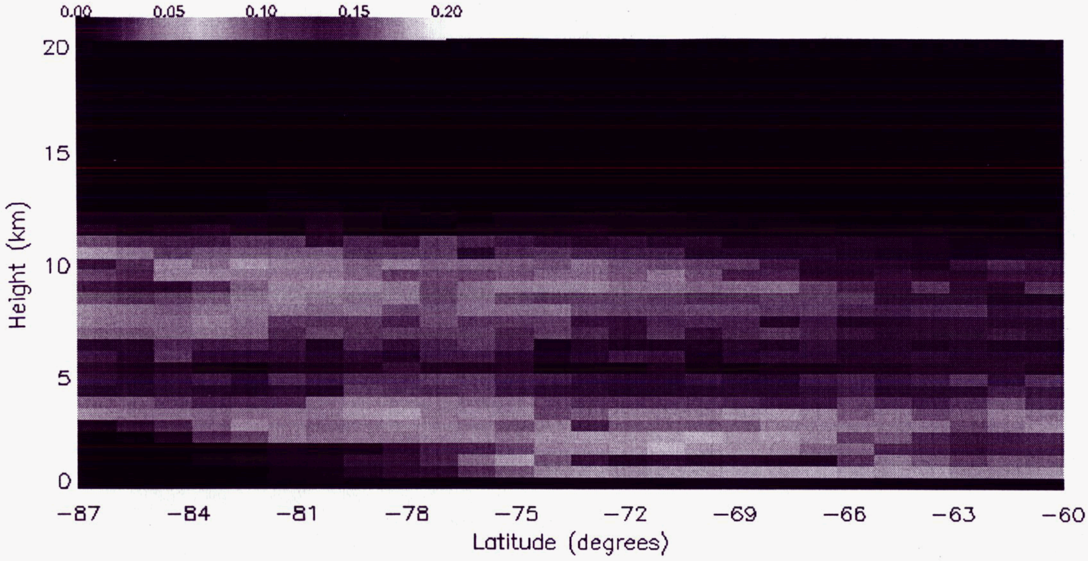

Figure 3

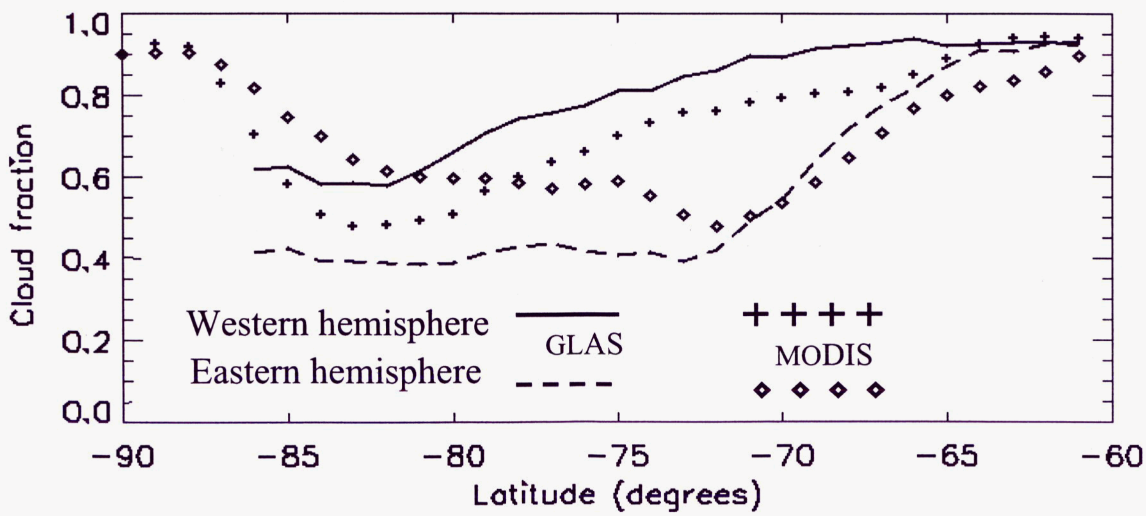

Figure 4