

Observations of Antarctic Polar Stratospheric Clouds by GLAS

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Polar Stratospheric Clouds (PSCs) frequently occur in the polar regions during winter and are important because they play a role in the destruction of stratospheric ozone. During late September and early October 2003, GLAS frequently observed PSCs over western Antarctica. At the peak of this activity on September 29 and 30 we investigate the vertical structure and extent, horizontal coverage and backscatter characteristics of the PSCs using the GLAS data. The PSCs were found to cover an area approximately 10 to 15 % of the size of Antarctica in a region where enhanced PSC frequency has been noted by previous PSC climatology studies. The area of PSC formation was found to coincide with the coldest temperatures in the lower stratosphere. In addition, extensive cloudiness was seen within the troposphere below the PSCs indicating that tropospheric disturbances might have played a role in their formation.

Observations of Antarctic Polar Stratospheric Clouds by the Geoscience Laser Altimeter System (GLAS)

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Abstract. The first satellite lidar observations of Polar Stratospheric Clouds (PSCs) are presented. During late September and early October 2003, GLAS frequently observed type II PSCs over western Antarctica. At the peak of this activity on September 29th and 30th we investigate the vertical structure and extent, horizontal coverage and backscatter characteristics of the PSCs using the GLAS data. The PSCs were found to cover an area roughly 10 to 15 percent the size of Antarctica in a region where enhanced PSC frequency has been noted by previous PSC climatology studies. We also show near simultaneous measurements from the POAM III and SAGE II satellites that confirm the presence of type I and II PSCs in the same region. The area of PSC formation was found to coincide with the coldest temperatures and highest geopotential height in the lower stratosphere. In addition, extensive cloudiness was seen within the troposphere below the PSCs indicating that tropospheric disturbances might have played a role in their formation.

Introduction

The Geoscience Laser Altimeter System (GLAS) was launched aboard the polar orbiting Ice Cloud and land Elevation Satellite (ICESat) in January of 2003 [Zwally *et al.*, 2003]. GLAS utilized 3 diode-pumped, ND:YAG lasers operating at the fundamental wavelength of 1064 nm for surface altimetry and clouds, and the frequency doubled 532 nm wavelength that provides high sensitivity (photon counting detectors) for atmospheric measurements of thin clouds and aerosols [Spinhirne *et al.*, 2005]. GLAS has to date collected over 6 months of data that have provided unique insights into global cloud and aerosol vertical distribution and transport processes. One area where GLAS can make an important contribution is polar clouds and in particular, Polar Stratospheric Clouds (PSCs).

It is well known that Polar Stratospheric Clouds are frequently observed during the Austral winter over Antarctica. Occurring from late fall to early spring, PSCs have been routinely observed over the last 30 years by limb-sounding instruments such as the Stratospheric Aerosol Measurement (SAM) II, the Stratospheric Aerosol and Gas Measurement (SAGE) I – III and the Polar Ozone and Aerosol Measurement (POAM) II and III. These limb-sounding spectrometers view the sun or moon through the earth's limb and obtain aerosol extinction along the line of sight. When the extinction exceeds the expected background level for clear air, it signifies that cloud or aerosol is present. If this high level of extinction occurs above the tropopause in the polar regions and the

temperature is below a critical value, the elevated level of extinction is assumed to be caused by a PSC. *Fromm et al.* [2003] present a very concise climatology of PSC occurrence in both hemispheres covering the period 1979 to 2000 using data from SAM II, SAGE II and POAM II/III. They found that when temperatures in the stratosphere are conducive to PSC formation (ie. $T < 195$ K), PSCs are detected from the limb measurements 60% of the time for both hemispheres. However, the overall frequency of occurrence of PSCs is some 5-10 times greater in the Antarctic because of the stability of the polar vortex and the lower temperatures found there.

The ubiquity of PSCs make them ideal targets for observation by a polar orbiting lidar such as GLAS. The excellent data coverage over the polar regions and the high sensitivity of the 532 nm channel make it very likely that GLAS will detect type II ice PSCs if they are present. As will be seen later, type I PSCs are very close to the detection limit of the 532 nm channel and could potentially be missed. The second GLAS observation period (September 25 – November 18, 2003) covered the later part of the Antarctic PSC season and provided the opportunity to sample PSCs from a satellite lidar for the first time. During the first week of this observation period, PSCs were evident in the GLAS data over a fairly large area of Antarctica. The PSC frequency and coverage peaked on September 30th and was entirely gone by October 3rd. PSC activity was not seen again in the GLAS data until a week later when they were detected during a two day period but were covering a much smaller area. The fact that GLAS did not detect PSCs during that time does not necessarily mean that they were not there. It is possible that type I PSCs were present, but that the backscatter signal from them was below the GLAS detection limit. In this paper we will focus on GLAS, SAGE II and POAM III PSC observations from the 29th and 30th of September, 2003. Section 2 will present the GLAS data, section 3 will discuss the GLAS observations in light of prior work and concurrent observations from SAGE II and POAM III and finally, conclusions are given in section 4.

Observations

On the 29th and 30th of September 2003, GLAS detected a large area of enhanced backscatter reaching to heights of 21 km and often extending down to the ground. During this 48 hour period, a total of nine (of a possible 28) GLAS tracks were found to contain PSCs. The locations of the tracks containing PSCs are shown in Figure 1. They are tightly clustered around a spot roughly half way between the Antarctic Peninsula and the prime meridian (0° E). A total of 3 and 6 tracks were found to contain PSCs on September 29th and 30th, respectively. Examples of the GLAS measured 532 nm backscatter ratio (total scattering divided by the molecular or Rayleigh scattering) for these two tracks are shown in figures 2 and 3. Figure 2, with the track location and PSC horizontal extent given by the thick orange line in figure 1a, shows an enormous PSC stretching roughly 3000 km from over the central portion of Antarctica, the Weddell Sea and ending near 62° south latitude. The very tenuous top portion of the cloud with backscatter ratios between 3 and 8 extends to a height of 21 km and is the highest PSC top seen by GLAS during this period. We believe this portion of the cloud (between 18 and 21 km) to be a type I PSC. Also of note is the slightly enhanced scattering region between 12 and 16 km altitude at the extreme left portion of the image (86S – 83S). This

is near the location of a POAM III retrieval indicating the presence of a PSC (small black dots in figure 1a). The magnitude of this enhanced area of scattering is so small, it is just barely discernable in the GLAS data and is most likely a type I PSC. This shows that the scattering from type I PSCs is very close to the detection limit for GLAS. Below 18 km to the tropopause, atmospheric temperatures are low enough to support type II water ice PSCs. The 532 nm backscatter ratios are as high as 40 throughout the cloud at altitudes of 17-18 km. Lower in the cloud (8-12 km) backscatter ratios exceed 50 but this portion of the cloud resides within the troposphere. A temperature sounding from September 29th taken at 70.9S, 8W indicated a tropopause height of about 13 km. Further, in figure 2, UKMO meteorological data were used to compute the tropopause height along the GLAS track based on a potential vorticity analysis *Swinbank and O'Neill* [1994]. The maximum tropopause height (13.2 km) occurs at 72.5S, which is very close to the deepest part of the PSC shown in figure 2. Also, note how the arching of the cirrus shield in figure 2 closely follows the tropopause height, especially in the right half of the figure.

Figure 3 shows the 532 nm backscatter ratio from a track on September 30th that is located to the east of the track shown in figure 2, with the track location shown as the thick orange line in figure 1b. The PSC is similar in character and appearance to the PSC shown in figure 2 from the day before. This cloud extends to 20 km and covers a distance of about 2800 km. Like the PSC in figure 2, there appears to be a separation or discontinuity at about 12 km altitude, which is in fact the location of the tropopause. A temperature sounding taken at 71S, 8W indicated a tropopause at 11.5 km and the dynamical tropopause height, shown as the yellow line on the image, agrees well with this value. The 532 nm backscatter ratio reaches a maximum value of 62 at about this level. The 532 nm backscatter coefficient values within the type I PSC above 18 km are typically about $3.0 \times 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}$. *Reichardt et al.* [2002] performed model calculations on the scattering characteristics of NAT crystals and found that the 532 nm extinction to backscatter ratio for crystals greater than about $1.2 \mu\text{m}$ is between 10 and 20. If we use an extinction to backscatter ratio of 10 for type I PSCs, we obtain an extinction value of $3.0 \times 10^{-3} \text{ km}^{-1}$ for the GLAS type I PSC measurements. This is very consistent with the POAM III extinction retrieval for this day at 86S, 38.1W which is shown in figure 4. The POAM extinction value at about 18 km is closer to 1.0×10^{-3} , but this smaller extinction could be due to the wavelength difference or the fact that at the POAM retrieval location, the PSC was more tenuous than what GLAS observed near 18 km altitude at 65S, 2E.

Discussion

Teitelbaum et al., [2001] argued that a major formation mechanism of Arctic PSCs is synoptic scale tropospheric disturbances. They conclude that anticyclonic potential vorticity anomalies near the tropopause induce an upward displacement of the isentropic surfaces in the lower stratosphere. This causes synoptic scale quasi-adiabatic lifting and cooling of the air resulting in the PSC formation or thickening. *Tuck* [1989] made a similar argument for Antarctic PSCs observed in Austral winter of 1987. If this is the causative mechanism for the PSCs seen by GLAS, it follows that they would have dimensions on the order of 1000 km since this is a characteristic dimension of synoptic scale disturbances. Additionally, there is extensive cloudiness within the troposphere

below both PSCs, indicating a likelihood that a tropospheric disturbance is playing a role in the PSC formation. It is possible that all the PSCs detected by GLAS over this two day period may be different portions of a single very large PSC that has persisted for at least 2 days and possibly much longer.

In addition to the GLAS tracks, figure 1 gives the UKMO geopotential height (black contour lines) of the 400 K potential temperature surface (roughly 15 km altitude), the location of the polar vortex (red) and the 200 K (green) and 192 K (blue) temperature contours for September 29th and 30th. The blue temperature contour represents the area below T_{ice} (192° K), where type II PSC formation is possible. Note the location of the geopotential height maximum with respect to the GLAS PSC observations. The deepest PSC activity is seen to occur over the ridge, where the isentropic surfaces have been uplifted with respect to the surroundings. The geopotential height pattern is a manifestation of synoptic scale planetary waves. The winds at this level are westerly and the 4-day trajectories (thick gray lines) are shown in figure 1. The winds are moving faster than the planetary waves and the air parcels are subject to vertical motions induced by the tilt of the isentropic surfaces. Namely, over the ridge, the air is rising and cooling causing saturation and formation of PSCs. Further east, the air is sinking and warming and PSC formation is suppressed. Note that the ridge propagates eastward with time as does the location of the deepest PSC as seen by GLAS.

Also shown in figure 1 are the locations of PSCs that were detected by POAM III (small black dots) and SAGE II (large black dots and asterisks). On the 29th, SAGE II detected two ice PSCs straddling the region of deepest PSCs seen by GLAS. That these are ice PSCs is inferred from the anomalously high SAGE II profile-termination altitude, a phenomenon *Fromm et al.* [1999 and 2003] call a High Zmin. SAGE also detected 3 type I PSCs that GLAS was unable to detect. POAM III measurements were confined to the 86° latitude circle around which type I PSCs were observed at nearly all longitudes. On the 30th, GLAS found type II PSCs over a larger areal extent but only type I PSCs were detected by SAGE and POAM. Put together, the SAGE/POAM, and GLAS PSC observations show how the true ice-PSC coverage is much smaller than the nominal ice pool. That strongly indicates dehydration, which we know has already occurred considering it is late in the PSC season. The POAM and SAGE clear-sky-only observations inside the type I pool (as well as the GLAS no-PSC tracks) also implicate dehydration and/or denitrification. All together, a very nice 3-D picture of PSCs, dynamics, and vortex cleansing emerges.

An interesting further observation to be made is the location of the PSCs observed by GLAS. The analysis performed by *Fromm et al.* [1997] on the distribution and frequency of Antarctic PSCs for the years 1994 – 1996 revealed that PSCs preferentially form in a certain region of Antarctica. For that time period at least, the maximum frequency of occurrence of PSCs is between 315 E and 0 E. The center of PSC activity seen by GLAS is directly in the middle of this area. If the primary cause of Antarctic PSC formation is related to tropospheric synoptic scale disturbances as mentioned earlier, then possibly this area of Antarctica is near a climatological mean storm track or that orographic forcing, possibly related to the Antarctic Peninsula, is playing a role.

Conclusions

We have presented the first satellite lidar observations of Antarctic PSCs. The observations shown here are from the last 2 days of September, 2003 and clearly demonstrate the enormous size and areal coverage of these clouds. Reaching at times from the tropopause to 21 km, PSCs as long as 3500 km in the horizontal were observed in the 532 nm backscatter channel of GLAS. Of the 28 total GLAS tracks over Antarctica during this time, 9 of them contained PSCs. This, together with the spatial pattern of the PSC observations leads us to believe that over these two days, GLAS was sampling different portions of a single large PSC or cluster of PSCs. The backscatter ratio of the clouds varied significantly with height, with low values (3-8) above 18 km, moderate values (10-30) between 12 and 18 km, and extremely large values (>60) in the region 8 - 12 km. Based on meteorological data (not shown), the tropopause is around 12-13 km in the region of deepest PSC formation and temperatures between 13 and 18 km were cold enough ($< 192^{\circ}$ K) to support water ice (type II) PSCs. Outside of this cold region, type I PSCs were observed on both days and were seen to be very close to the detection limit for GLAS. The PSCs were observed over a large area of Antarctica and the Weddell Sea between roughly 280° E and 0° E., congruent with the coldest stratospheric temperatures and highest geopotential height. Prior work has shown that this is a region displaying a climatological maximum of PSC occurrence. Other work has shown a relationship between tropospheric synoptic scale disturbances and PSCs. While this aspect could not be fully explored here, GLAS does observe a substantial amount of tropospheric cloudiness below the PSCs indicating the possible presence of a tropospheric disturbance. This remains a topic worthy of future research in which GLAS could play a substantial role.

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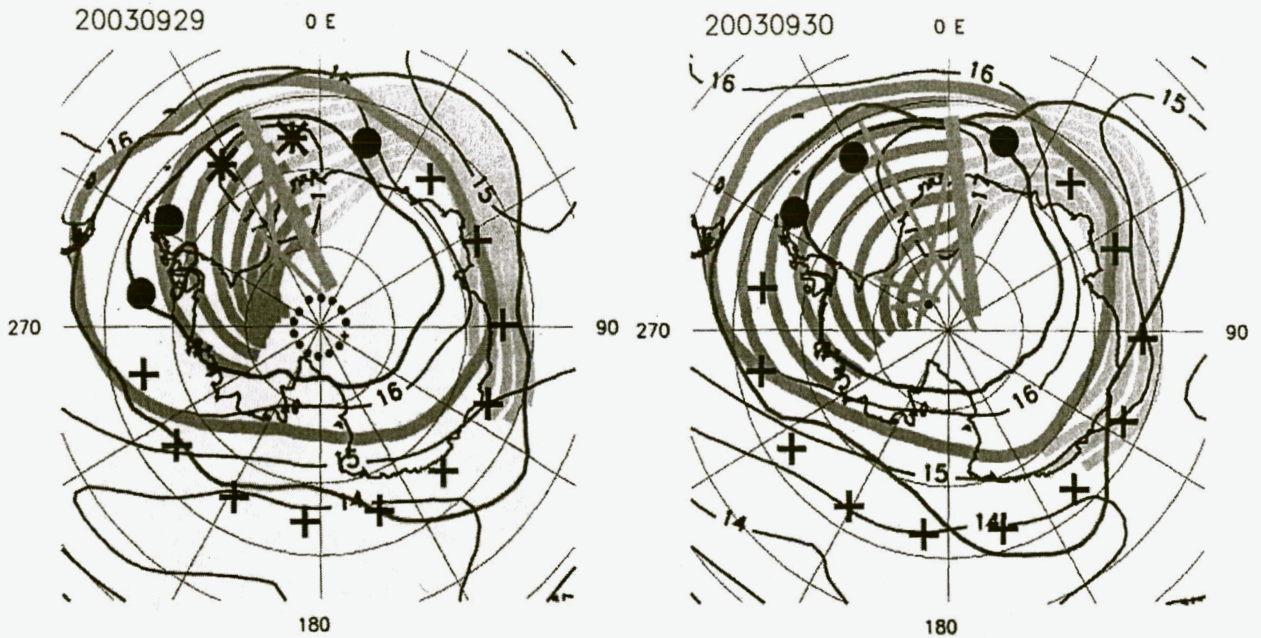


Figure 1. Map of Antarctica showing the GLAS observed PSC locations (orange lines), geopotential height (km) of the 400 K potential temperature surface (back contours), PSC locations from POAM III (small black dots) and SAGE II (large black dots and asterisks) and 4-day air parcel trajectories (thick gray lines) for September 29th (top) and 30th, 2003. The blue and green contours represent the area within which air temperatures are less than T_{ICE} and T_{NAT} , respectively. The red line marks the position of the edge of the polar vortex.

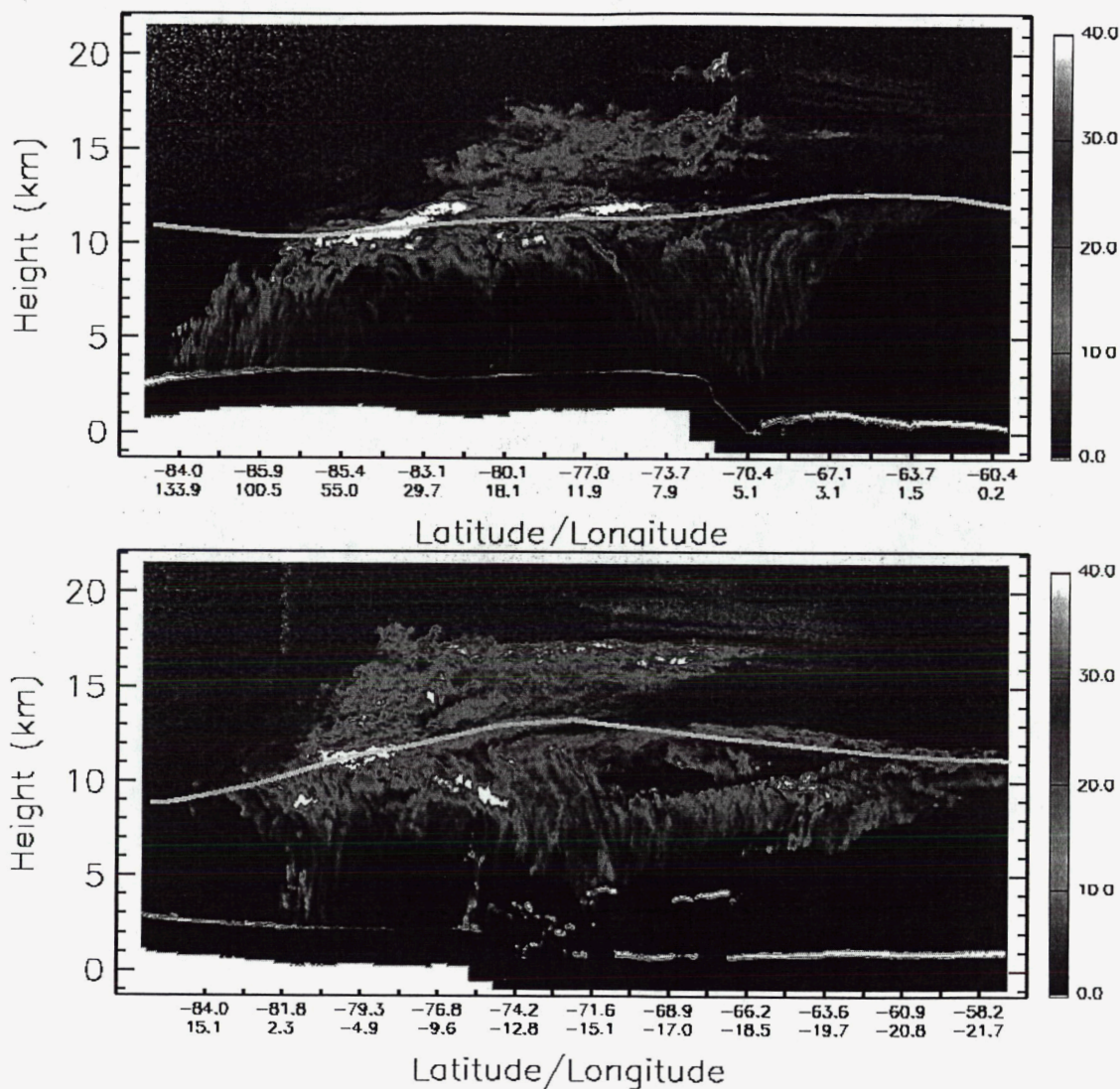


Figure 2. GLAS measured 532 nm attenuated backscatter ratio (total scattering / molecular) for September 29th, 2003 22:03 GMT. Highest backscatter ratios exceed 50 between 8 and 12 km. The total length of the PSC is roughly 3000 km. This track is the thicker of the orange lines in figure 1a. The yellow line is the height of the tropopause.

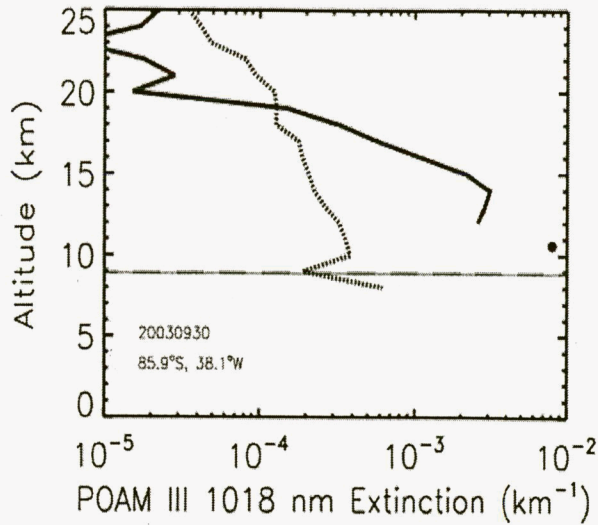


Figure 4. POAM III extinction retrieval (solid line) at 85.9S, 38.1W for September 30th, 2003. The dashed line represents the expected clear air extinction. The dot marks the height where the POAM III measurement reached saturation. The altitude of the tropopause is indicated by the horizontal dashed line.