Multi-year measurements of cloud base heights at South Pole by lidar

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Received 12 November 2004; revised 16 February 2005; accepted 10 March 2005; published 13 May 2005.

[1] The Micropulse Lidar Network has operated a full-time lidar measurement program at South Pole Station since 2000. Observations from this instrument are an important multi-year record of clouds over the Antarctic plateau. Earlier South Pole observations relied mostly on passive measurements to characterize clouds; the lidar's active profiles present an opportunity to validate current understanding of Antarctic clouds, as well as study properties that are not adequately captured in passive measurements. Lidar observations show clouds to be present roughly 40 percent of the time, and often appearing in wind-swept layers immediately above ground-based scattering layers such as blowing snow and suspended ice particles. There is very little indication of seasonal variability in cloud base heights; this contradicts earlier observations from an interferometer made in 1992 when it was determined that the distribution of cloud base heights in the summer months was different from that seen at other times. Those observations had also indicated that cloud base heights over the high plateau are distributed bimodally, with many near-surface clouds, and a second mode of other clouds well above the surface–based inversion. The lidar observations, however, suggest that this may be true only of the optically thicker clouds and even then only in the spring. **Citation:** Mahesh, A., J. R. Campbell, and J. D. Spinhirne (2005), Multi-year measurements of cloud base heights at South Pole by lidar, *Geophys. Res. Lett.*, *32*, L09812, doi:10.1029/2004GL021983.

1. Introduction

[2] High latitude climate remained poorly understood for many decades after routine observation programs were instituted elsewhere in the world. Climate models from past decades either ignored the polar regions altogether or included very little of their complexity. The Antarctic interior was especially poorly studied; even the few stations established along the coast of the continent were lacking here, and Amundsen-Scott South Pole Station is the only weather station on the high plateau continuously in operation since the International Geophysical Year 1957. Satellite observations of the high latitudes have also been of less value than elsewhere; clouds and snow-covered surfaces show similar spectral signatures both at visible and infrared wavelengths [*Yamanouchi et al.*, 1987], making it difficult to separate them reliably. Early polar cloud-cover assessments made by the International Satellite Cloud Climatology Project (ISCCP), for example, were considerably different from surface-based observations of cloud occurrences [*Rossow et al.*, 1993], being up to 25% lower in the summer [*Hahn et al.*, 1995, Figure 13].

[3] As it became clearer – in recent decades – that the polar regions would show the largest and earliest signs of global warming [*Manabe and Stouffer*, 1979], and that cloud properties greatly influence climate [*Cess*, 1989], scientific programs to understand these climates were initiated. However, most major multi-instrument studies were conducted in the Arctic (e.g., The Atmospheric Radiation Measurement Program [*Stamnes et al.*, 1995] and The Surface Heat Budget of the Arctic project [*Perovich et al.*, 1999]). In the Antarctic, no similarly large effort was undertaken; however the potential for climate change here too — especially influenced by clouds — began to be examined. *Dutton et al.* [1991] studied interannual variations in solar radiation, cloudiness, and surface temperature at South Pole. Data from two pyranometers indicated incoming solar fluxes during the austral summer decreased by 15% between 1976 and 1987, but most of this change was limited to the late summer months. A coincident 20% increase in cloud cover led the authors to believe that reduced insolation may have resulted from the increased sky-cover. But this trend was partially reversed in subsequent years, and even within the data record, the correlation between temperature and cloud cover was not convincing.

[4] The first yearlong observation of sky conditions over the Antarctic plateau was carried out in 1992 [*Walden and Warren*, 1994]. A Fourier-transform interferometer measured downward spectral longwave radiance from 550 to 1500 cm^{-1} (7–18 μm) at a resolution of 1 cm^{-1}. Radiance measurements were usually made twice daily, coincident with routine launches of radiosondes made by the South Pole Weather Office; 223 radiance measurements (40% of the observations) were of cloudy-sky conditions. Cloud-base heights were retrieved from

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the data using a ground-based version of the radiance-ratioing method [*Smith and Frey*, 1990]. Atmospheric opacity varies with wavenumber; this permits the determination of cloud height by the use of spectral observations at wavenumbers best suited to distinguish a given height. The first year-long climatology of Antarctic cloud properties was obtained from these observations; cloud frequencies, base heights, optical depths and effective particle radii were determined [*Mahesh et al.*, 2001a, 2001b].

[5] The annual cycle of cloud-base heights from the 1992 observations showed a bimodal distribution [see *Mahesh et al.*, 2001a, Figure 7]. Although retrieved heights were uncorrelated with heights estimated by visual observers, both the retrieved and observed data indicate that base heights were bimodal. Most clouds have bases in the lowest few hundred meters, within the surface-based temperature inversion. The second mode is of higher clouds with base heights 1.5–3 km above the surface. Even the highest tropospheric clouds were within 6 km of the surface. The bimodality of base heights was observed in all seasons except during the brief summer (December–January). Cloud-base heights were typically higher in the summer than in winter. Further, it was seen that radiance ratioing could also be used to detect the presence of polar stratospheric clouds, but their base heights could not be reliably determined by the method.

[6] More recently, Walden and Warren repeated the yearlong observations at South Pole of cloud spectra using an improved instrument, supported by lidar observations of sky conditions using a micro pulse lidar [*Spinhirne*, 1993]. This collaboration, the South Pole Atmospheric Radiation and Cloud Lidar Experiment (SPARCLE [*Walden et al.*, 2001]), collected simultaneous spectral and lidar observations. Because clouds over the high plateau are usually optically thin, multiple layers of clouds are seen regularly in the laser measurements. These data also act as a verification tool; cloud heights obtained by laser ranging can be compared with values from the spectral observations, to understand the errors in the latter method. Since cloud heights are routinely determined from satellite data using passive imagery only, such an assessment is needed. Uncertainties in cloud properties derived from spectral data using the "single-layer" assumption can also be estimated.

[7] In this paper, we supplement knowledge of cloud frequency and heights obtained from the 1992 data, by deducing heights from a new set of observations. In doing so, we examine the bimodality of base heights obtained by radiance ratioing from the earlier observations.

2. Data and Method

[8] The Micro-Pulse Lidar system operated at South Pole station is a single channel (523 nm), autonomous, eye-safe lidar system that is used to determine the vertical structure of clouds and aerosols [*Spinhirne et al.*, 1995]. The NASA Micro-pulse Lidar Network (MPLNET) [*Welton et al.*, 2001] consists of MPL sites co-located with AERONET [*Holben et al.*, 1998] sunphotometers. The MPL at the South Pole site is operated inside a climate-controlled laboratory. Routine observations from the MPL are available from the beginning of 2000. Intermittently, lidar operations had to be halted for maintenance of the instrument, and the record of observations is therefore not continuous. These non-operational times were typically during the spring months (September–November); a full record for these months, especially September and October, is available only from 2003, and in other years only small portions of data are available for these months. Nonetheless, a substantial record of observations from the lidar (roughly three-quarters of the period since January 2000) is now available for study, and routine data collection at South Pole is still ongoing.

[9] Backscatter of incident photons by atmospheric particles records the presence of clouds and aerosol layers. Raw MPL data of this scattering was acquired at 1-minute time resolution, and 30-m vertical resolution. The raw data were converted into uncalibrated lidar signals [*Campbell et al.*, 2002; *Welton and Campbell*, 2002]. These signals were then calibrated to sense layer boundaries; the calibration is especially important to detect cloud tops and to record the presence of extremely optically thin layers.

[10] From a vertical profile of the strength of backscatter, the lowest height at which the backscatter exceeds a threshold value and remains above it for at least 100 meters was chosen as the base of the lowest cloud. This threshold is necessary to differentiate scattering in atmospheric layers from the background molecular scattering. With instrument errors and uncertainties, this threshold must be sufficiently high to exclude clear-sky signals, but not so high as to exclude some extremely thin layers. For the purpose of this study, a backscatter value of 0.2×10^{-5} $m^{-1}sr^{-1}$ was chosen as the threshold of cloud detection. The lower threshold and the check for vertical extent may, however, be passed for ground-based scattering layers such as blowing snow, that are commonly present over the high plateau; *Mahesh et al.* [2003] found that blowing snow layers can be several hundred meters thick, and occasionally extend up to a kilometer from the surface. Another source of uncertainty in determining cloud boundaries in this manner is the common presence of near-surface suspended ice particles, known as diamond-dust. When clouds immediately overlie such near-surface or ground-based layers, the difficulty in distinguishing the cloud boundary – as also the boundary of the near-surface layers, such as those reported by *Mahesh et al.* [2003] – is greater. The higher the threshold value, however, the less likely that it would be passed by scattering in these other optically thin layers.

[11] The selection of cloud base heights is illustrated in Figure 1. The upper panel shows the lidar measurements for a complete day in February 2000, and the lower panel shows the cloud base height selected from each profile. The observations shown here, with streaky clouds in the lowest 1–2 km, are typical of the clouds seen at South Pole. The base heights identified are easily related to the lidar image when the cloud base is distinct and continuous (as in the first half of the day), but show more variability when the clouds become streaky. Such streakiness, presumably related to the high winds common over the plateau, is often seen in the lidar observations and also confirmed by recent space-borne observations by the Geoscience Laser Altimeter System [*Cohen et al.*, 1987] launched in January 2003. The atmospheric layer struc-

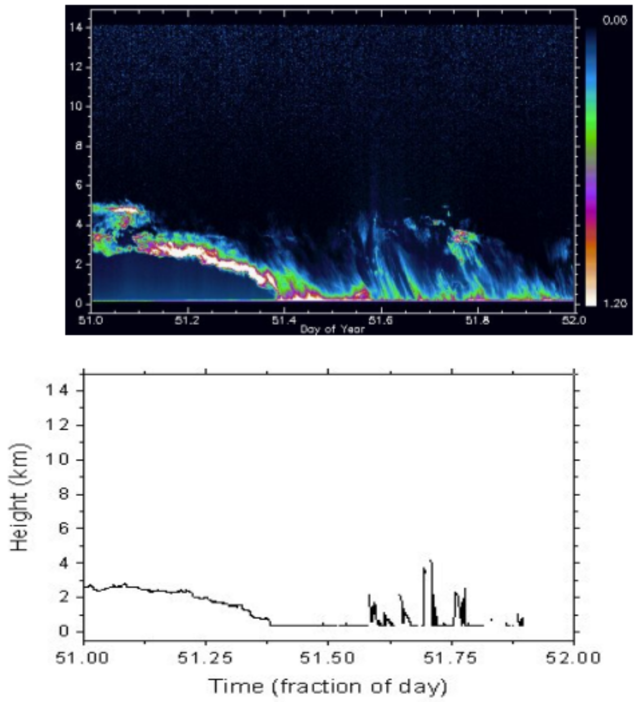

Figure 1. An example to illustrate the determination of cloud base height from lidar data (February 20 2000).

ture produced by such conditions complicates the determination of the lower cloud boundary; indeed the optically thinnest and lowest clouds may be indistinguishable from such surface-based phenomena.

3. Discussion

[12] The percentage of lidar profiles identified as 'clouds' – i.e. with a lower boundary detected at the threshold value used to filter out blowing snow and diamond dust — was determined for each day of the observing period; approximately 40% of the lidar profiles were of clouds. This annual average is similar to that seen in the spectral observations taken in 1992, and also to that

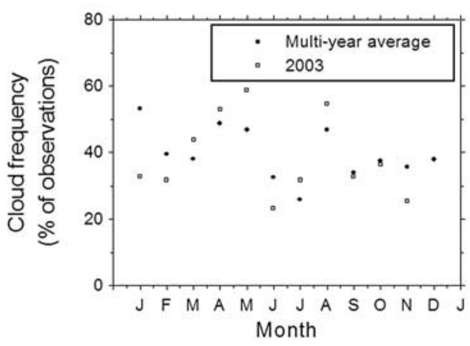

Figure 2. Monthly average cloud frequencies from lidar observations between January 2000 and July 2004. The values for 2003 alone are shown separately (hollow squares); in other years spring data is incomplete.

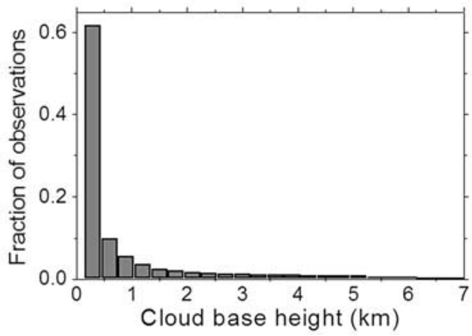

Figure 3. Histogram of cloud heights seen by the micropulse lidar.

determined by *Hahn et al.* [1995]. Monthly averages are computed for the entire duration; these are shown in Figure 2. Some scatter about the mean annual frequency is seen. The lowest values are seen in winter months (June–July), but higher cloud frequencies are also noted in other months (May, August). The highest average is in January, when slightly more than half the observations included clouds. Since, as noted earlier, complete data for the Antarctic spring is available only for 2003, the corresponding values for this year alone are shown (hollow squares). The 2003 data are broadly similar to the multi-year average, except in January, where during this year significantly fewer clouds were observed.

[13] A key advantage of the lidar observations is the increased reliability and unambiguity in determining layer heights, compared to those determined from passive data. In applying the carbon-dioxide-slicing technique commonly used to determine cloud heights from spectral observations, *Mahesh et al.* [2001a] noted the sensitivity of their findings to atmospheric temperature lapse rates. The base heights of higher clouds, in particular, could not be determined with much accuracy from the spectra. With a resolution of only 30 meters, the lidar provides a far more reliable record of cloud heights than could be obtained from the spectra.

[14] The distribution of cloud base heights found for the entire period of observation is shown in Figure 3. A significant number of the detected layers are very close to the ground. This is similar to the observations from 1992, when 60% of cloud base heights were within the lowest 400 meters. However, Figure 3 shows one striking difference from the earlier observation — the bimodality of cloud base heights seen in the spectral observations from 1992 is not seen here. This is of particular interest; not only did *Mahesh et al.* [2001a] report a bimodal distribution of cloud base heights, their finding was also borne out by the (admittedly less accurate but still broadly useful) routine synoptic record from visual observations by station personnel. Their absence in the (longer time series of) lidar observations, thus, contradicts some of the current understanding of cloud heights over the plateau.

[15] One explanation may be that the lidar observations are disproportionately from summer months (much of the period when the lidar was not operating was during the Antarctic winter), and summer is the one season in which the bimodal distribution was not found in the 1992 data

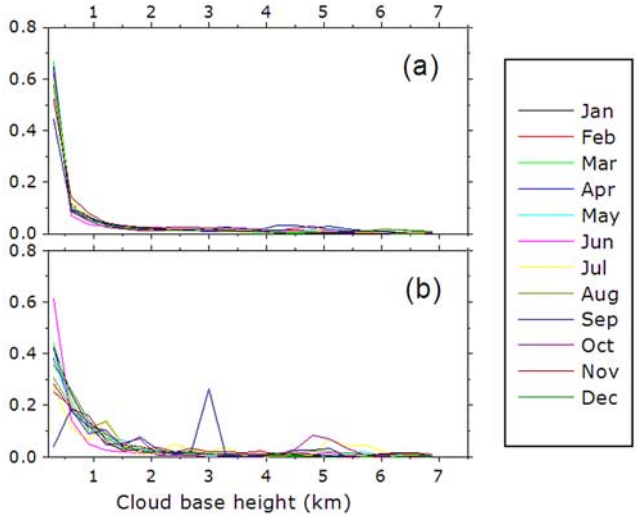

Figure 4. (a) Monthly cloud base height distribution shows no significant bimodality of heights. (b) When a higher threshold of backscatter is used to detect atmospheric layers, the bimodality is more evident in the spring months.

as well [see *Mahesh et al.*, 2001a, Figure 6]. However, this possibility was not borne out; when the annual distribution was separated into monthly distributions (Figure 4a), the bimodality was still not seen. Only in the spring months (September and October) when Polar Stratospheric Clouds (PSCs) form at very low temperatures is there any indication of a second mode, and even this is minimal.

[16] It is possible that despite the threshold used to filter out diamond dust crystals, the lidar data include these near-surface layers of suspended ice particles, and the distribution of base heights is skewed as a result. The large number of near-surface entries in all the monthly distributions suggests that this is the case. A higher threshold for 'cloud' layers might remove many of these; the lower panel (Figure 4b) shows monthly distributions of cloud heights recalculated with a higher threshold of detection (backscatter = 1.0×10^{-5} $m^{-1}sr^{-1}$) used to eliminate very thin near-surface layers. A second mode of higher cloud bases is now pronounced in September and noticeable in October and July as well. Clearly, the base heights of optically thicker layers are distributed very differently from those of thin clouds during these months. This is especially important in comparing lidar derived cloud heights to values from spectral observations, since the latter do not detect the particulate boundary but instead provide estimates of the height of the emitting temperature within a layer. As a result, the heights of optically thicker clouds obtained from spectra are more easily compared to those from lidar, whereas the heights of optically thin layers could show greater differences between the two techniques.

4. Conclusions

[17] Multi-year observations of atmospheric scattering layers from a ground-based lidar at South Pole show clouds are present about 40% of the time. This is consistent with earlier estimates from spectral data analyzed by *Mahesh et al* [2001a], (clouds were seen in 40% of the observations in 1992) as well as routine visual observations made at the station for several decades [*Hahn et al.*, 1995] (multi-year average cloud cover at the station was reported as 43%). The data also show that cloud structure is complex, with wind-driven layers often immediately adjacent to or mixed with blowing snow and suspended ice particles just above the surface. These non-cloud layers were filtered out to obtain a climatology of clouds alone, but especially thin layers may also have been omitted as a result. Earlier research had suggested that cloud heights may be distributed bimodally over the high plateau, but we were unable to confirm that from this data. The lidar observations instead suggest that any bimodality in cloud heights may be limited to observations in the late winter and early spring and not evident during other months.

[18] **Acknowledgment.** Micropulse lidar research at the Goddard Space Flight Center is funded by the NASA Earth Observing System program and the NASA Sensor Intercomparison and Merger fund for Biological and Interdisciplinary Oceanic Studies.

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