Observations of blowing snow at the South Pole

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[1] Observations of blowing snow from visual observers' records as well as ground-based infrared and lidar measurements at South Pole Station are analyzed to obtain the first climatology of blowing snow over the Antarctic Plateau. Occurrence frequencies of blowing snow, wind direction and speed during blowing snow events, typical snow layer heights, as well as optical depths are determined. Blowing snow is recorded in roughly one third of the visual observations and occurs under a narrow range of wind directions. Blowing snow layers are usually less than 400 m in thickness but can exceed 1000 m. During blowing snow conditions, these near-surface layers are apparent in lidar backscatter profiles. These layers emit radiances similar to those from optically thin clouds frequently seen over the Antarctic Plateau. Because the near-surface blowing snow layers are frequently present, they are a factor in space-borne laser altimetry and other satellite remote sensing. *INDEX TERMS:* 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 1863 Hydrology: Snow and ice (1827); 5462 Planetology: Solid Surface Planets: Polar regions; 0933 Exploration Geophysics: Remote sensing; *KEYWORDS:* blowing snow, Antarctica, polar climate

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1. Introduction

[2] The extreme conditions and remote location of the Antarctic have long inhibited the systematic study of its climate. With the establishment of a few weather stations following the International Geophysical Year 1957, routine records of local weather conditions at these stations became available. Nearly all these stations, however, were established along the Antarctic coast; the few in the interior of the plateau were widely separated and therefore provided spatially limited information. Observations from polar-orbiting satellites have partly overcome the paucity of stations, but over the polar regions the usefulness of satellite observations is limited. Physical and radiative similarities between clouds and the snow-covered surfaces hinder the determination of critical elements of the energy balance over Antarctica from satellites alone [*Yamanouchi et al.*, 1987]. Ground-based programs to study specific aspects of climate on the plateau are necessary to provide a better understanding of Antarctic climate. This paper concerns such measurements from Amundsen-Scott South Pole Station.

[3] The extremely cold temperatures of the snow-covered Antarctic surface produce nearly constant radiative surface-based temperature inversions. A highly stable boundary layer is nearly always present, only weakening slightly in the summer months [*King and Turner*, 1997]. This, and the slightly sloped surface of the Antarctic Plateau, gives rise to unique weather phenomena. Inversion winds form in response to the radiational cooling of the surface and the strong temperature inversion. These winds over the continent are dependent on the orientation of the ice-surface topography and the strength of the inversion. The key properties of the surface winds are directional constancy and higher speeds with stronger inversions or more pronounced terrain [*Schwerdtfeger*, 1984]. Wind speeds between 5 and 10 m s^{-1} are commonly reported, as are occasional observations of wind gusts to 20 m s^{-1}.

[4] These high wind speeds often produce blowing snow events, masses of fine snow particles carried by the wind to fill the near-surface atmospheric layer and to limit the horizontal visibility, sometimes to less than a few meters. Under strong conditions, the blowing snow obscures vertical visibility as well, limiting visual observers' ability to detect overlying layers. Several past studies, theoretical as well as observational, have focused on the relationship between wind speeds and blowing snow events. *Budd et al.* [1966] suggested that a wind speed of 14 m s^{-1} is necessary in the first meter above the surface to overcome the snowpack resistance, which is dependent on snow-particle bonding, cohesion, and kinetic properties. *Schmidt* [1980] showed that fluid drag in the lower atmosphere is usually inadequate to dislodge and move snow particles, and that additionally the impacting force of saltating snow is needed to break surface-cohesive bonds. *Schmidt* [1982a] also later showed that the cohesion of the surface determines the threshold speeds at which surface particles are dislodged. *Bromwich* [1988] found that wind speeds greater than 13 m s^{-1} could cause blowing snow in summer

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(7 m s^{-1} in winter), with surface melting and greater adhesion requiring a higher wind speed for blowing snow in summer. *Dover* [1993] showed that wind speeds of 5–10 m s^{-1} at a height of 10 m above the surface were necessary to initiate blowing snow. *Li and Pomeroy* [1997] examined wind speeds at 10 m for threshold values at which snow transport occurs on the prairies of western Canada and found a range from 4 to 11 m s^{-1} with an average of 7.7 m s^{-1} for dry snow transport. *Holmes et al.* [2000] studied the relationship between high wind speed events and blowing snow at Pegasus Runway between 1991 and 1996, and determined precursors to the high wind speeds and blowing snow events. *Bintanja et al.* [2001] compared drift densities and transport rates over the blue-ice areas of Dronning Maud Land with those in ice-free areas and found that lighter winds could sustain snow transport in the smoother ice areas, but with fewer particles available for transport, drift densities are lower.

[5] Other scientific research has focused on the frequency of blowing snow events, the optical properties of blowing snow, the impact of blowing snow on visibility, typical size of blowing snow crystals, and the relationship of blowing snow to katabatic winds. *Mann et al.* [2000] found that blowing snow was reported to occur between 27 and 37% of the time during the 1991 winter at Halley Station, on the Antarctic Peninsula. *Pomeroy and Male* [1988] determined that for typical blowing snow-particle size distributions the geometric optics approximation is adequate to calculate broadband extinction and visual range. *Kodama et al.* [1985] studied the effect of blowing snow on katabatic winds in Adelie Land and found that downslope winds were significantly reduced by blowing snow densities of more than a few grams per cubic meter. *Wendler et al.* [1993] examined whether blowing snow could force katabatic winds and concluded that katabatic forcing cannot sustain wind speeds greater than 12 m s^{-1}. From photomicrograph images taken at South Pole, *Harder et al.* [1996] calculated the average radius of blowing snow particles. The particles, nearly spherical, were typically between 8 and 20 μm in radius, and the authors computed an effective radius of 15 μm. Other researchers, however, have reported much larger values, ranging from 10 to 150 μm. [*Budd et al.*, 1966; *Pomeroy and Male*, 1992; *Schmidt*, 1982b].

[6] These studies provide much insight into blowing snow over the Antarctic Plateau. Nonetheless, a climatology of blowing snow events based on observations on the high plateau itself has not been compiled. Also, it is only in recent years that instruments capable of directly recording the structure and radiative contribution of blowing snow have been installed at South Pole. Research from recent years indicates that understanding the sensitivity of climate in the polar regions is critical to improved global climate modeling [e.g., *Manabe and Stouffer*, 1979], and that improved representation of surface processes in high-latitude regions is needed. Over Antarctica, as in the Arctic, there is evidence of significant recent climate changes [e.g., *Vaughan and Doake*, 1996] and the possibility of even greater changes in response to a warming planet is being actively debated. Blowing snow is possibly a factor in the radiative balance of the Antarctic Plateau. Also, because downslope katabatic winds are present nearly all the time over the plateau, blowing snow is transported to large distances and in great quantities, redistributing precipitation [e.g., *Takahashi et al.*, 1988] and in extreme instances leading to negative mass balance at the surface, resulting in blue-ice fields [e.g., *van den Broeke and Bintanja*, 1995].

[7] Blowing snow is also relevant to satellite remote sensing. It is a possible but unknown factor in passive sensing but clearly important to the emerging field of active sensing. The Geoscience Laser Altimeter System (GLAS), launched aboard the Ice, Cloud, and land Elevation Satellite (ICESat) in January 2003 is the first experiment in space-based laser radar altimetry. A primary objective of this mission is to monitor changes in ice sheet elevations over Greenland and Antarctica from space-based lidar observations [*Cohen et al.*, 1987]. Blowing snow, like other atmospheric layers, could limit the range of conditions under which space-based altimetry measurements can be made [*Mahesh et al.*, 2002]. Scattering from blowing snow layers delays photons from the space-borne laser traveling to the Earth's surface and back, thereby providing biased estimates of surface elevation. Accurate knowledge of the frequency and physical characteristics of blowing snow layers will permit such scattering to be modeled, improving the reliability of ICESat altimetry.

[8] We present here a study of blowing snow based on data acquired at the Amundsen-Scott South Pole Station. At 2835 m, the station altitude is comparable to the average elevation of the extensive plateau, and surface radiative conditions here are fairly representative of a large region. This research is the first to examine records of multiyear (1989–2001) routine visual observations of blowing snow on the Antarctic Plateau. The visually observed data are combined with lidar and spectral observations to investigate the physical characteristics and radiative effects of blowing snow. The lidar observations are used to examine the vertical extent of the blowing snow layer, and spectral observations are analyzed to obtain the radiative effect of blowing snow.

2. Visual Observations

[9] Visual observers at South Pole Station make routine observations of sky conditions, which are included in the synoptic reports from the station. Typically, data are taken every 6 hours, at 0000, 0600, 1200, and 1800 UTC; however, more frequent observations are sometimes made, especially in the summers and during flight times. A total of 36,046 visual observations of sky conditions made between 1989 and 2001 was available for study. From this, the subset of observations made during blowing snow events was extracted. Blowing snow is indicated by "BS" in reports prior to November 1997 and as "BLSN" since then. Drifting snow is separately denoted as "DS" prior to November 1997 and as "DRSN" since. *Schwerdtfeger* [1984] differentiated between blowing snow and drifting snow in that drifting snow does not limit the horizontal visibility at the height of the observer's head, whereas blowing snow does. Visual observers at South Pole have only recently begun to keep records of drifting snow events; observations prior to November 1997 made no distinction between the two types of snow transport. Data from the last 3 years indicate that relative to blowing snow, observations of drifting snow are few, comprising about 5% of the total

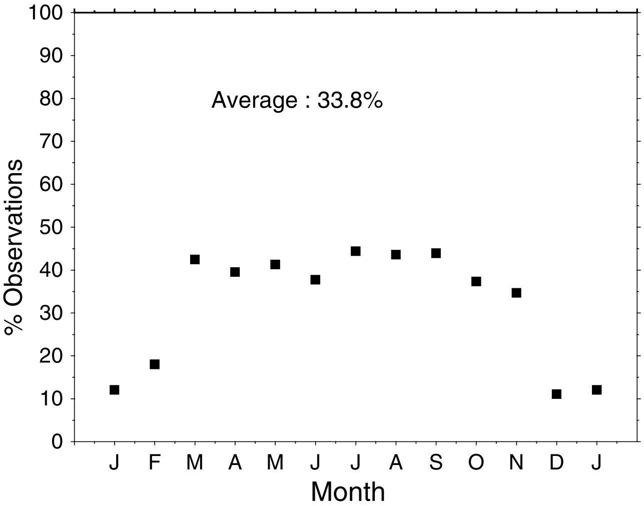

Figure 1. The percentage of observations from each month during 1989–2001 that included blowing snow. Blowing snow is seen significantly more often during the winter months (March–September) than at other times. (Note that January data are shown at both ends.)

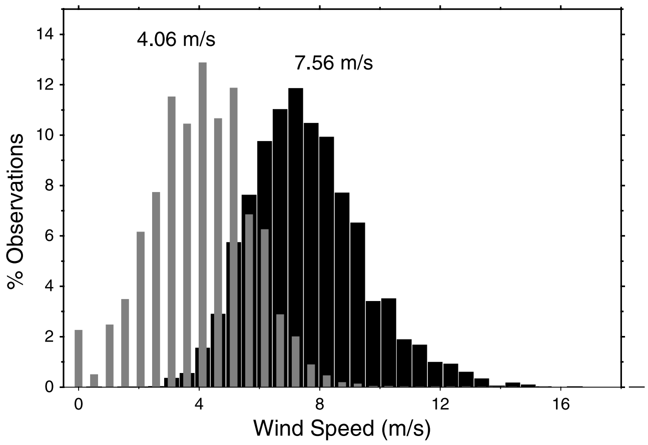

Figure 3. Percentages of blowing snow (solid bars) and nonblowing snow (shaded bars) observations, 1989–2001, occurring during wind speeds of 0–18 m s^{-1}. Blowing snow observations typically occur during higher wind speeds (average 7.56 m s^{-1}) than nonblowing snow observations (4.06 m s^{-1}).

number of events. Also, because the average wind speed during drifting snow events is similar to that during blowing snow, these observations are included in this study. This produced a data set of 9757 observations, 98% of which were of blowing snow and the rest of drifting snow.

[10] Monthly occurrences of blowing snow were obtained by dividing the number of blowing snow observations in each month by the total number of visual observations in that month. A multiyear record of occurrences during each month was then computed by averaging the monthly values over the 1989–2001 period. Figure 1 shows the monthly average occurrence of blowing snow conditions during the observation period, while the time series from the annual averages is shown in Figure 2. Overall, blowing snow is recorded 33.8% of the time in the visual observations. Considerable variability is seen in the occurrence of blowing snow; the annual averages range from a low of 22.1% of the observations (the average for 1997) to a high of 53.3% (1998). Figure 1 also shows a higher incidence of blowing snow in the winter months (42.4% of the time) than during the rest of the year (21.5%). Note that winter is defined as the 7-month period from March to September. The rise in blowing snow frequency with the onset of winter is dramatic and not gradual; this may be in response to changes in surface temperature. Unlike in the Arctic, surface temperatures on the Antarctic Plateau drop rapidly to a "coreless" minimum; i.e., we do not observe increasing cold as the winter deepens and warmth as it passes. Instead, temperatures very near the yearly lows are reached immediately after the sun falls below the horizon, and not gradually.

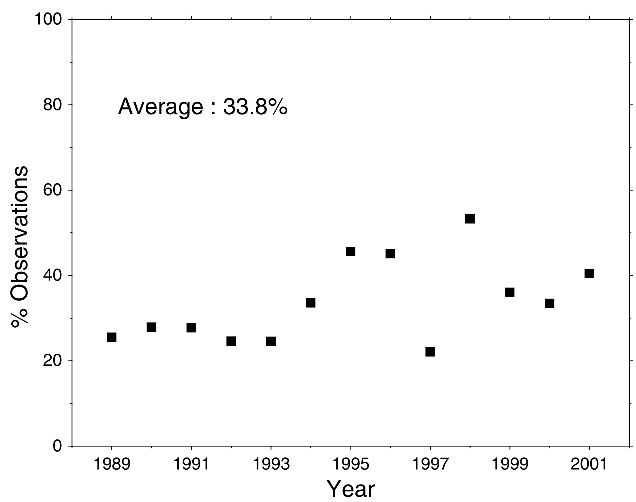

Figure 2. Blowing snow events at South Pole between 1989 and 2001. For each year, the fraction of observations during each month that indicates "blowing snow" is first determined, and these are averaged to produce annual average values.

[11] Routine observations of wind speeds and directions at South Pole are available from an anemometer located 15 m grid northeast of the geographic pole marker and 10 m above the ground (K. Hess, personal communication, 2002). Observations of wind speed and direction during blowing snow events were examined. As with the analysis of blowing snow occurrences, wind speeds were examined for annual and seasonal patterns. Average wind speeds were also separately obtained for all visual observations and for blowing snow observations alone. The average of wind speeds measured during all visual observations is 4.06 m s^{-1}, whereas blowing snow typically occurs at a significantly higher wind speed (average of 7.56 m s^{-1}, Figure 3). There is little difference between the average wind speed at which blowing snow occurs in winter and other months.

[12] The figure also shows wind speeds during non-blowing-snow observations; these are largely distinct from observations made under blowing snow. However, there is a small overlap. About a quarter of the observations are of wind speeds between 4 and 8 m s^{-1}, and at these speeds, blowing snow is sometimes observed and sometimes not. A likely explanation is that these low speeds represent periods

immediately following snowstorms, during which time particles elevated into the atmosphere may be still present, even though wind speeds have dropped below the value that would be necessary to dislodge them if they were still on the ground. A second possibility is that snow particles that can be dislodged from the surface are not always present, and despite wind speeds adequate to create blowing snow, none are observed. Variations in compactness of surface snow, the size of snow particles, time elapsed since the most recent precipitation event, and persistence of winds may also account for differences between the two classes of observations. Some of these are unknown, and others (e.g., precipitation times) are not routinely recorded, this precludes a study of the influence of the individual factors.

[13] Observations of blowing snow were also similarly examined alongside measurements of wind direction. Histograms are shown (Figure 4) for wind directions during blowing snow observations, as well as non-blowing-snow observations. At the South Pole every direction is north; the following discussion assumes that the direction of the prime meridian is "north" (as shown in Figure 5), and directions east and west of this line are to the northeast and northwest of South Pole, respectively.

[14] The dominant direction of surface winds at South Pole is from the northeast [*Mather and Miller*, 1967]; this is largely determined by the orientation of the fall line of the sloped terrain. The constancy of the wind direction at the surface at South Pole is also extremely high; three quarters of the routine observations show winds from the north and northeast (between 20°W and 80°E of the Prime Meridian). Only a few observations of southerly winds (blowing from longitudinal directions between 150° and 260°) are seen; these occur two orders of magnitude less often. Wind directions during blowing snow events are even more narrowly grouped; blowing snow is typically seen during winds from a longitudinal band between 340° (i.e., 20°W of the Prime Meridian) and 50° (east of the Prime Meridian). The non-blowing-snow observations, in comparison, were made during winds from a wider range of directions, up to 100°E. Snowfall at the South Pole usually results from storms that blow in from the Weddell Sea with sufficient force that some moisture remains despite the precipitation due to increasingly higher elevations along the path to the pole; it may be that freshly precipitated snow is dislodged by winds from the north and northwest, and this would explain the westward shift of observed wind directions during blowing snow events. Seasonally separated data are also shown (Figure 6); a slightly greater range of wind directions is observed during blowing snow events in the winter months.

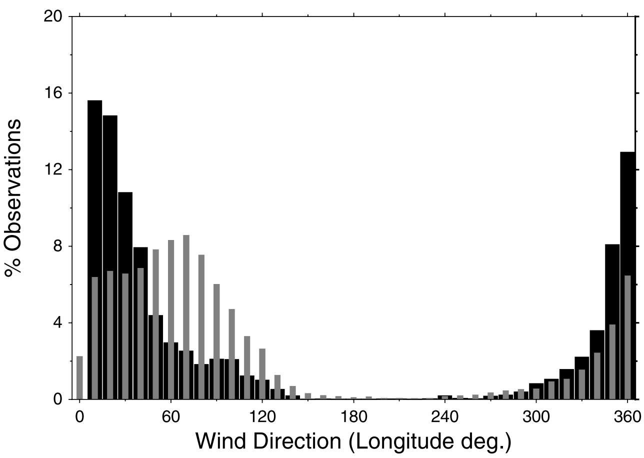

Figure 4. Wind directions during blowing snow (solid bars) and non-blowing-snow (shaded bars) observations, 1989–2001. Blowing snow observations occur most frequently with winds from 360° to 30°. Nonblowing snow observations occur under a wider range of wind directions.

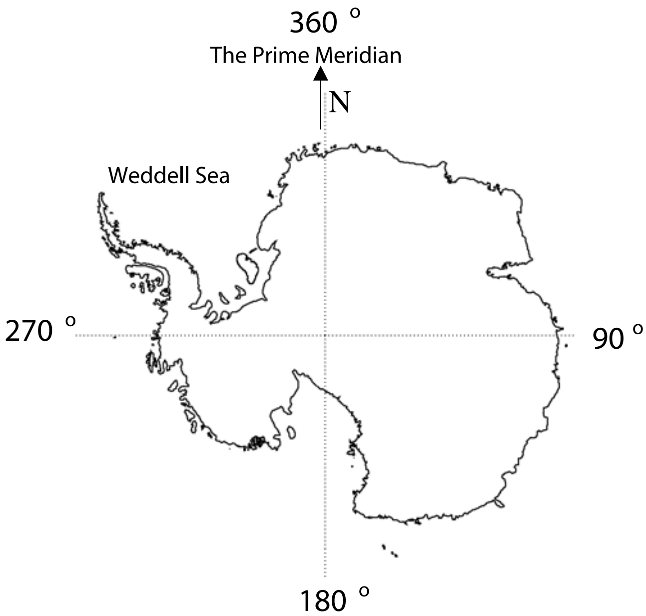

Figure 5. Outline map of Antarctica showing the direction of the Prime Meridian, and the Weddell Sea. Since at the South Pole all directions are north, the Prime Meridian is chosen as the northward direction for the discussion in this paper; longitudes run clockwise around this direction from 0° to 360°.

3. Lidar Observations

[15] In recent years, micropulse lidars [*Spinhirne*, 1993] have been installed at specific locations to make continuous autonomous observations of nearly all significant atmospheric layers [e.g., *Campbell et al.*, 2002]. Between 1999 and mid-2002 (and continuing), one such instrument was operational at South Pole Station; data from this instrument are available for analysis through the Micropulse Lidar Network (MPL-Net information is available online from http://mplnet.gsfc.nasa.gov). The instrument is located approximately 10 m above the ground and has a resolution of 30 m along the beam direction. During most of the day, South Pole lidar backscatter profiles are obtained by pointing the instrument vertically. However, the blowing snow cannot be fully resolved from the zenith-pointing lidar data only. There are two limitations for detecting blowing snow. One is that the sampling resolution is only 30 m. More significantly there is a near-range signal limitation for all lidar known as the overlap function where the signal scattered from the transmitted pulse is not yet fully focused

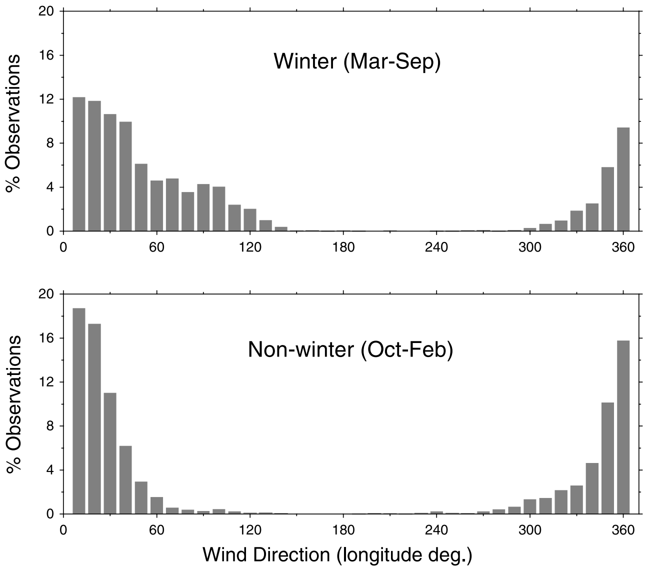

Figure 6. Seasonal wind directions during blowing snow events, South Pole.

at the detector. The MPLs have a particularly long overlap function in terms of range, and the signal is not useable for the first 100 m. In order to readily observe the structure of blowing snow and other layers, the South Pole MPL was equipped with automated elevation pointing. By stepping through angles of low elevation, the vertical resolution becomes better by a factor of secant of the zenith angle, θ_z, of the observation. Angles to a secant θ_z of 6 were used. The data are acquired along a slant path rather than over a single point. However, for each profile, data are averaged for 6 min, and profiles are an average of the scattering particles advected through the slant path. The profiles thus represent a time and space average through layers.

[16] At approximately 2100 UTC each day for the data reported here, a sequence of measurements at low-elevation angles were taken with the lidar. The near-horizon-looking observations permit profiling near-surface atmospheric layers including blowing snow to the surface with good resolution, between 5 and 20 m. Figure 7 shows lidar observations made during one full day (20 April 2001) as a function of range. Initially, in the day period shown, the lidar is vertically pointing, and the data reveal broken clouds up to approximately 2 km. In addition, just at the surface is seen structure indicative of a continuous scattering layer. The peak in the backscatter at 110.95 is the beginning of the hour period when low-angle observations are made. The extended signal at range also reveals the presence of a near-surface layer. Visual observers reported at 2000 UTC blowing snow not associated with clouds.

[17] Blowing snow occurs both during cloudy periods and under clear-sky conditions. Therefore we must verify that lidar observations of snow layers are not contaminated by signals from any overlying or included cloud layers additionally. To ensure this, for the lidar analysis, a subset of the visual observations of blowing snow was obtained as follows. Only those days were selected when blowing snow was reported by surface observers at or after 2000 UTC, provided such observations either contained no observations of clouds, or any clouds that were reported occurred above 4000 feet. The case shown in Figure 7 meets these criteria and is thus one of the cases used in our analysis. Although our criteria do not preclude the possibility that cloud layers unobserved by visual observers may be present in addition to the blowing snow, such selection reduces potential confusion between blowing snow layers and any near-surface clouds. Further, days on which near-horizon lidar observations were not made, due to mechanical problems or otherwise, were discarded. Data from 40 days met the selection criteria. The low-angle data were only available for a subset of the total South Pole MPL observational record, which started in December 1999 and continues to present day. The periods where MPL data were applied in this study are March–August 2000, January–April 2001, and January 2002.

[18] Figure 8 shows the lidar backscatter profile from a blowing snow case made at a large zenith angle on 24 June 2000. A derived molecular backscatter profile, the signal with no particles, for polar atmospheres is also indicated (dashed line). The larger near-surface values of the measured profile are caused by the snow particles. This scattering diminishes at higher elevations until it reaches the molecular scattering value. Following an algorithm introduced by *Campbell et al.* [2003], a lidar calibration constant (via the lidar equation) is first derived for using a 0.50-km range interval well above the surface-based scattering layer (cloud-screened, typically 1.00–1.50 km). The top of the blowing snow layer is derived as the height (working from the calibration interval downward) where the first significant positive deviation from molecular scattering is observed (approximately 0.16 km in Figure 7). Significant scattering from blowing snow is clearly seen below this height.

[19] The height of the blowing snow layer was found from the lidar data for the total of 40 cases meeting criteria described before. The distribution of blowing snow layer thickness for these cases is shown in Figure 9. The average of the values obtained from all the observations is 416 m. Approximately 50% of the layers were less than 200 m in thickness. From the histogram, we see that nearly all observations are of layers less than 600 m in thickness, but in some cases blowing snow is found carried to higher

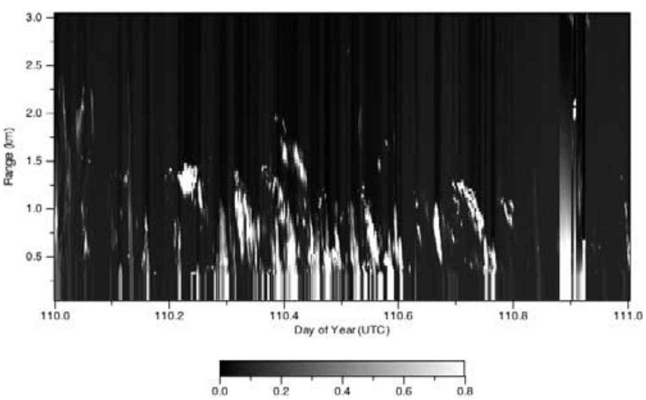

Figure 7. Typical lidar observation from South Pole. A full day's data (20 April 2001) are shown; the backscatter peak near 110.9 is from looking through the near-surface scattering layer at a large off-zenith viewing angle.

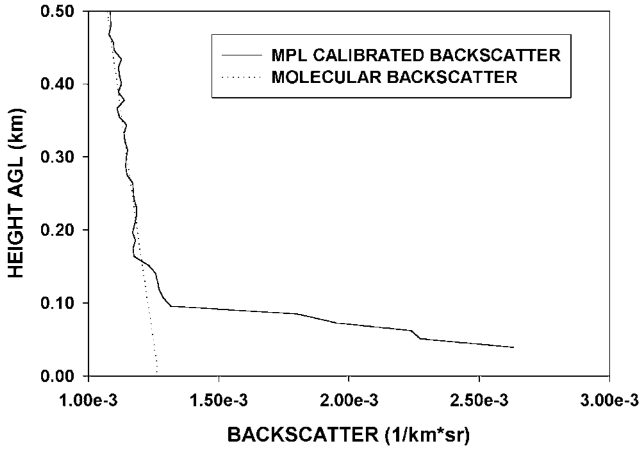

Figure 8. Backscatter profile from lidar observation of 24 June 2000. The contribution from molecular scattering alone is also shown.

elevations. Surface-based temperature inversions at South Pole are typically less than a kilometer thick [*Mahesh*, 1999]; average inversion heights range between 500 and 750 m. The blowing snow appears limited to the near-surface inversion layer in nearly all cases.

[20] The lidar observations of blowing snow layers are made using larger viewing zenith angles. This allows thin surface-based layers to be profiled in detail but has a disadvantage; uncertainties in the viewing angle translate into larger errors in the derived layer thickness than would be the case if observations were made at smaller angles. The resolution and calibration of the scanner were initially better than 0.1°, but over time, shifts in the mechanism were noted. We estimate the overall uncertainty in the observing angle to be less than 1°; and correspondingly, errors in the derived layer thickness values are less than a few tens of meters.

[21] We considered the possibility that the larger values of blowing snow layer thickness correspond to higher wind speeds, but such a relationship is not apparent (Figure 10). Over the range of wind speeds at which blowing snow events are seen, the layer thickness varies considerably. One explanation for this is that snow particles, once blown into the atmosphere by winds of a given speed, may remain in the atmosphere for some time afterward, even though wind speeds subsequently drop below the threshold speed required to dislodge them from the surface. Wind speeds immediately following snowstorms can be extremely low (M. Towne, personal communication, 2003). Some observations, thus, reflect the tail end of a blowing snow event or even times immediately following such events, and a correspondence between layer heights and wind speeds cannot be expected for such periods.

[22] A second explanation as to why wind speeds may not be correlated with layer thickness is that wind speed is only one determinant of the likelihood of snow-particle displacement from the surface; other variables, notably the compactness of surface snow, will also affect layer heights. Lighter and looser snow could be transported to greater heights even under lighter wind conditions, whereas denser snow is less likely to be removed to large heights. Precipitation events are not, however, individually recorded at South Pole, and such examination is precluded. Another possibility is that stronger winds promote greater sublimation of blowing snow particles through greater entrainment of dry air [*Mobbs and Dover*, 1993; *Pomeroy et al.*, 1993; *Mann et al.*, 2000]; this may allow particles to completely sublime in strong winds, whereas in medium-strength winds they may remain saturated with respect to ice.

[23] Nonetheless, the larger values in Figure 9 are considerably greater than is reported by surface observers at the station itself. Visual estimates of blowing snow thickness almost never exceed 200 m, although whiteout conditions at that height have been known to occur during wind speeds of

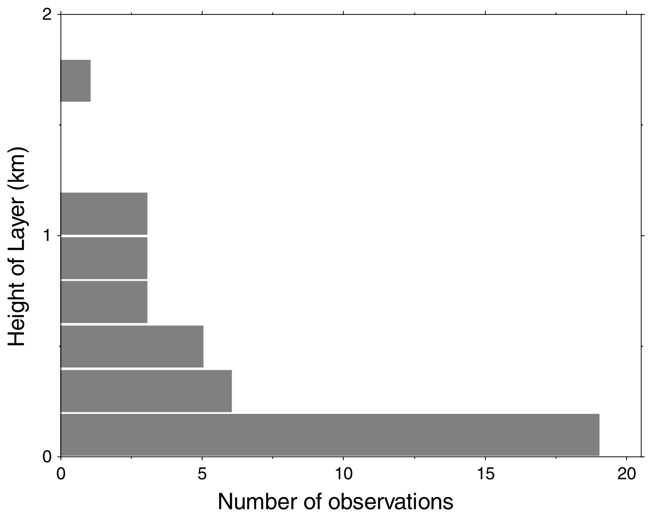

Figure 9. Distribution of blowing snow layer thickness (in kilometers) obtained from near-horizon-looking lidar backscatter profiles, 2000–2002.

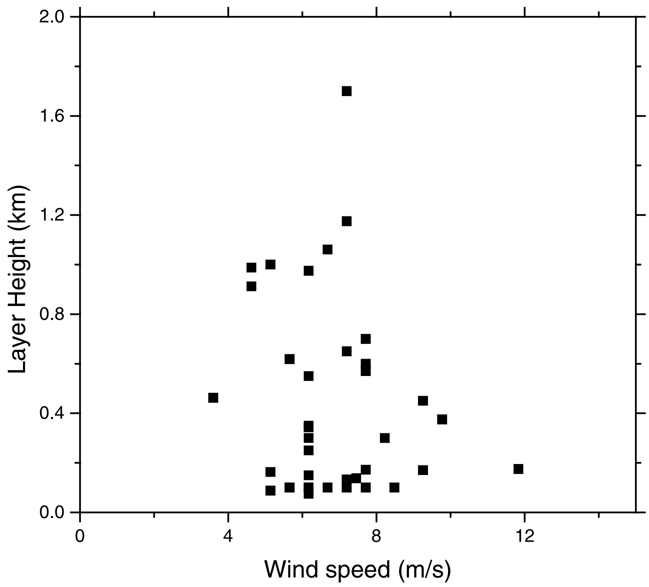

Figure 10. The height of blowing snow layers appears uncorrelated with wind speeds. Over a range of wind speeds, blowing snow is elevated to several heights from 200 m to over a kilometer.

45 m s^{-1} [*Gosink*, 1989]. *Budd et al.* [1966] report from aircraft observations that plumes of suspended blowing snow can reach heights of up to 1 km, but only during very strong wind episodes. This suggests that layer thickness values greater than a few hundred meters in Figure 9 are likely from observations of subvisual blowing snow particles or even possibly of suspended clear-sky precipitation in the lower atmosphere, known as "diamond dust." The presence of subvisual clouds above blowing snow layers also cannot be ruled out. The frequent presence of a continuous scattering layer from the surface to the heights reported here is shown unequivocally in the lidar data; whether these layers are entirely due to blowing snow cannot yet be fully known.

4. Spectral Observations and Calculations

[24] The Antarctic troposphere contains very little water vapor; downwelling infrared radiances under clear-sky conditions in the atmospheric window regions are negligible. Therefore any additional radiance from clouds, suspended ice particles, or blowing snow layers is clearly seen in spectral observations. Figure 11 shows infrared spectral radiances from a blowing snow layer measured on 15 October 1992 by a surface-based interferometer at the South Pole [*Walden and Warren*, 1994], along with a calculated clear-sky profile created using radiosonde, ozonesonde, and surface visual observations by radiative-transfer modeling using the Line-By-Line Radiative Transfer Model (LBLRTM) [*Clough et al.*, 1992]. Between 750 and 1250 cm^{-1}, clear-sky radiances are small, indicating the relative absence of water vapor, the most important emitter at these wavenumbers. Radiances from the blowing snow layer, while not large, are still sufficiently above the clear-sky background to be detectable in such spectra. Therefore the radiative effect of blowing snow layers can be quantified from spectral observations provided such measurements do not contain additional radiances from overlying clouds or other atmospheric layers.

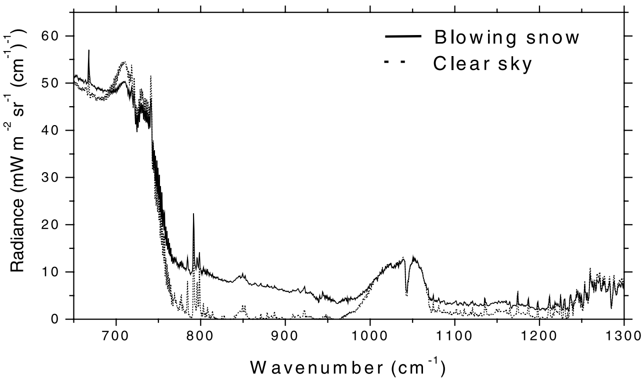

Figure 11. Window radiances from clear-sky (dotted curve) and under blowing snow (solid curve) from 15 October 1992, at an off-zenith viewing angle of 75°. The blowing snow spectrum is a measurement; the clear-sky is computed from radiosonde and ozonesonde data by radiative-transfer modeling. The contribution of blowing snow alone is the difference between the two curves.

Table 1. Monthly Average Surface Temperatures Under Clear Skies and Blowing Snow Conditions Under Otherwise Clear Skies for 2001[a]

	Clear Skies	Blowing Snow Under Otherwise Clear Skies
January	−29.85	−28.72
February	−39.21	−36.07
March	−57.71	−54.75
April	−62.91	−59.62
May	−62.47	−58.47
June	−60.61	−58.29
July	−61.69	−53.26
August	−68.48	−64.55
September	−65.23	−61.24
October	−53.93	−52.36
November	−41.53	−39.50
December	−27.5	−24.73

[a]September and November values are from 1994 and 1999, respectively, because insufficient observations were available in 2001 during those months.

[25] *Walden and Warren* [1994] made observations of downwelling infrared radiance throughout 1992 at South Pole Station. These observations were made twice daily, at three different viewing zenith angles (45°, 60°, and 75°). A similar field program of spectral observations was carried out in 2001 [*Walden et al.*, 2001]; in contrast to the earlier study, in this case continuous measurements of downwelling longwave radiances were made. Observations of blowing snow were selected from both data sets as follows. First all radiance measurements that were at or below the clear-sky levels were discarded. Following this, all observations of atmospheric layers that were too optically thick to be blowing snow were also dropped. The remainder, spectral observations of small optical depth layers, was examined along with routine visual observations made by station personnel, and those observations where visual observers reported blowing snow under otherwise clear skies were chosen. In all, seven spectra were determined to be observations of blowing snow uncontaminated by other overlying atmospheric layers.

[26] The radiance contribution from blowing snow is found as the difference between integrated clear-sky and blowing-snow spectra (Figure 11) across the entire atmospheric window between 750 and 1250 cm^{-1}. The integrated radiances from blowing snow were found to be typically less than 1 mW m^{-2} sr^{-1}; these radiances are comparable to those obtained from clouds with optical depths between 0.05 and 0.15. This will likely produce only a small warming of the surface temperature; at South Pole even thick cloud cover during the winter months (typical τ values between 2 and 5) does not destroy the surface-based inversion entirely. From the visual observations for the year 2001, the likely warming of the surface by blowing snow layers was investigated as the difference between monthly average surface temperatures for (1) clear-sky conditions, and (2) blowing snow under otherwise clear skies. During the 2 months, September and November, insufficient data points were available from 2001, and other years are substituted. The results are shown in Table 1. Surface temperatures are typically 1°–4° warmer when blowing snow is observed, the larger difference in July is possibly due to a number of extremely cold days when no blowing snow was reported. These differences in surface temperature

are comparable to those seen under optically thin clouds that occur frequently over the plateau as well [*Mahesh et al.*, 2001].

[27] Even at these small optical depths, however, blowing snow will cause scattering-induced bias in surface altimetry observations planned from the Geoscience Laser Altimeter System [*Mahesh et al.*, 2002]. Annual precipitation over much of the plateau is only a few centimeters typically, and scattering from even thin layers can produce errors in altimetry that are comparable to interannual variability is precipitation.

5. Conclusions

[28] This study presents the first climatology of blowing snow over the Antarctic Plateau from multiyear observations at South Pole Station. The use of lidar and spectral data, in addition to routine visual observations, permitted the determination of several properties of blowing snow that cannot be determined from any one of the observations alone. An unexpected new result is that the surface layer of scattering particles is several hundred meters thick. The height of blowing snow layers was found to be usually less than 400 m, but scattering particles are sometimes observed higher than 1 km. Blowing snow is almost always contained within the surface-based temperature inversion. Surprisingly, the thickest scattering layers are not seen during the strongest winds; precipitation data and routine estimates of surface-snow densities are necessary to understand this further. Occurrences of blowing snow were also compared with wind direction; a majority of the blowing snow events are seen during northerly winds, marking a slight westward shift from the dominant wind direction at the station itself. Precipitation events typically result from more northerly and northwesterly flows from the Weddell Sea; and this may account for the difference. From the spectral data the longwave radiative effect of blowing snow on the surface of the plateau is quantified; this effect is comparable to that seen from clouds with small optical depth around 0.1. The occurrence and radiative properties of blowing snow are likely to be a factor in satellite cloud retrievals and to cause small biases in space-based laser altimetry studies of the Antarctic surface. At the same time, satellite laser radar sensing techniques will likely extend detection and understanding of blowing snow layers.

[29] The analyses in this paper were based on the combination of observer and instrument sources. More sophisticated processing of the lidar data record alone for cloud and blowing snow cover climatologies at the South Pole is possible, and should be reported in the future.

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