Blowing snow over the Antarctic Plateau

Mahesh, Ashwin et al., 2002

Popular summary

In recent years, researchers have begun to realize that the polar regions are more sensitive to global warming than other regions of the world. Unfortunately, because these regions are remote and are characterized by extreme weather conditions, there hasn't been as much data collection in the high latitudes, and the weather and climate phenomena unique to the high latitudes have not been studied extensively. Global climate models, as a result, often include incomplete representations of the polar regions, and are sometimes highly deficient for this reason. This study attempts to fill the gap partly by focusing on one such topic – namely, blowing snow over the high plateau of the Antarctic.

Space-based observations of the polar surface are often partially obscured by blowing snow, and this means that measurements from space must be corrected for the occurrence of blowing snow. It is important, therefore, to understand the occurrence, physical and radiative properties of this layer. Blowing snow is also important to the energy balance at the surface. In the typical Antarctic atmosphere, there is very little water vapor; therefore when blowing snow is present there is increased emission from the atmosphere that warms the surface marginally.

Three different sources of observation are used. Visual observers at the South Pole weather station have made routine observations of sky conditions since the

International Geophysical Year 1957. From the last decade of this dataset, observations of blowing snow conditions are studied to determine the occurrence frequency, and to look for correlations with wind speeds and directions under which blowing snow occurs. Additionally, laser measurements of the Antarctic atmosphere were made as part of the Micro Pulse Lidar network's instrument installed at South Pole. Backscatter measurements from this lidar are used to determine the typical heights of blowing snow layers. Finally, spectral observations of downward radiances from blowing snow layers were recorded by an interferometer operated by the University of Idaho. These provide measurements of the contribution of blowing snow to the surface energy budget of the South Pole.

Blowing Snow Over the Antarctic Plateau

Ashwin Mahesh
Goddard Earth Sciences and Technology Center, Greenbelt MD

Rebecca Eager
Valparaiso University, Valparaiso IN

James R. Campbell
Science Systems and Applications, Inc., Lanham MD

James D. Spinhirne
NASA Goddard Space Flight Center, Greenbelt MD

For submission to the *Journal of Geophysical Research (Atmospheres)*, December 2002

ABSTRACT

Studies of blowing snow over Antarctica have been limited greatly by the remoteness and harsh conditions of the region. Space-based observations are also of lesser value than elsewhere, given the similarities between ice clouds and snow-covered surfaces, both at infrared and visible wavelengths. It is only in recent years that routine ground-based observation programs have acquired sufficient data to overcome the gap in our understanding of surface blowing snow. In this paper, observations of blowing snow from visual observers' records as well as ground-based spectral and lidar programs at South Pole station are analyzed to obtain the first climatology of blowing snow over the Antarctic plateau. Occurrence frequencies, correlation with wind direction and speed, typical layer heights, as well as optical depths are determined. Blowing snow is seen in roughly one third of the visual observations and occurs under a narrow range of wind directions. The near-surface layers typically a few hundred meters thick emit radiances similar to those from thin clouds. Because blowing snow remains close to the surface and is frequently present, it will produce small biases in space-borne altimetry; these must be properly estimated and corrected.

1. Introduction

The extreme conditions and remote location of the Antarctic 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 were necessary to provide a better understanding of Antarctic climate; in recent years a few such programs have been conducted at Amundsen-Scott South Pole station.

The extremely cold temperatures of the emissive snow-covered Antarctic surface produce nearly constant 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 to 10 m/s (i.e., between 10 and 20 knots approximately; wind speeds are recorded in knots; one knot=0.5144 m/s) are commonly reported, as well as occasional observations of wind gusts to 20 m/s.

These high wind speeds often result in 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 very severe conditions, the blowing snow can obscure vertical visibility as well, limiting visual observers' ability to detect overlying layers. Several past studies have focused on the relationship between wind speeds and blowing snow events. *Budd et al.* [1966] suggested a threshold wind speed of 14 m/s for snow transport is necessary in Antarctica 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. He also later showed (*Schmidt*, 1982] 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 (7 m/s) can cause blowing snow in summer (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 were necessary to initiate blowing snow. *Li and Pomeroy* (1997] examined wind speeds for threshold values at which snow transport occurs on the prairies of western Canada and found a range from 4 to 11 m/s with an average of 7.7 m/s 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.

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 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. 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.

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, however, 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 accurate representation of high latitude from studies of polar conditions 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. The Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud, and land Elevation Satellite (ICESat) due to launch at the end of 2002 will take an important step towards finding answers; the primary objective of the 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], and a climatology of blowing snow conditions will permit the proper understanding and use of ICESat data.

This research is the first to examine records of multi-year (1989-2001) routine visual observations of blowing snow on the Antarctic Plateau. This is supplemented by 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

Visual observers at the 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 00, 06, 12, and 18 UTC; however, more frequent observations are sometimes made, especially in the summers and during flight times. A total of 36046 visual observations of sky conditions made between 1989 and 2001 were 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 three years indicates that relative to blowing snow, observations of drifting snow are few, comprising about 5% of the total 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 dataset of 9757 observations, 98% of which were of blowing snow and the rest of drifting snow.

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 multi-year 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 seven-month period from March to September.

Correlations of blowing snow with wind speed and direction were studied. 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 4.96 m/s, whereas blowing snow typically occurs at a significantly higher wind speed (average: 7.56 m/s, figure 3). The figure also shows wind speeds during non-blowing snow observations, these are clearly distinct from observations made under blowing snow. Seasonally, there is little difference between the average wind speed at which blowing snow occurs in winter and other months.

Correlations of blowing snow with wind direction were found in a similar manner. At the South Pole every direction is north; the 360° longitude in the figure corresponds with the Prime Meridian. Histograms are shown both for wind directions during blowing snow observations, as well as non-blowing snow observations (figure 4). 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, at 76%; this is clearly seen in the histogram. Only a few observations of southerly winds (blowing from longitudinal directions between 150° and

260°) occur two orders of magnitude less often than northerly winds (350° to 100°). Wind directions during blowing snow events are even more narrowly grouped; blowing snow is typically seen during winds from a more focused longitudinal band (between 340° to 50°). 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 is also shown (figure 5); a slightly higher concentration of westerly winds is observed during blowing snow in the winter months.

3. Lidar Observations

In recent years, micro pulse 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, one such instrument was operational at South Pole station; data from this instrument is available for analysis through the Micro Pulse Lidar Network (MPL-Net; data available online from http://mplnet.gsfc.nasa.gov). During most of the day, lidar backscatter profiles at South Pole were obtained by pointing the instrument vertically. At about 2100 UTC each day, several scans were taken with the lidar pointing at large off-zenith angles. These near-horizon looking observations permit the study of near-surface atmospheric layers such as blowing snow. Figure 6 shows lidar observations made during one full day (February 17, 2000). The peak in the backscatter towards the end of the day's data reveals the presence of a near-surface layer; visual observers reported blowing snow on this date.

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, a subset of the visual observations of blowing snow was obtained as follows. Only those days were selected when blowing snow was reported in observations made at or after 20 UTC, provided such observations either contained no observations of clouds, or any clouds that were reported occurred above 4000 feet. This selection reduces potential confusion between blowing snow layers and any near-surface clouds. Further, days on which near-horizon lidar observations were not made were discarded. Data from 40 days met all the selection criteria; several scans were taken on each of these days.

Figure 7 shows the lidar backscatter profile from a blowing snow case made at a large zenith angle on June 24, 2000. A derived molecular backscatter profile for polar atmospheres is also indicated (dashed line). The larger near-surface values 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], the calibration constant (via the lidar equation) is first solved for using a 0.50 km range well above the surface-based scattering layer (cloud-screened, typically 1.00 – 1.50 km). We assume no particulate attenuation below this range, such that the top of the blowing snow layer is solved for as the height (working from the calibration range downward) where the first significant positive deviation from molecular scattering is observed (approximately 0.16 km in this example). Significant scattering from blowing snow is clearly seen below this height.

A distribution of blowing snow layer thickness is obtained from all high-angle lidar observations; this is shown in figure 8. The average of the values obtained from all the observations is 416 m. However, nearly 50% of the layers were less than 200 meters in thickness. From the histogram, we see that nearly all observations are of layers less than 600 m in thickness, although blowing snow can be carried to higher 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 meters. The blowing snow appears limited to the near-surface inversion layer in nearly all cases.

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 9). Over the range of wind speeds at which blowing snow events are seen, the layer thickness varies considerably. One explanation for this observation 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.

Nonetheless, the larger values in figure 8 are considerably greater than is reported by surface observers at the station itself. Visual estimates of blowing snow thickness almost never exceed 200 meters, although whiteout conditions at that height have been known to occur during wind speeds of 45 m/s [Gosink 1989]. This suggests that layer thickness values greater than a few hundred meters are likely from observations of sub-visual blowing snow particles, or even possibly of suspended clear-sky precipitation in the lower atmosphere, known as 'diamond dust'. The presence of sub-visual clouds above blowing snow layers cannot also be ruled out.

The lidar observations of blowing snow layers are made at very high 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. We estimated the uncertainty in the observing angle to be less than 1 degree; correspondingly errors in the derived layer thickness values are a few tens of meters.

4. Spectral Observations and Calculations

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 10 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.

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 datasets 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 – were 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 7 spectra were determined to be observations of blowing snow uncontaminated by other overlying atmospheric layers.

The radiance contribution from blowing snow is found as the difference between integrated clear-sky and blowing-snow spectra (Figure 10) 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 $mWm^{-2}sr^{-1}$; these radiances are comparable to those obtained from clouds of optical depths between 0.05 and 0.15. This will likely produce only a small warming of the surface temperature; at South Pole even the thickest cloud cover during the winter months does not destroy the surface-based inversion entirely, and most thin clouds warm the surface by only a few degrees [Mahesh 1999]. 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].

5. Conclusions

This study presents the first climatology of blowing snow over the Antarctic Plateau from multi-year observations. 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. The height of blowing snow layers was found to be usually less than 400 meters, although snow particles are sometimes blown to higher elevations during stronger winds. Blowing snow is almost always contained within the surface-based temperature inversion. Occurrences of blowing snow were also correlated 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 of small optical depths 0.1. The occurrence and radiative properties of blowing snow are likely to cause small biases in space- and aircraft-based altimetry studies of the Antarctic surface.

Acknowledgements

Micro Pulse Lidar (MPL) research at the Goddard Space Flight Center is funded by the National Aeronautics and Space Administration (NASA) Earth Observing System program, and the NASA Sensor Intercomparison and Merger fund for Biological and Interdisciplinary Oceanic Studies. Spectral observations from South Pole were obtained from Michael Town at the University of Washington under the South Pole Atmospheric Radiation and Cloud Lidar Experiment (SPARCLE). The authors thank Stephen Warren for helpful discussions.

References

Bintanja, R., H, Lilienthal, and H. Tug, Observations of snowdrift over Antarctic snow and blue-ice surfaces. *Ann. of Glaciology*, **32**, 168-174, 2001.

Bromwich, D.H., Snowfall in high southern latitudes. *Rev. Geophys.,* **26,** 149-168, 1988.

Budd, W.F., W.R.J. Dingle, and U. Radok, The Byrd snowdrift project: Outline and basic results. *Studies in Antarctic Meteorology.* M.J. Rubin, Ed., Antarctic Research Series, Vol. 9, American Geophysical Union, 71-134, 1966.

Campbell, J. R., D. L. Hlavka, E. J. Welton, C. J. Flynn, D. D. Turner, J. D. Spinhirne, V. S. Scott III, and I. K. Hwang, Full-time eye-safe cloud and aerosol lidar observation at Atmospheric Radiation Measurement Program sites: Instruments and data processing. *J. Atmos. Oceanic Tech.*, **19**, 431-442, 2002.

Campbell, J. R., E. J. Welton, J. D. Spinhirne, Q. Ji, S. -C. Tsay, M. Barenbrug, S. J. Piketh, and B. N. Holben, Micro pulse lidar observations of tropospheric aerosols over northeastern South Africa during the ARREX and SAFARI-2000 dry season experiments, *J. Geophys. Res.,* accepted, 2003

Clough, S.A., M. J. Iacono, and J. L. Moncet, Line-by-line calculations of atmospheric fluxes and cooling rates: Application to water vapor. *J. Geophys. Res.*, **97**, 15,761-15,785, 1992.

S. Cohen, J. Degnan, J. Bufton, J. Garvin, and J. Abshire, The Geoscience Laser Altimetry/ranging System. *IEEE Trans. Geoscience Remote Sensing*, **GE-25**, pp. 581-592, 1987.

Dover, S.E., *Numerical modeling of blowing snow.* Ph.D. Thesis. Univ. Leeds, 237 pp., 1993.

Gosink, J.P., The extension of a density current model of katabatic winds to include the effects of blowing snow and sublimation. *Bound.-Layer Meteor.*, **49**, 367-394, 1989.

Harder, S. L., S. G. Warren, R. J. Charlson, and D. S. Covert, Filtering of air through snow as a mechanism for aerosol deposition to the Antarctic ice sheet. *J. Geophys. Res.* **101,** 18,729–18,744, 1996.

Holmes, R.E., C.R. Stearns, G.A. Weidner, and L.M. Keller, Utilization of Automatic Weather Station Data for Forecasting High Wind Speeds at Pegasus Runway, Antarctica. *Weather and Forecasting,* **15,** 137-151, 2000.

King, J.C. and J. Turner, Antarctic Meteorology and Climatology. Cambridge Univ. Press, New York, 409 pp., 1997.

Kodama, Y., G. Wendler, and J. Gosink, The effect of blowing snow on katabatic winds in Antarctica. *Ann. of Glaciology,* **6,** 59-62, 1985.

Li, L., and J. W. Pomeroy, Estimates of Threshold Wind Speeds for Snow Transport Using Meteorological Data. *J. App. Meteor.,* **36,** 205-213, 1997.

Mahesh, A, *Ground-based infrared remote sensing of cloud properties over the Antarctic plateau.* Ph.D. thesis. University of Washington. 134 pp., 1999.

Mahesh, A, J. D. Spinhirne, D. P. Duda, and E. W. Eloranta, Atmospheric multiple scattering effects on GLAS altimetry. Part II: Analysis of expected errors in Antarctic altitude measurements. *IEEE Transactions in Geoscience and Remote Sensing,* 2002,in press.

Manabe, S., and R. J. Stouffer, A CO_2-climate sensitivity study with a mathematical model of the global climate. *Nature,* **282,** 491-493, 1979.

Mann, G.W., P. S. Anderson, S.D. Mobbs, Profile Measurements of blowing snow at Halley, Antarctica. *J. Geophys. Res.,* **105,** 24491-24508, 2000.

Mather, K. B., and G. S. Miller, Notes on topographic factors affecting the surface wind in Antarctica, with special reference to katabatic winds; and bibliography. *Univ. Alaska Tech. Report* UAG-R-189; 125 pp., 1967.

Pomeroy, J. W., and D. H. Male, Optical properties of blowing snow. *J Glaciology*, **34**, 3-10, 1988.

Schmidt, R.A., Threshold wind speeds and elastic impact in snow transport. *J. Glaciology.*, **26**, 453-467, 1980.

Schmidt, R. A., Properties of blowing snow. *Rev. Geophys.*, **20**, 39-44, 1982.

Schwerdtfeger, W., *Weather and Climate of the Antarctic*, Elsevier Sci., New York, 1984.

Spinhirne, J. D., Micro pulse lidar. *IEEE Trans. Geosci. Remote Sens.*, **31**, 48-55, 1993.

Stamnes, K., S-C. Tsay, W. Wiscombe and K. Jayaweera, A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, *Appl. Opt.* **27**, 2502-2509, 1988.

Vaughan, D. G., and C. S. M. Doake, Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature*, **379**, 328-331, 1996.

Walden, V.P., and S.G. Warren, Atmospheric longwave radiation spectrum and near-surface atmospheric temperature profiles at South Pole Station, *Antarct. J. U.S.,* **28(5),** 269-271, 1994.

Walden, V.P., S. G. Warren, J. D. Spinhirne, A. Heymsfield, R. E. Brandt, P. Rowe, M. S. Town, S. Hudson, and R. M. Jones, The South Pole Atmospheric Radiation and Cloud Lidar Experiment (SPARCLE). In *Proceedings of the Sixth Conference on Polar Meteorology and Oceanography, American Meteor.* Soc., San Diego, CA, 297-299, 2001.

Wendler, G., J.C. Andre, P. Pettre, J. Gosink, and T. Parrish, Katabatic winds in Adelie Coast. In: *Antarctic Research Series, Volume 61, Antarctic Meteorology and Climatology: Studies based on Automatic Weather Stations.* D.H. Bromwich and C.R. Stearns, editors. American Geophysical Union, Washington, pp. 23-46, 1993.

Yamanouchi, T., K. Suzuki, and S. Kawaguchi, Detection of clouds in Antarctica from infrared multi-spectral data of AVHRR. *J. Met. Soc. Japan*, **65**, 949-962, 1987.

List of Figures

Figure 6. Typical lidar observation from South Pole. A full day's data (Feb 17, 2000) is shown; the backscatter peak at 48.9, corresponding to 2136 UTC indicates blowing snow in the near-surface layer

Figure 7: Backscatter profile from lidar observation of June 24, 2000; the contribution from molecular scattering alone is also shown.

Figure 8. Distribution of blowing snow layer thickness obtained from near-horizon looking lidar backscatter profiles, 2000-2002.

Figure 9. 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.

Figure 10. Window radiances from clear-sky (solid) and under blowing snow (dotted) from 15 October 1992, at a viewing zenith 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.

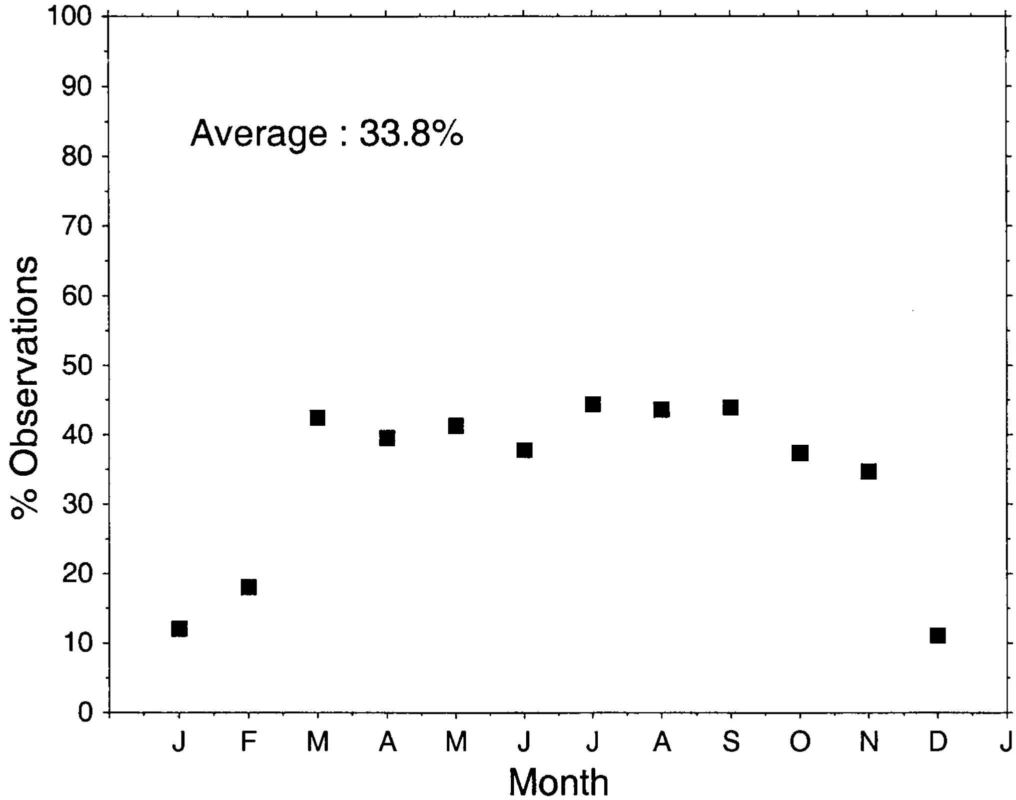

100
90
80
70
60
50
40
30
20
10
0
% Observations
Average : 33.8%
J F M A M J J A S O N D J
Month

Figure 1

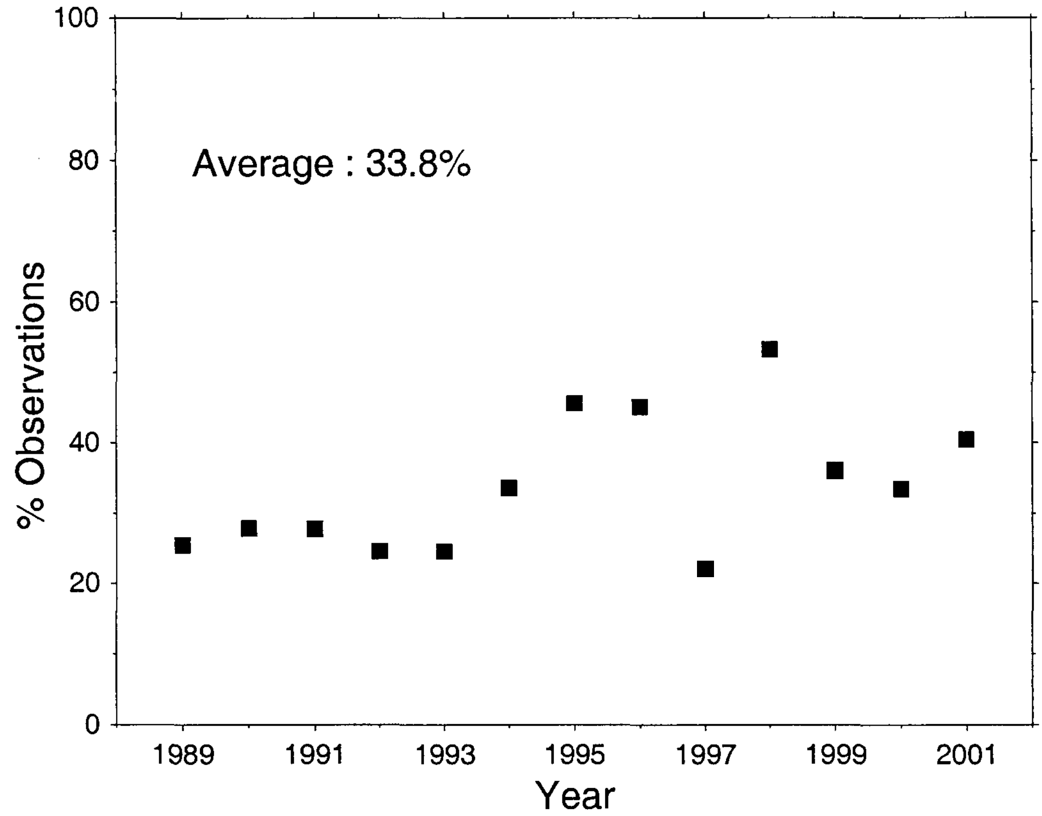
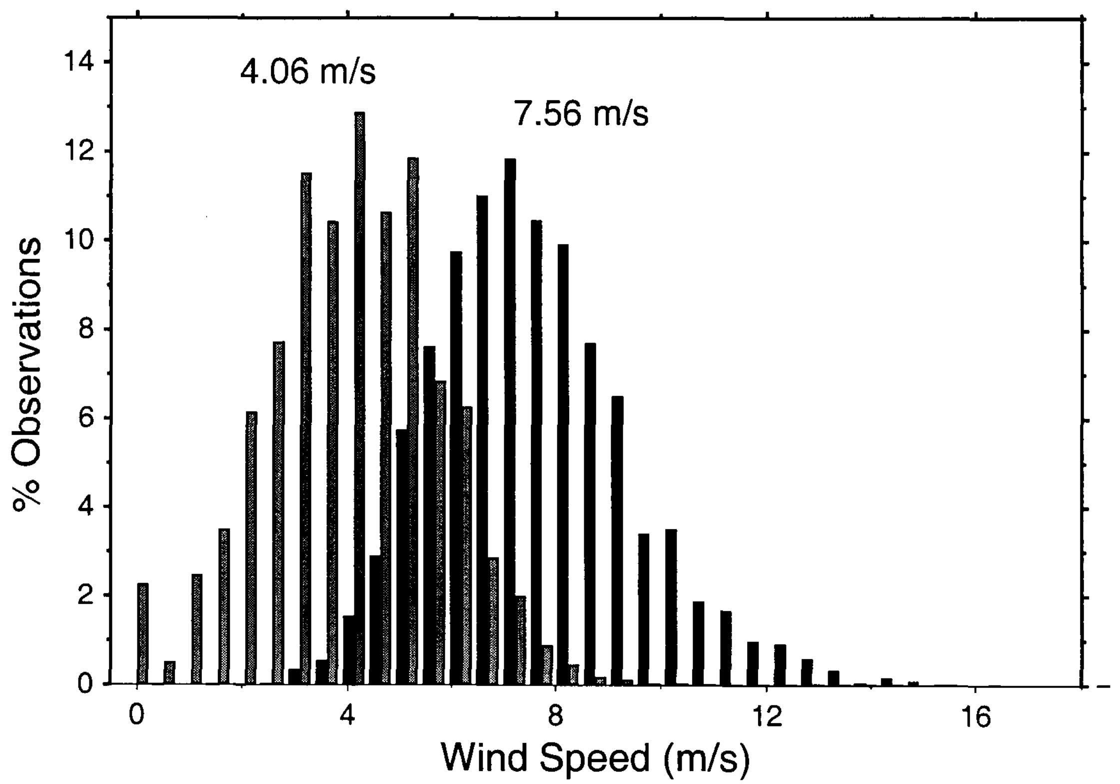
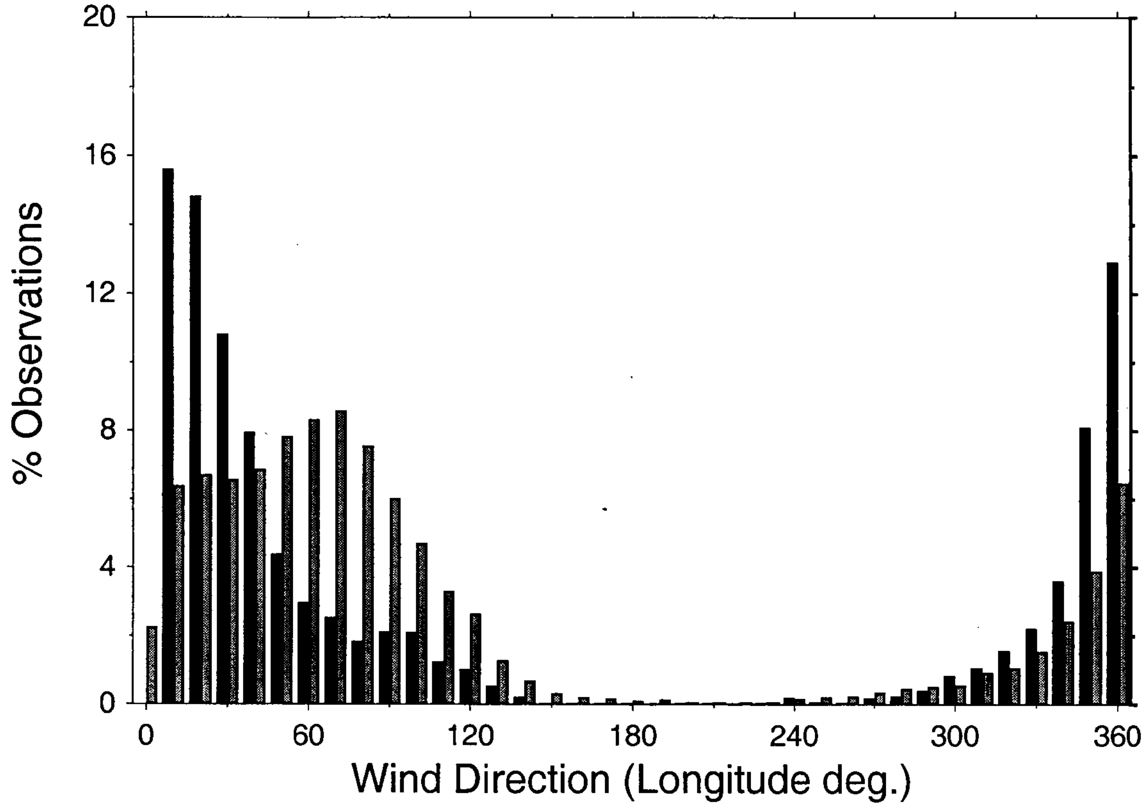

100
80
60
40
20
0
Average : 33.8%
% Observations
1989
1991
1993
1995
1997
1999
2001
Year

Figure 2



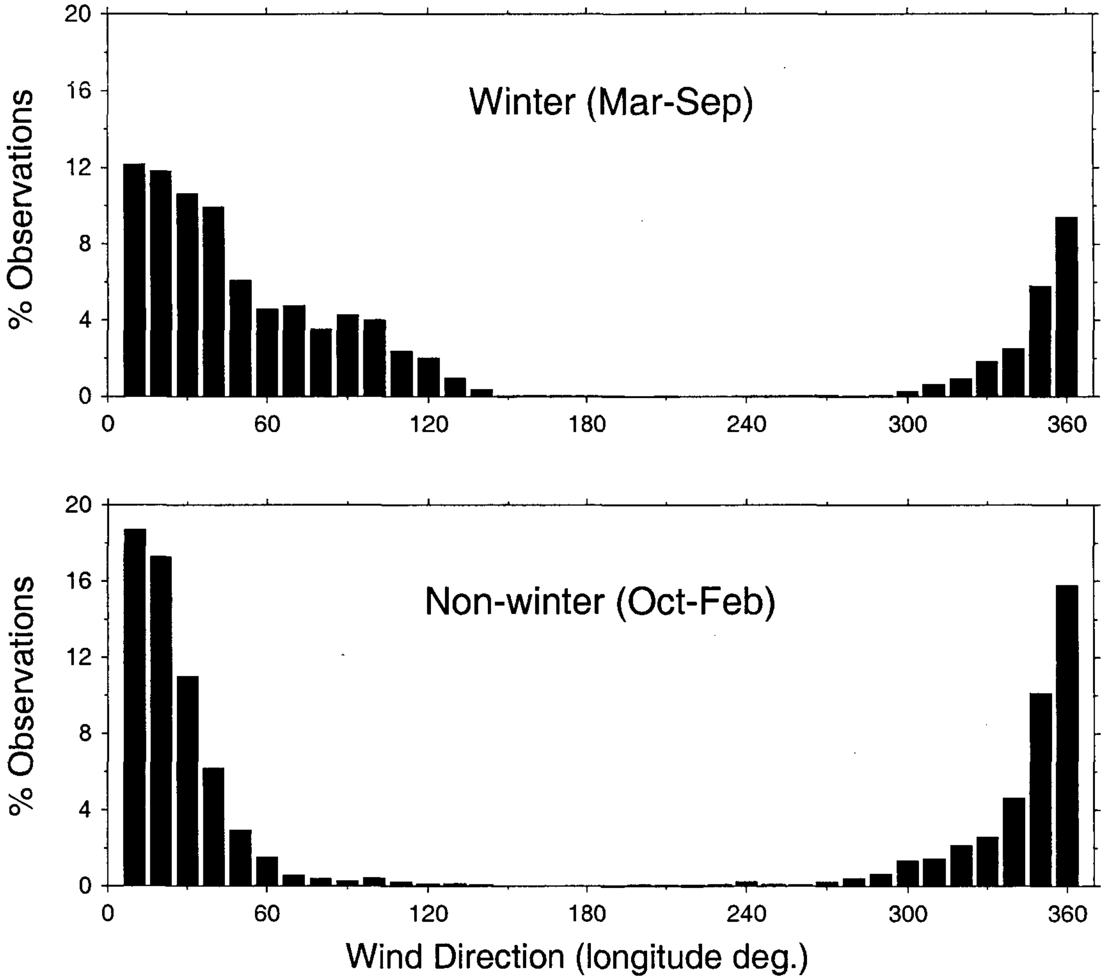
4.06 m/s
7.56 m/s
% Observations
Wind Speed (m/s)
0
2
4
6
8
10
12
14
0
4
8
12
16

Figure 3



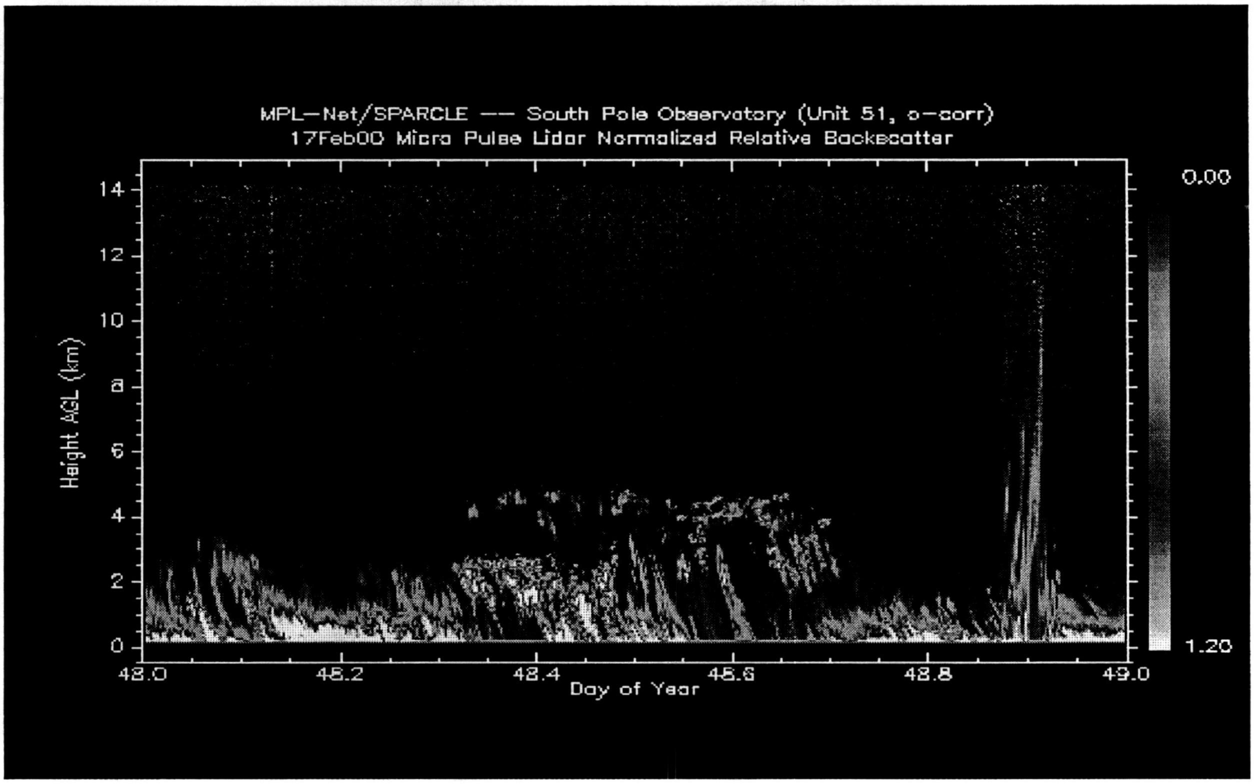
20
16
12
8
4
0
% Observations
0
60
120
180
240
300
360
Wind Direction (Longitude deg.)

Figure 4



Winter (Mar-Sep)
% Observations
20
16
12
8
4
0
0
60
120
180
240
300
360
Non-winter (Oct-Feb)
% Observations
20
16
12
8
4
0
0
60
120
180
240
300
360
Wind Direction (longitude deg.)

Figure 5


MPL-Net/SPARCLE -- South Pole Observatory (Unit 51, o-corr)
17Feb00 Micro Pulse Lidar Normalized Relative Backscatter
Height AGL (km)
Day of Year
0.00
1.20
0
2
4
6
8
10
12
14
48.0
48.2
48.4
48.6
48.8
49.0

.

Figure 6

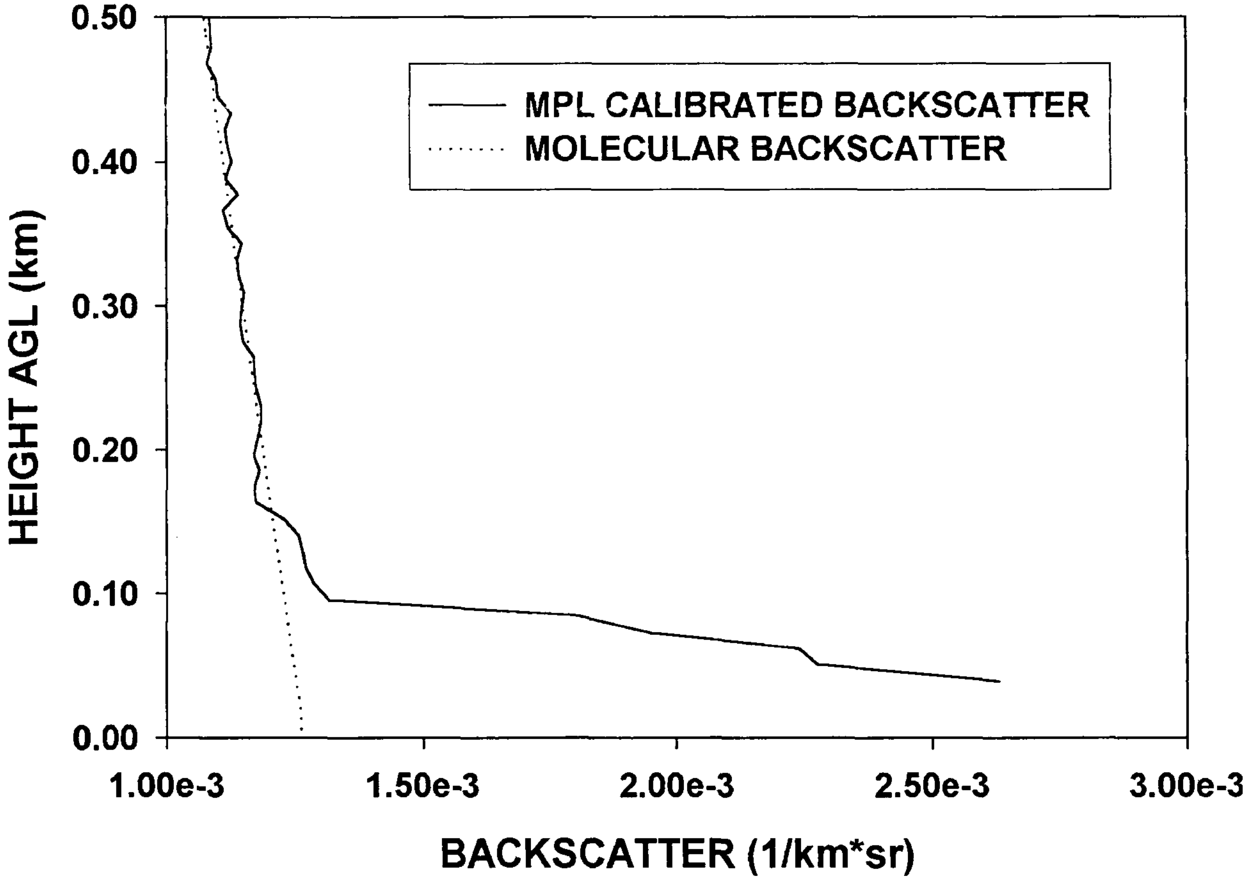

0.50
0.40
0.30
0.20
0.10
0.00
HEIGHT AGL (km)
MPL CALIBRATED BACKSCATTER
MOLECULAR BACKSCATTER
1.00e-3
1.50e-3
2.00e-3
2.50e-3
3.00e-3
BACKSCATTER (1/km*sr)

Figure 7

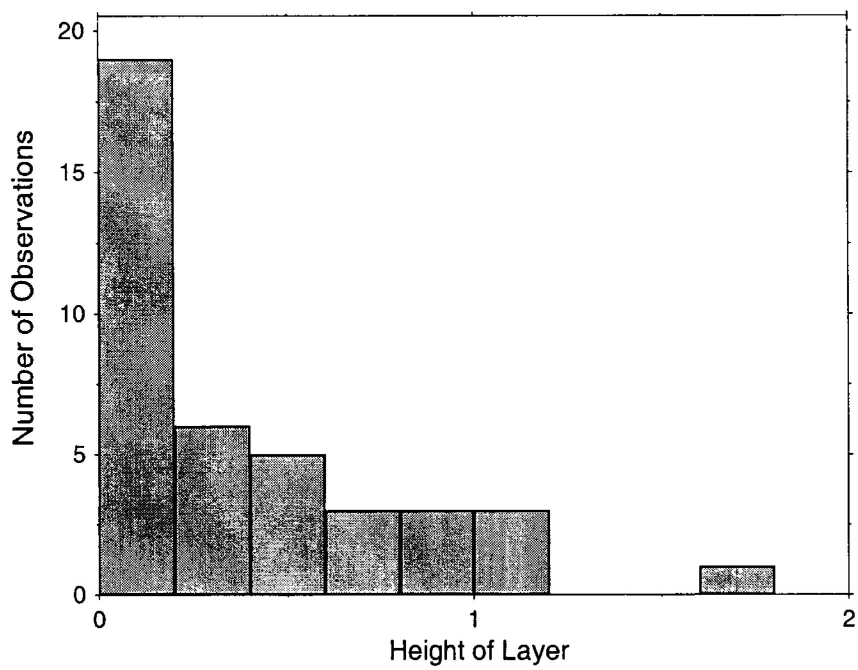


Figure 8

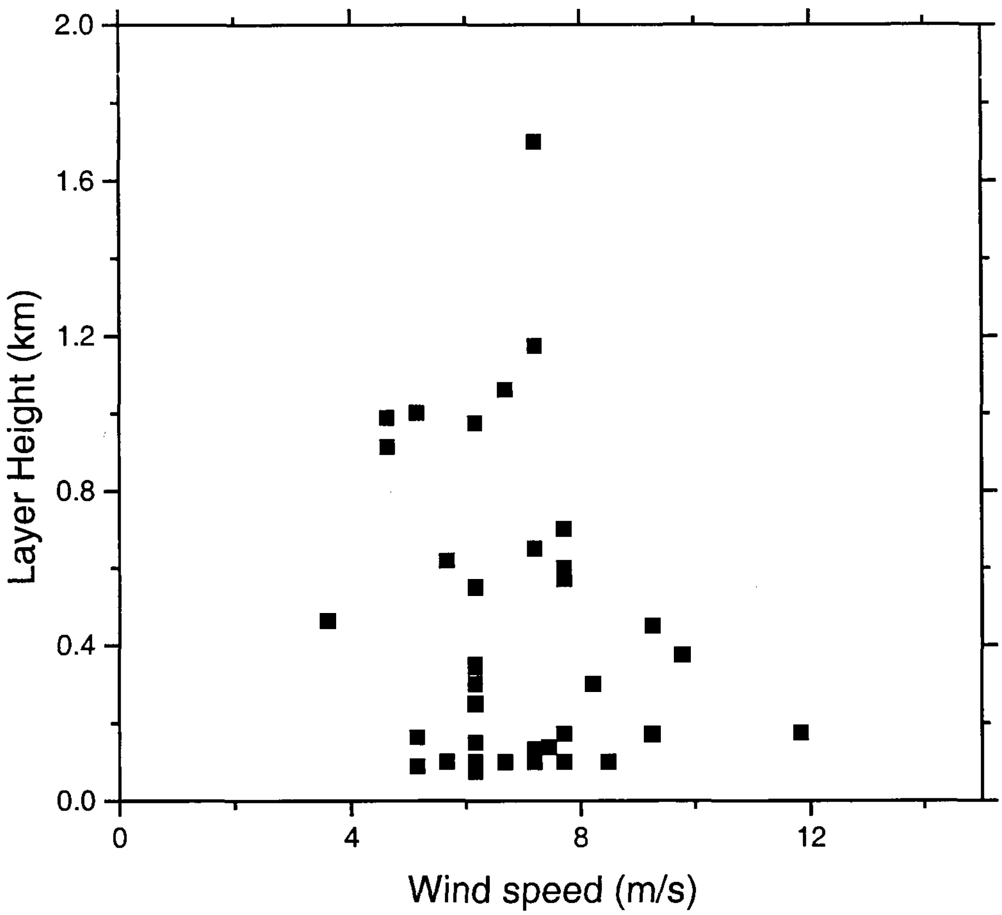


Figure 9

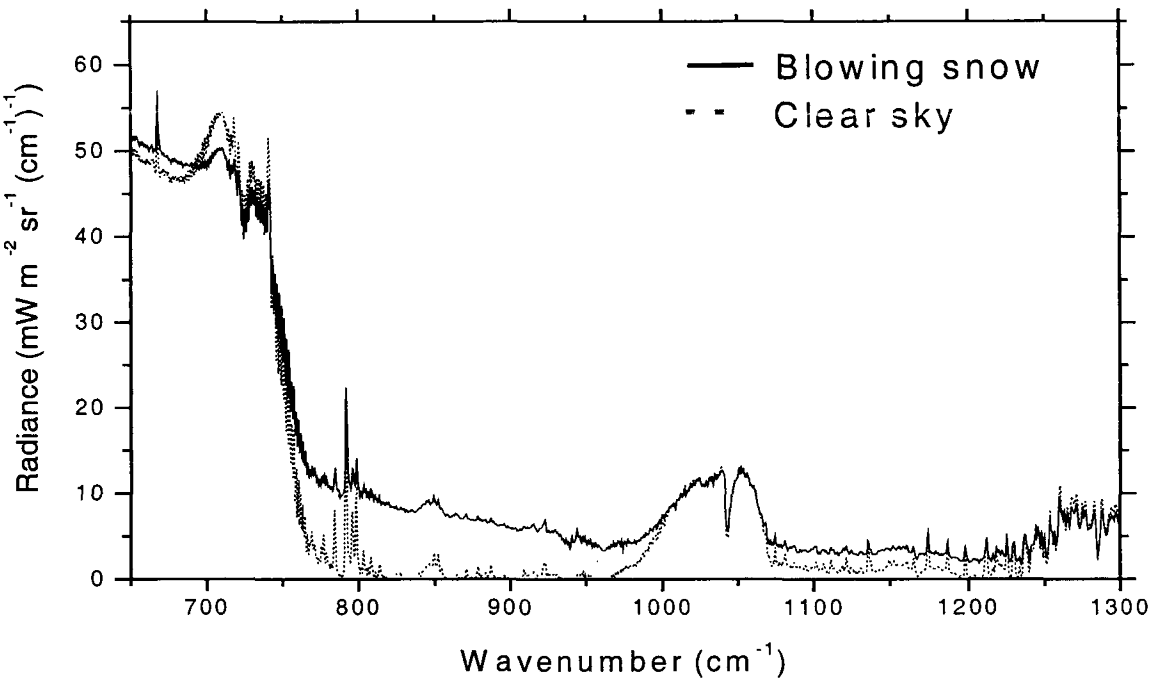

Blowing snow
Clear sky
Radiance (mW m^{-2} sr^{-1} (cm^{-1})$^{-1}$)
Wavenumber (cm^{-1})
0
10
20
30
40
50
60
700
800
900
1000
1100
1200
1300

Figure 10