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Direct measurements of episodic snow accumulation on the Antarctic polar plateau

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Abstract. During a 1-year field experiment at a remote location on the Antarctic polar plateau (85.67°S, 46.38°W) influenced by moderate magnitude katabatic winds, snow accumulation was characterized at three different spatial and temporal scales using snow stakes, tracer material dispersed periodically on the snow surface, and an acoustic depth gauge. The spatial variability of snow accumulation was found to be large, on both annual and intra-annual timescales, and is attributed to the high frequency of moderate to strong winds at the site. Accumulation throughout the year was observed to be episodic in nature, with a small number of snow accumulation events producing the majority of the annual total accumulation for the site, averaging 0.174 m. In the intervals between observed accumulation events (up to several months), negative changes to snow surface height caused by sublimation and densification of the firn were quantified using an acoustic depth gauge. The rate of decrease in snow surface elevation was largest during the austral summer, as expected, and the overall change in snow surface elevation due to sublimation/densification during the year was estimated to be about -0.10 m. Using the precise timing of accumulation events provided by the acoustic depth gauge, meteorological surface observations, numerical model analyses, and satellite imagery were used to gain insights into whether the event was associated with precipitation or related exclusively to blowing snow and to diagnose the meteorological conditions producing the event. Meteorological conditions during the accumulation events were found to strongly support an association with precipitation events caused by mesoscale or synoptic-scale cyclones along the coastal margin. Dating of the accumulation profile using the dispersed tracer technique identified several other accumulation events that were not measured within the target area of the acoustic depth gauge, suggesting that snow accumulation data from a single acoustic depth gauge cannot be extrapolated over a broad area.

1. Introduction

Antarctica plays an important role in the Earth's climate system [*Simmons and Wu*, 1993] by its influence on the energy balance dynamics of the planet and by strongly influencing the dynamics of the atmosphere and oceans. Antarctica also stores more than 90% of the land-based ice and could play a major role in global sea level variations if the overall ice sheet mass balance were to change. Efforts to evaluate whether polar ice sheets are currently growing or shrinking have used both a modeling approach and direct measurements. Using standard products available from the international weather centers, *Giovinetto et al.* [1997], *Bromwich et al.* [1995], and *Budd et al.* [1995] have developed techniques to calculate net moisture flux to the Antarctic continent. *Noone et al.* [1999] used European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data to examine the precipitation characteristics in the interior of Antarctica and found that a large fraction of the snow accumulation comes from a relatively small number of precipitation events. Remote sensing techniques that include an aircraft-based laser [*Krabill et al.*, 1995] and radar [*Gogineni et al.*, 1998] altimeter systems have been used to accurately measure the thickness of the Greenland ice sheet over large regions. Recent results from the aircraft-based laser altimeter system have shown stunning decreases in the elevation of the Greenland ice sheet in some locations; however, processes that have caused these changes have yet to be fully understood [*Krabill et al.*, 1999]. The scheduled launch of NASA's Geoscience Laser Altimeter System (GLAS) in July 2001 will provide the research community with an instrumentation system capable of measuring the distance between the spacecraft and the ice sheet within a 70-m-diameter footprint with a precision of better than 10 cm, as well as of characterizing surface roughness. Coverage will extend between 87°N and 87°S, with tracks repeated every 183 days, providing the capability to assess accumulation on a semiannual basis.

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While a long-term, annually averaged ice sheet mass accumulation climatology for Antarctica based on glaciological data is available [*Giovinetto and Bentley*, 1985; and *Vaughan et al.*, 1999], intra-annual snow accumulation information is sparse. The difficulties of obtaining frequent, direct measurements of precipitation amount and snow accumulation in the remote interior regions of Antarctica have long been acknowledged [*Bromwich*, 1988], yet these data are critical in determining whether general circulation models (GCMs) and other numerical techniques are correctly simulating the seasonal forcings that control mass input to the ice sheets. In fact, the relationship between precipitation and accumulation in regions dominated by strong winds is not well understood. In a previous study [*Braaten*, 1997], precipitation observations at McMurdo Station (made by manually recording the intensity and duration of precipitation) were compared with snow surface height changes from an acoustic depth gauge 10 km away on the Ross Ice Shelf. Results showed that most accumulation events were associated with observed precipitation events, but less than half of the precipitation events resulted in a measurable accumulation on the Ross Ice Shelf.

Katabatic winds that dominate the surface wind flow patterns of Antarctica [*Parish*, 1988] and the associated blowing snow present the greatest challenges to both automated and manual observations of snow accumulation and/or precipitation, as well as to obtaining representative measurements of accumulation due to the presence of wind-generated surface features such as dunes and sastrugi. For example, snow collection gauges commonly used in middle latitudes and alpine regions are not favored by Antarctic observing stations because they rapidly fill with blowing snow and are not representative of either the local accumulation or the precipitation received [*Turner et al.*, 1997]. There are also technical constraints in developing instrumentation to measure precipitation and accumulation in a harsh and remote polar environment, such as low power consumption and the ability to operate at extremely low temperatures. Snow accumulation measurements are most commonly made manually using a snow stake array on a relatively flat surface of the ice sheet well removed from obstacles. Intra-annual snow accumulation measurements from snow stakes are only available from stations with a year-round staff such as Amundson-Scott South Pole Station. Here meteorological staff take monthly snow height measurements from an array of 50 snow stakes over an area of ~3000 m^2. A subset of these data has been analyzed by *McConnell et al.* [1997] for seasonal variability of accumulation rate, and these results have shown a seasonal accumulation preference. Frequent manual snow stake measurements can produce erroneous accumulation results, however. In a 1-year winter-over study at Byrd station (80.02°S, 119.53°W), *Budd et al.* [1966] made frequent manual snow accumulation measurements at a snow stake field, but these measurements raised suspicions of an accumulation bias caused by walking on the snow surface. It was observed by station personnel that soft snow compacted into footprints remained after the surrounding snow had been removed by wind action, producing an unnatural sastrugi that interfered with the natural behavior of the accumulation area.

Using several different methods to measure snow accumulation at different temporal and spatial scales, the present paper describes the results from a 1-year investigation at an unmanned research platform on the Antarctic polar plateau. In addition to identifying individual accumulation events, data from this experiment have allowed characterization of spatial accumulation variability and have quantified the rate of change in snow surface height resulting from sublimation and densification of the firn.

2. Experimental Design

The objective of this experiment was to obtain a detailed temporal and spatial characterization of snow accumulation at Automatic Geophysical Observatory P2 (AGO-2), located at 85.67°S, 46.38°W (elevation 1860 m) on the polar plateau

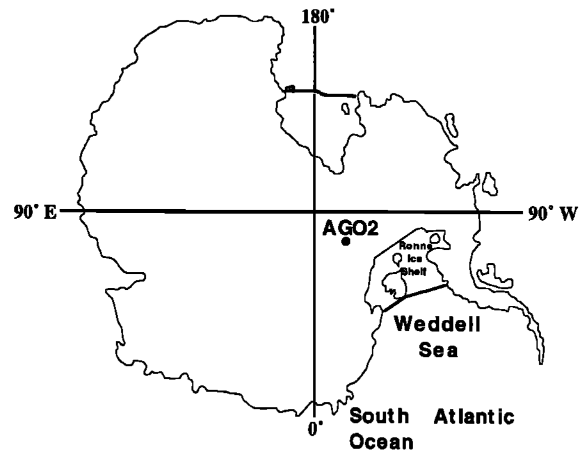

Figure 1. Map of Antarctica showing the location of Automatic Geophysical Observatory P2 (AGO-2).

(Figure 1), and was carried out between November 1996 and November 1997. AGO-2 is an unmanned facility of dimensions 4.9 x 2.4 x 2.4 m and is positioned ~2 m above the snow surface on struts. AGO-2 is one of six facilities supporting scientific experiments at remote Antarctic sites by providing power, data acquisition, heat, and shelter to operate instrumentation that would not otherwise survive in the ambient environment. AGO-2 is visited once annually for maintenance and refueling, and it was during these visits that field work for this experiment was carried out.

The snow accumulation study site at AGO-2 was located ~30 m from the facility (Figure 2) in a direction approximately perpendicular to the prevailing wind direction. While annual accumulation in the region surrounding AGO-2 was found to be highly variable, the accumulation characteristics of the study site described in this investigation were not unusual or adversely influenced by its proximity to the AGO facility. This conclusion is based on both snow stake measurements and a visible snow pit stratigraphy comparison at the accumulation study site and at a location ~250 m upwind from AGO-2 (D. Voigt, personal communication, 1997). Snow pits at the two widely separated locations showed remarkable agreement in the location of crust layers and the first hoar frost layer, providing confidence that the physical presence of the AGO-2 facility did not have a significant influence on the snow accumulation characteristics of the study site.

Snow accumulation was characterized using three different methods, each representing different spatial scales and providing different temporal resolution. These methods included linear snow stake arrays, the use of tracer material dispersed on the snow surface that allowed later dating of accumulation layers, and frequent measurement of the snow surface elevation using an acoustic depth gauge. In addition, meteorological parameters were measured by the AGO-2 facility, which included wind speed, wind direction, temperature, and barometric pressure.

2.1. Snow Stake Method

Snow stake lines were surveyed at the start and finish of the experiment to characterize annual variability of snow accumulation over a broad area. What is lacking in these data is any information about the actual accumulation processes

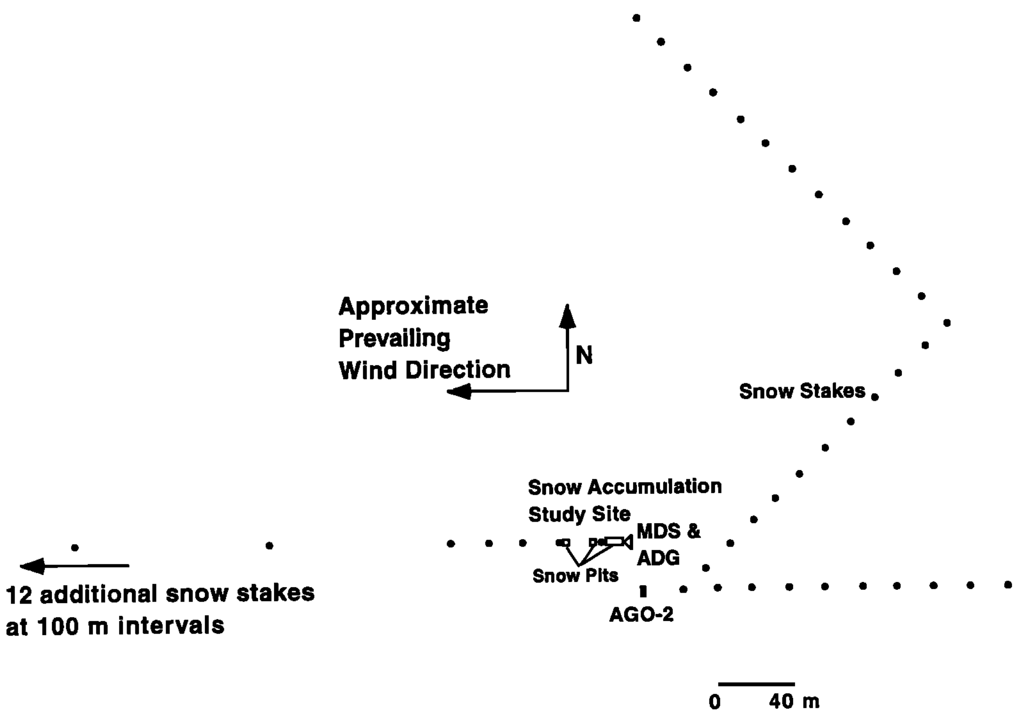

Figure 2. Site map showing the locations of snow stakes, the microsphere dispersal system (MDS), the acoustic depth gauge (ADG), and snow pits in relation to the AGO-2 facility.

that occurred throughout the year. Five linear snow stake lines totaling 53 bamboo poles were surveyed, with height above the snow measured from the top of each pole to the surface within ~0.30 cm. The difference between the measured heights at the start and finish of the study period give the snow accumulation at the stake location. The dots on the site map in Figure 2 indicate the locations of the snow stakes relative to AGO-2. Three of the snow stake lines were aligned along the prevailing wind direction: Line 1 consisted of 14 snow stakes over a distance of 1300 m starting 200 m downwind of the snow accumulation site; line 2 consisted of 10 snow stakes over an upwind distance of 180 m beginning 40 m upwind from the AGO facility; and line 3 has five snow stakes beginning at the snow accumulation study site and continuing for 85 m in the downwind direction. Two snow stake lines were aligned at a 45° diagonal from the prevailing wind direction: Line 4 has 12 snow stakes starting 20 m upwind from the AGO facility and continuing for 210 m, and line 5 has 12 snow stakes and extends for 230 m at a 90° angle from the end of line 4. Table 1 gives the annual accumulation observed at each snow stake as well as the mean and standard error for each snow stake line. The mean snow accumulation for all snow stakes is 0.174 ±0.022 m, with a maximum accumulation of 0.565 m and a minimum of –0.099 m.

Table 1. Annual Accumulation Measured at AGO-2 Snow Stakes

Line 1		Line 2		Line 3		Line 4		Line 5	
Distance[a]	Accumulation	Distance[b]	Accumulation	Distance[a]	Accumulation	Distance[b]	Accumulation	Distance[b]	Accumulation
200	0.034	40	0.152	15	0.102	20	0.038	238	0.092
300	0.341	60	0.371	40	0.171	39	0.121	246	-0.001
400	0.235	80	0.273	60	0.445	58	0.031	254	0.159
500	0.286	100	0.207	80	0.425	77	0.178	262	0.235
600	0.076	120	0.321	100	0.184	96	-0.044	270	0.337
700	-0.010	140	0.190			116	0.159	278	0.146
800	0.565	160	0.136			135	0.257	285	-0.099
900	0.261	180	0.028			154	0.530	293	0.064
1000	0.143	200	-0.006			173	0.375	301	0.121
1100	0.008	220	0.025			192	0.368	309	0.114
1200	0.096					211	0.213	317	-0.076
1300	0.149					230	0.565	325	0.073
1400	0.034								
1500	0.027								
Mean	0.160±.043	Mean	0.170±.041	Mean	0.265±.071	Mean	0.233±.056	Mean	0.097±.035

Both distance and accumulation are given in meters.
[a] Distance from snow accumulation study site.
[b] Distance from AGO facility.

Assuming a mean density of the annual accumulation layer of 0.45 g cm^{-3}, this gives an average water equivalent accumulation of 0.078 m. This is in good agreement with the long-term climatological mean values derived from glaciological data by *Giovinetto and Bentley* [1985] and a more recent assessment by *Vaughan et al.* [1999] using passive microwave observations as well as in situ data. It is clear from these results that the spatial variability of the annual accumulation at this site is large, and there does not appear to be an accumulation bias in the vicinity of the AGO facility.

2.2. Microsphere Tracer Method

To characterize snow accumulation with much higher time resolution than the snow stake method but representative of a more limited area, an automated device called the microsphere dispersal system (MDS) [*Braaten and Ratzlaff*, 1998] was used in this experiment. The operating principle of MDS is the automatic dispersal of inert, colored (high albedo) glass microspheres onto the snow surface to act as a time marker and tracer to allow the accumulation rate over an extended area to be quantified with a high temporal resolution. MDS consists of three aerosol generator units mounted on aerodynamic masts and a pneumatic system located inside the AGO-2 facility controlled by a microcontroller-based timing system to activate the aerosol generators and disperse the microspheres. Microsphere dispersal was programmed to activate every 14 days for 10 s. During each activation, high-velocity air (~100 m s^{-1}) with a volumetric flow rate of ~1.7 x 10^{-3} m^3 s^{-1} from a regulated N_2 cylinder entered a chamber of each of the three aerosol generator units, aerosolized the microspheres located in the lower half of the chamber, and exited through the round outlet nozzle, dispersing a total of ~75 mL of the inert, colored microspheres (~5x10^7 microspheres) during the 10-s activation from a height of ~1.2 m onto a snow surface area of ~100 m^2. The microspheres are solid, with a median diameter of 120 μm and a density of 2.5 x 10^3 kg m^{-3}, and had a terminal settling speed of 0.9 m s^{-1} (similar to the less dense, but generally larger snow grains), resulting in a rapid fallout of the microspheres to the snow surface. Four different microsphere colors were used throughout the 12-month deployment (pink, purple, red, and brown), with each microsphere color dispersed during successive 14-day periods shown in Table 2. Hence any given microsphere color is dispersed in a 56-day cycle.

While on the snow surface, it was possible for the microsphere tracer to be spread over a much larger area by strong winds, and microspheres were identified in snow cores extracted as far as 1400 m downwind from AGO-2. As snow accumulates after the activation, however, the microspheres are entombed as thin horizons in the firn. The horizontal and depth distribution of microsphere horizons and vertical snow density profiles were determined by snow pit sampling and subsequent laboratory analysis of the snow samples. Although it was uncommon to visually observe a microsphere horizon in a snow pit because of typically very small microsphere concentrations, one horizon in two different snow pits was visually observed.

All sampling and analyses were conducted in November 1997. After excavating a snow pit ~0.8 m in depth, snow slab samples were removed from a snow pit wall oriented along the

Table 2. Microsphere Dispersal System Activation Schedule Showing the Say of Activation Starting in 1996 and Ending in 1997, the Color of Microspheres Dispersed, and the Depth at Which Microspheres Were Recovered

Dispersal,	Microsphere	Mean Depth of Identified Microspheres cm					
Julian Day	Color	5-m Pit	7-m Pit	10-m Pit	12-m Pit	13-m Pit	20-m Pit
337	pink						
351	purple		46.9	40.9	44.6		
365	red						
13	brown	47.6	46.9				
27	pink			36.9			
41	purple	41.6	40.9		40.3		
55	red		36.9				
69	brown	37.6			36.3		
83	pink						
97	purple				36.3		29.8
111	red	32.2		23.4			27.0
125	brown	32.2		23.4	30.5		26.3
139	pink	28.1	23.1	23.4	30.5	30.9	26.3
153	purple	28.1		23.4			
167	red						22.5
181	brown	23.8				26.7	
195	pink					26.7	
209	purple				26.5	22.4	
223	red				26.5	22.4	
237	brown	14.8					12.0
251	pink			10.0		18.4	
265	purple	14.8			22.5		
279	red		6.0				
293	brown						6.0
307	pink				2.0		2.0
321	purple						

Mean wind speeds during microsphere-identified dispersals are as follows: 5-m pit, 6.2 m s^{-1}; 7-m pit, 5.6 m s^{-1}; 10-m pit, 6.4, m s^{-1}; 12-m pit, 7.8 m s^{-1}; 13-m pit, 8.2 m s^{-1}; and 20-m pit, 7.8 m s^{-1}.

prevailing wind direction. The dimensions of the snow slab samples were ~0.17 x 0.17 x 0.07 m (0.002 m^3), and after removal, these samples were placed into a plastic container for transport. The container was kept frozen in an insulated ice core box during transport back to McMurdo Station. Microsphere horizons in each snow pit were identified by slicing each snow slab sample horizontally into four sections, each representing a depth thickness of ~0.04 m. The sample was allowed to melt, the meltwater was filtered, and the filter medium was analyzed for microspheres using visual microscopy, noting the number and color of microspheres present, if any. Using these procedures, it was routine to identify a single microsphere in any given snow sample.

In all, eight snow pits located 5, 7, 10, 12, 13, 15, 20, and 40 m from the microsphere generators in the prevailing downwind direction were sampled. A total of 20 snow slabs were returned from the field, and these were divided into 80 sections, providing a depth resolution of ~0.04 m. Of the 80 snow samples analyzed, microspheres were identified in 42 samples. Using the microsphere activation schedule given in Table 2, the identified microsphere horizons were assigned dates, allowing the accumulation periods to be reconstructed chronologically at six of the eight snow pits. Two snow pits, located 15 and 40 m from the microsphere generators, were excluded from this analysis due to the small number of horizons identified (three and two, respectively), which resulted in large horizon dating uncertainties. Table 2 provides a summary of the depth at which each individual microsphere horizon was found in the six analyzed snow pits. The uncertainty in the depth of the microsphere horizons is generally ±0.02 m. This is the case for both microsphere horizons found in a single analysis section and for the small number of horizons found in two adjacent sections, which were attributed to a sloping snow surface at the time of deposition. Several crust layers visually observed in the snow pits showed a degree of curvature that could cause a microsphere horizon (if associated with the crust layer) to be identified in two adjacent analysis sections. Of the 26 microsphere dispersal events that occurred during the 12-month period, 22 were accounted for in one or more of the six snow pits. Microspheres from the four dispersal periods not identified were either dispersed in areas that were not sampled or were eroded by wind action. Table 2 also gives the mean wind speed during identified dispersal events for each snow pit. As expected, the mean wind speeds associated with the microsphere dispersal events identified in the three snow pits closest to the microsphere generators were lower than the mean wind speeds of the dispersal events of microspheres identified in snow pits farther downwind.

A snow density profile was also determined for each snow pit, and these measurements were used to transform observed snow depth accumulation zones into water equivalent accumulation. The overall mean density for all snow pits was 0.45×10^3 kg m^{-3}. A typical density profile is shown in Figure 3 for the snow pit located 7 m from the microsphere generators. The mean density of this profile was 0.45×10^3 kg m^{-3}. For each snow accumulation zone located between two identified microsphere horizons or between a microsphere horizon and the surface, the mean density of the zone is calculated and the mean snow density to water density ratio is multiplied by the depth of the accumulation zone to determine the water equivalent (w.e.) accumulation, in meters. The w.e. accumulation therefore represents one or more accumulation events that occurred between the time the lower microsphere horizon was deposited and the time the upper horizon was deposited (or the end of the study period). The minimum uncertainty in dating these events is ±7 days, which is due to the microsphere activation schedule; the maximum time uncertainty was ±70 days for the 7-m pit during the winter season and into the spring. The mean time uncertainty for all accumulation zones was ±23.9 days.

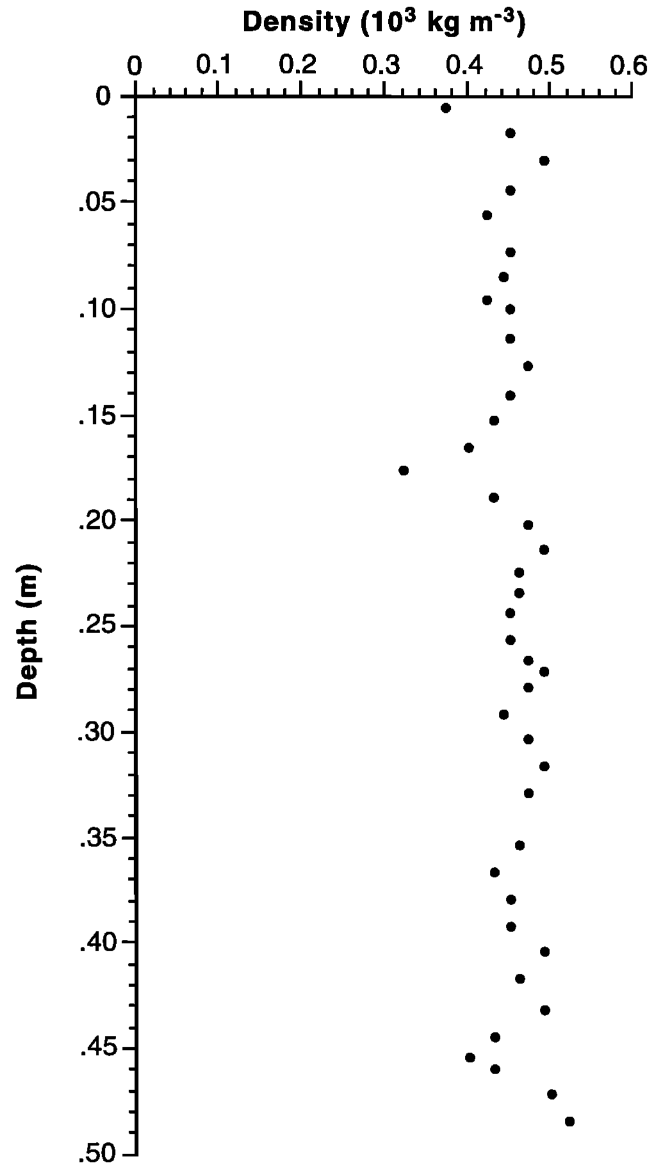

Figure 3. Measured snow density profile for the snow pit located 7 m downwind from the microsphere generators.

Figure 4 shows the w.e. accumulation time series derived from dated microsphere horizons identified in the six snow pits analyzed. A total of 33 dated accumulation zones were determined from the identified microsphere horizons given in Table 2. The horizontal bars in Figure 4 show the time period and the cumulative w.e. accumulation that was deposited during one or more events that occurred during this period. Because of the analysis technique used, the uncertainty of these w.e. accumulation measurements is ±0.009 m. The symbol identifies the snow pit location and the midpoint of the time period. From these data, two distinct accumulation patterns

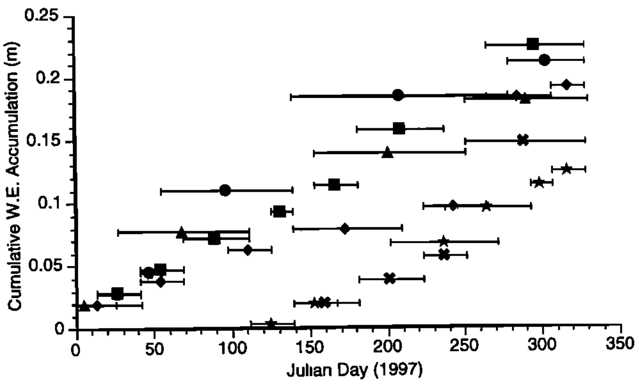

Figure 4. Cumulative water equivalent accumulation time series from dated microsphere horizons identified in each of six snow pits analyzed. Horizontal bars indicate the uncertainty in the timing of one or more accumulation events producing the mass input. Symbols identify the snow pit location in distance from the microsphere generators as follows: squares, 5-m pit; circles, 7-m pit; triangles, 10-m pit; diamonds, 12-m pit; crosses, 13-m pit; and stars, 20-m pit. The uncertainty in the water equivalent accumulation was about ±0.009 m.

emerge for the snow accumulation study area. The four snow pits closest to the microsphere generators (the 5-, 7-, 10-, and 12-m pits) displayed a similar accumulation pattern throughout the year, with a total annual w.e. accumulation ranging from 0.18 to 0.22 m. Despite the large uncertainty in dating a few of the events, the bulk of the accumulation at these locations occurred late summer to early fall and late winter to early spring. The accumulation amount among the individual snow pits also varied from event to event. An interesting example is the accumulation pattern of the 12-m pit, which lagged behind the accumulation amounts at snow pit locations closer to the microsphere generators for most of the study period and then experienced at least one large accumulation event during the spring season. This input made up for the initial deficit and brought the annual accumulation for the study period at this location within the range of snow pit locations closest to the microsphere generators. This accumulation pattern is not unusual for a windswept site and could be explained by the formation of a local trough and later filling of the trough by drift-snow transport [*Takeuchi*, 1980].

The second accumulation pattern was identified at the 13- and 20-m-pit locations and was characterized by smaller annual accumulation, with a notable absence of significant accumulation during the summer season, which was in contrast to locations closer to the microsphere generators. This again can be attributed to wind action on the snow surface soon after precipitation events. For the remainder of the study period, accumulation amounts are seen in Figure 4 to be comparable to the other four snow pit locations, but owing to the lack of early season accumulation these locations end the study period with a relative accumulation deficit.

2.3 Acoustic Depth Gauge

The third technique used to characterize snow accumulation relied on a Campbell Scientific, Inc., SR50 acoustic depth gauge (ADG) to obtain frequent (30 min) and accurate (±0.01 m) measurements of snow surface height. Of the three techniques used in this investigation to characterize snow accumulation, this technique had the best time resolution but the smallest spatial representation, sampling snow height changes within an area of only ~0.14 m^2 within its field of view of 22° and from its initial position ~1.1 m above the snow surface. All ADG snow surface height measurements (corrected for temperature changes) were collected and stored independent of the AGO-2 data acquisition system by a CR10 data logger with a SM192 data storage module. In addition to identifying the time of occurrence and the increase in snow surface elevation due to episodic snow accumulation events, the ADG provided detailed information on negative snow surface height changes due to densification and sublimation. The ADG operated reliably to ambient temperatures of -40° to -45°C, but at lower temperatures the sensor significantly underestimated the distance between the probe and the snow surface due to temperature limitations of the ADG sensor components. At AGO-2, approximately 36% of the 30-min ADG measurements were invalid. However, during most of the study period the invalid data were intermittent and interspersed with valid snow height measurements. The ADG data set contained only two periods longer than a few days without any valid measurements. During these periods, changes to snow surface height could not be determined and were from May 23 to June 21, 1997 (Julian days 143-172), and from September 1 to 22, 1997 (Julian days 244-265). At least one accumulation event occurred during the first missing data period.

The ADG results during the study period show that the snow accumulation process at this site is episodic, with most of the annual accumulation being associated with only five events. While it is likely that other precipitation events are occurring periodically (e.g., clear-sky precipitation), it is not possible to quantify the frequency of occurrence or magnitude of these inputs due to snow transport by winds and resolution limitations of the ADG. Figure 5 is an example of the ADG snow accumulation time series for February 1997 at AGO-2, where zero represents the snow height at the start of the study period. Between November 18, 1996 and February 5, 1997, the ADG measured a gradual decrease in the elevation of the snow surface due to sublimation and densification of the firn, which resulted in a negative accumulation of –0.06 m just prior to the first snow accumulation event of 0.08 m on February 6, 1997. This accumulation event was followed by a second accumulation event of 0.09 m of snow on February 26.

In order to represent the episodic accumulation over a broader area, all ADG-identified accumulation events were normalized by the ratio of the total measured accumulation at the ADG (0.42 m) to the average annual snow stake accumulation (0.174 m), and the normalized accumulation was multiplied by the ratio of mean snow density (4.5 x 10^2 kg m^{-3}) to liquid water density, resulting in a normalized water equivalent accumulation. Figure 6 is a time series of each of the five accumulation events and provides the normalized water equivalent accumulation for each event. The dating of event 4 has an uncertainty of ±17 days (horizontal bar) due to missing ADG data and may actually be subdivided into more than one event. The sum of all five events gives a normalized water equivalent accumulation of 0.086 m.

According to the ADG results, the largest contribution to snow accumulation at AGO-2 was observed during three events in late summer to early fall (37.5% of total accumulation) and during one event in early spring (32.1% of total accumulation). During the same time period, *Noone et al.*

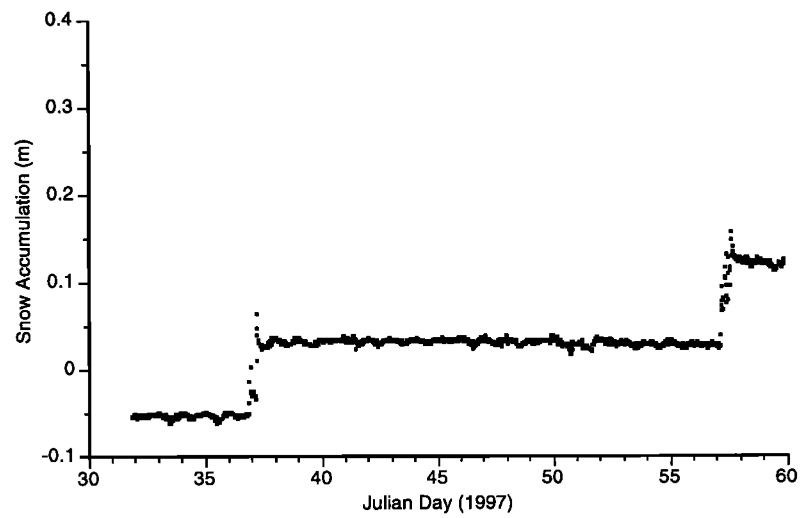

Figure 5. Snow surface elevation at AGO-2 during February 1997 measured every 30 min using an acoustic depth gauge.

[1999] measured accumulation using a thermistor string located on the Antarctic plateau at 77°S, 10°W and observed a similar distribution of snow accumulation events during the year. *Noone et al.* [1999] attributed the smaller spring maximum to a semiannual oscillation (SAO) in the atmospheric dynamics of the hemisphere; however, more observations are required before the influence of the SAO on precipitation at AGO-2 can be determined. Using data sets with at least 5 years of observations, *Bromwich* [1988] shows that the maximum precipitation for a coastal station along the Weddell Sea occurs in March, with a secondary maximum in October. Using a multiyear data set, *Turner et al.* [1997] also observed a similar pattern in the frequency distribution of precipitation events along the west coast of the Antarctic Peninsula, although the number of observed precipitation events observed along the continental margin is far greater than the number of accumulation events observed on the polar plateau. *McConnell et al.* [1997] used over 7 years of monthly snow stake measurements at South Pole Station to characterize the timing of accumulation and found that the largest accumulations occur during September, October, and November, with a secondary maximum occurring during April and May. These similarities in the accumulation patterns with AGO-2 could be due to a fraction of maritime air trajectories passing over both locations [*Hogan*, 1997].

Snow surface elevation measurements from the ADG also allow firn sublimation/densification processes to be examined. These processes are expressed as a decreasing trend in the ADG snow surface elevation data over a period of days to weeks. An example of this trend is shown in Figure 7 for a 27-day period in December 1996. The short-term fluctuations seen in the ADG signal generally do not reflect changes in the surface elevation but are due to temperature differences in the path between the ADG probe and the snow surface. Only one ambient temperature measurement is made to characterize the speed of sound along the path, and this measurement is not always equal to the actual integrated path temperature. Negative snow surface elevation trends were quantified for periods during each month with sufficient valid ADG data by applying a linear least squares fit to the time series data. The slope of this fit provides the overall rate of decrease of snow surface height. Table 3 lists each period examined, the number of days of data used in the least squares fit, and the rate of change of snow surface height. As expected, the decrease in snow surface height is greatest during the warmer months, which is mainly attributable to the larger saturation mixing ratio of water vapor in air at higher temperatures. For

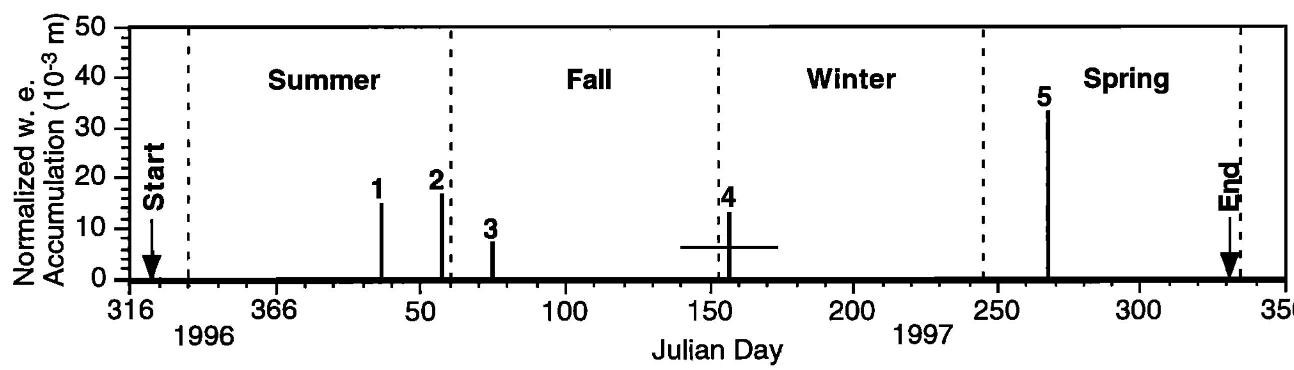

Figure 6. Time series of the five ADG-identified snow accumulation events, with accumulation amounts given as a normalized water equivalent.

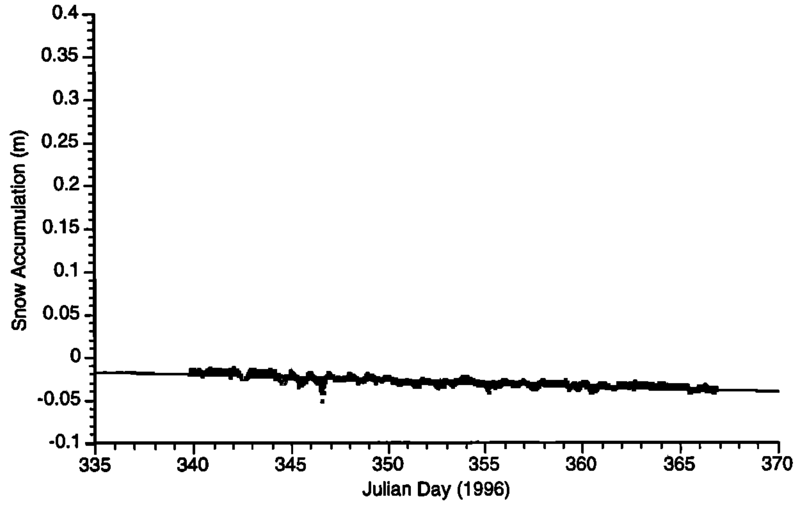

Figure 7. Example of the gradual decrease in snow surface elevation measured by the ADG at AGO-2 during December 1996.

example, the saturation mixing ratio of air at -25°C is 5 times greater than at -40°C. Using the values given in Table 3 and assuming a small rate of change of surface elevation (-1.0×10^{-4} m d^{-1}) for months with insufficient ADG data (May, June, July August, and September), the total surface elevation change due to sublimation/densification of the firn is calculated to be approximately -0.10 m during the study period.

3. Meteorological Assessment of Accumulation Events

Since the ADG provides good precision in the timing of four of the five observed snow accumulation events, the meteorological situations associated with accumulation events 1, 2, 3, and 5 have been examined using meteorological data from the site, available satellite imagery, and output from operational forecast models. The satellite imagery used is a product generated by the Space Science and Engineering Center, University of Wisconsin-Madison, and consists of 3-hourly infrared composite images centered at 90°S from geostationary and polar-orbiting satellites. Operational forecast model analyses used are the surface pressure fields of the National Centers for Environmental Prediction medium range forecast (MRF) model initialization. These observations and analysis fields provide insights into not only the local conditions associated with an accumulation event, but also the associated mesoscale or synoptic-scale atmospheric forcing.

Table 3. Rate of Change of Snow Surface Elevation at AGO-2 From Acoustic Depth Gauge Measurements for Individual Months With at Least 12 Consecutive Days of Valid Data

Month and Year	Julian Days	Number of Days	Rate of Change of Surface Elevation, m d^{-1}
Nov. 1996	323-335	13	-7.5×10^{-4}
Dec. 1996	340-366	27	-7.1×10^{-4}
Jan. 1997	1-31	31	-6.4×10^{-4}
Feb. 1997	38-57	20	-2.7×10^{-4}
March 1997	75-90	16	-3.5×10^{-4}
April 1997	96-107	12	-1.1×10^{-4}
Oct. 1997	284-304	20	-6.8×10^{-5}
Nov. 1997	318-331	13	-4.3×10^{-4}

An accumulation event as observed by the ADG can be due to precipitation alone, windblown snow alone, or some combination of the two, and measured wind speed during an event can offer some insights into the mechanism or mechanisms responsible. The formation of snowdrifts by windblown snow requires the movement of snow grains along the surface in a process called saltation [*Pettré et al.*, 1986]; however, this process only occurs if the wind speed exceeds some threshold speed. Typically, the threshold wind speed for saltation ranges from 6 to 10 m s^{-1} depending on snow surface conditions, and when wind speeds are below the saltation threshold speed, any snow accumulation observed by the ADG must be due to precipitation alone. Table 4 gives the observed wind speed ranges at AGO-2 during each accumulation event examined. For all events, wind speeds were within the range required for saltation at the start of each event, but for events 2 and 5 the wind speed tendency was to decrease throughout the event, ending the event with a wind speed that was below the saltation threshold speed. During events 1 and 3 the meteorological data were lost by the AGO-2 data acquisition system, and only the meteorological data contained in the once-per-day health and status message broadcast to the ARGOS satellite was available. Therefore the wind speed changes shown for events 1 and 3 are based on two measurements, whereas the assessment of wind speed trends for events 2 and 5 is based on 10-min averages of 1-min observations. Despite these data limitations, wind speeds observed during these accumulation events indicate that precipitation is likely to be associated with the ADG-observed accumulation events.

Temperature and atmospheric pressure trends from surface measurements can often provide limited information on mesoscale and synoptic-scale atmospheric processes that are capable of producing precipitation. Table 4 shows the observed temperature and pressure tendencies that do not show the same consistency as wind speed trends. Only in event 2

Table 4. Summary of Observed Wind Speed, Temperature, and Atmospheric Pressure Trends Associated With ADG-Identified Snow Accumulation Events at AGO-2

Event	Wind Speed, $m\ s^{-1}$	Temperature Change, $°C\ d^{-1}$	Pressure Change, $Pa\ d^{-1}$
1[a]	$8 \rightarrow 5$	-1.0	-200
2	$9 \rightarrow 4$	+7.0	-1300
3[a]	$8 \rightarrow 7$	-2.0	-200
5	$9 \rightarrow 5$	+10.0	+900

[a] Only one observation per 24 hours was available.

are the temperature and pressure trends consistent with what would be expected by the approach of a synoptic-scale cyclone north of the site. In this case, warm, moist air is advected toward the site, resulting in the observed temperature increase, and atmospheric pressure decreases as the low-pressure center approaches the site and/or deepens. Synoptic-scale cyclones are readily observed in an animation of a series of satellite images from the cloud bands associated with the frontal zones and the clockwise rotation of the cloud shield of the system. These cyclones are also generally depicted on numerical surface pressure analyses (e.g. the MRF model) as a closed low-pressure center. Mesoscale atmospheric disturbances in polar regions are also capable of producing precipitation [*Carrasco et al.*, 1997] but are generally more difficult to identify due to their smaller horizontal dimensions. Mesoscale cyclones are generally identified by the clockwise rotation of the cloud shield in an animation of sequential satellite images and are occasionally depicted by a closed low-pressure center on MRF numerical surface pressure analyses.

For each of the four accumulation events at AGO-2 listed in Table 4, meteorological data from the site, a time sequence loop of 3-hourly composite satellite images, and surface pressure MRF model initialization plots (0-hour forecast) available every 12 hours were used to characterize the meteorological processes responsible for precipitation at the site and to assess the source region of the moisture. Because of frequent missing satellite data from high latitudes, the actual time resolution in characterizing clouds and determining their trajectories on the polar plateau in the vicinity of AGO-2 was about 12 hours. Nonetheless, excellent coverage along the coastal margin permitted the identification of cyclones and flow patterns that had the capability of transporting heat and moisture inland. A meteorological overview during each event is summarized as follows:

During event 1, temperature and pressure at the site decreased slightly, and accumulation was attributed to a west-to-east frontal cloud band associated with a mesoscale low-pressure disturbance over the Weddell Sea and the Ronne Ice Shelf.

During event 2, temperature at the site increased moderately along with a large atmospheric pressure decrease. A synoptic-scale low-pressure disturbance was observed to move south over the South Atlantic Ocean and merge with a second low-pressure disturbance near the eastern edge of the Weddell Sea. This intensified low-pressure system was judged to be responsible for the precipitation observed at the site.

During event 3, temperature and pressure decreased slightly at the site, and a synoptic-scale low-pressure disturbance observed over the eastern edge of the Weddell Sea was likely linked to this accumulation event.

During event 5, a dramatic warming along with increasing pressure was observed at the site. The accumulation event was attributed to a warm, moist air mass lifted onto the polar plateau by an intense synoptic-scale low-pressure disturbance located over the South Atlantic Ocean.

4. Conclusion

Using three different techniques to quantify snow accumulation on different temporal and spatial scales, a 1-year study of snow accumulation at AGO-2 on the Antarctic polar plateau has observed a process spatially variable and episodic in nature. This work has important implications to development and validation of numerical model parameterization of high-latitude precipitation [*Dickinson et al.*, 1993] and in understanding the variations of important chemical species such as $\delta^{18}O$ in ice cores [*Steig et al.*, 1994] by providing (1) the timing and magnitude of the mass inputs to the ice sheet, (2) local meteorological conditions, especially winds, before, during, and after an event, (3) mass loss due to sublimation, and (4) characterization of large-scale atmospheric disturbances associated with an event.

On the basis of ADG measurements, only a few accumulation events were observed, but these events provided ~88% of the total annual accumulation at AGO-2 assuming an elevation change due to sublimation/densification of -0.10 m. These results are very similar to a precipitation assessment of the Antarctic interior made by *Noone et al.* [1999] based on ECMWF reanalysis data. ADG measurements provided excellent temporal resolution of snow height changes, but ADG only measures changes to a very small area of the ice sheet. Using these high time resolution data, sublimation/densification rates were quantified, and diagnostic assessments of the meteorological conditions associated with accumulation events were made using archived observational data, model output, and satellite images. While no single meteorological pattern was associated with these accumulation events, the winds during each event were observed to decrease in magnitude to a wind speed below the threshold speed for blowing snow. This observation confirms that precipitation is a contributing factor in these accumulation events, but contributions from blowing snow were also possible early in the event.

Other precipitation events not detected as accumulation events by the ADG are likely to have occurred throughout the study period, including clear-sky precipitation, but the frequency of these events is not known. Strong winds associated with precipitation events commonly prevent snow from accumulating on exposed, relatively flat surfaces, such as the small area monitored by the ADG. Over a broader area, pockets of accumulation are possible even with high winds, especially on the lee side of a snow surface feature such as a dune. In fact, accumulation results from the larger area characterized by the MDS instrumentation do indicate that several other accumulation events occurred during periods when the ADG did not measure a positive change in snow surface height. From Figure 4 it can be seen that accumulation events ranging from 0.01 to 0.05 m w.e. not observed by the ADG were found from the snow pit identification of microsphere horizons. These accumulation events were identified (1) at the snow pit 12 m downwind between Julian days 100 and 130; (2) at snow pits 5 and 13 m downwind between Julian days 180 and 250; and (3) at snow pits 7, 12, and 20 m downwind between Julian days 280 and 330. It is not possible to determine whether these accumulation events result from precipitation, blowing snow, or a combination of these processes because of the MDS dating uncertainty of 2 weeks or longer; however, these data allow the dynamic spatial variability of snow accumulation in windswept locations to be quantified. The MDS results also confirm that ADG measurements of a small target area do not provide a complete picture of the highly variable snow accumulation dynamics at a windswept site.

The observed spatial variability of snow accumulation on timescales of up to 1 year underscore the limitations of attempting to characterize the snow accumulation based on a single point measurement. While frequent point measurements are very valuable in providing precise timing of accumulation events, allowing meteorological forcing and microphysical mechanisms of individual snow accumulation events to be examined in detail, it is not likely that observed accumulation from the small target area of a single ADG can be extrapolated over a broad area. On the basis of MDS results, ADG measurements are representative of an area with a diameter of the order of 10 m. Hence, to properly characterize intra-annual snow accumulation in windswept regions, several ADGs separated by 100 m or more are required. Local characterization of accumulation processes will continue to be important to properly interpret future surveys by aircraft and satellite laser altimeter systems, but it is the laser altimeter platform that offers the most promise in understanding complex snow accumulation dynamics on a regional scale.

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