The Influence of Blowing Snow and Precipitation on Snow Depth Change across the Ross Ice Shelf and Ross Sea Regions of Antarctica

SHELLEY L. KNUTH
Antarctic Meteorological Research Center, University of Wisconsin—Madison, Madison, Wisconsin

GREGORY J. TRIPOLI
University of Wisconsin—Madison, Madison, Wisconsin

JONATHAN E. THOM AND GEORGE A. WEIDNER
Antarctic Meteorological Research Center, University of Wisconsin—Madison, Madison, Wisconsin

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ABSTRACT

Measuring snowfall in the polar regions is an issue met with many complications. Across the Antarctic, ground-based precipitation measurements are only available from a sparse network of manned stations or field studies. Measurements from satellites promise to fill in gaps in time and space but are still in the early stages of development and require surface measurements for proper validation. Currently, measurements of accumulation from automated reporting stations are the only available means of tracking snow depth change over a broad area of the continent. The challenge remains in determining the cause of depth change by partitioning the impacts of blowing snow and precipitation. While a methodology for separating these two factors has yet to be developed, by comparing accumulation measurements with meteorological measurements, an assessment of whether these terms were a factor in snow depth change during an event can be made. This paper describes a field study undertaken between January 2005 and October 2006 designed to identify the influences of precipitation and horizontal snow transport on surface accumulation. Seven acoustic depth gauges were deployed at automatic weather stations (AWS) across the Ross Ice Shelf and Ross Sea regions of Antarctica to measure net accumulation changes. From these measurements, episodic events were identified and were compared with data from the AWS to determine the primary cause of depth change—precipitation or horizontal snow transport. Information regarding the local impacts of these two terms, as well as climatological information regarding snow depth change across this region, is also provided.

1. Introduction

The International Precipitation Working Group (IPWG) was established in 2001 to improve the development and utilization of satellite-based precipitation measurements as well as to foster collaborations among scientists working toward the advancement of this data (Turk and Bauer 2006). Part of the IPWG involves the advancement of satellite-derived products of precipitation through the continued improvement of ground-based measurements used as validation. Unfortunately, over the polar regions, and specifically the Antarctic, these surface measurements are extremely limited. This paper introduces the development of a network of ground-based snow accumulation instruments across the Antarctic Ross Ice Shelf, which has provided the first measurements of its kind available for use by the IPWG in this region of the globe.

Antarctica has the most extreme weather on earth, from high wind speeds to bitterly cold temperatures, which has historically made the collection of meteorological measurements across the continent extremely challenging. Until 1980, real-time measurements of surface weather conditions in many remote regions of the Antarctic were unavailable largely because of the inaccessibility of these areas by personnel. With the introduction of unstaffed automatic weather stations (AWS)
to supplement the few staffed field camps already in place, daily meteorological measurements are now taken in real time at over 100 locations across the continent (Stearns et al. 1993) (Fig. 1).

While the AWS program provides valuable weather information for many remote locations, one important piece of the measurement puzzle has been missing—precipitation. The AWS cannot take precipitation measurements, as a low-power automated measurement system that can accurately measure falling snow has yet to be developed. Even in areas with adequate power and personnel, the horizontal transport of snow can greatly alter any measurements of precipitation that are taken (Braaten 2000). Currently, the only source of real-time ground-based precipitation measurements is staffed Antarctic stations where personnel, with large turnover rates, collect the observations on a limited temporal basis and where distances between measurements can be upward of 1300 km. As such, very little is known from real-time measurements about precipitation across a broad area of the continent. What is known has been acquired through other methods, including ice core, model, and reanalysis data.

In lieu of precipitation measurements, continuous measurements of snow depth change are possible to obtain. However, how much accumulation was received at a point site is the only measurement available—the means of its arrival, either through precipitation or advection, is unknown (Braaten 2000). Precipitation, when occurring as part of a synoptic or mesoscale event, can and does occur concurrently with high wind speeds. As the system intensifies, it can produce more precipitation, but also stronger winds. As well, synoptic and mesoscale cyclones can also intensify katabatic winds, produce or enhance a barrier wind along strong topography, or generate flow around obstacles that can lead to an increase or a decrease in precipitation (Parish and Bromwich 1998). These winds, and in particular the katabatic wind flow, can frequently reach wind speeds in excess of a wind speed threshold, above which particles at the surface...
Positive or negative changes in snow depth can be caused by several factors—precipitation, blowing snow, deposition of hoar frost, surface sublimation, snowdrift sublimation, wind-induced compaction, snow settling over time, meltwater, or any combination of the above (Li and Pomeroy 1997b). Some of these factors, such as compaction or simply the age of the snow, can also change the water content of the snow particles over time, thus changing the particle’s mass. A reduction in the mass of the particles can result in a reduction in the snow layer, thus changing the depth. Determining the specific causes of snow depth change, including the changes in depth caused by changes in snow mass, from only surface measurements is not feasible at this time. However, determining whether or not these terms have an impact on snow depth change can be made by comparing the accumulation measurements to meteorological measurements made on site, even if the absolute values of the change cannot be used for determining the impact.

Several field studies have been conducted measuring the relative importance of these factors on changes in snow depth (Howard 1948; Budd et al. 1966; Braaten 1997, 2000; Bintanja 2001; Dahe et al. 2004; and others). While providing important information regarding the causes of snow depth change, these studies are nonetheless conducted over specific lengths of time, at one point site on the continent, and generally with personnel on site. More spatially and temporally expansive studies using model and reanalysis data, in particular those by Briegleb and Bromwich (1998), Gallée (1998), Bromwich et al. (2004), Monaghan et al. (2005) and others, have also provided important information about the influences of precipitation and blowing snow on snow depth change over a large region, but still need to be complemented by surface measurements that can provide on-the-ground verification of these results. Studies using satellite data to track precipitation over the Antarctic are sparse, with a few notable exceptions (Massom et al. 2004; Adams 2004; Turner et al. 1993). The bulk of satellite studies of precipitation over Antarctica is generally confined to a specific event rather than a widespread examination of the continent.

During a field study conducted between January 2005 and October 2006 across the Ross Ice Shelf and on icebergs in the Ross Sea, seven AWS were fitted with automated acoustic depth gauges to provide the first extensive network of ground-based snow depth change measurements in Antarctica. The full suite of AWS measurements was then used to determine the relative influences of two of the factors—horizontal snow transport and precipitation—on changes in snow depth during a significant event. As in the other field studies described above, an absolute separation between horizontal snow transport and precipitation could not be determined, but by using meteorological measurements of wind speed and temperature, an assessment of whether these terms were a factor in snow depth change during an event could be made. The importance of horizontal snow transport and precipitation was then examined for trends by geographic location, season, and local weather influences in each location. In addition, important climatological information regarding accumulation trends, seasonal effects, and the duration of events was determined.

2. Contributors to snow depth change

The factors influencing snow depth change, including changes in snow amount that lead to changes in snow depth, are described by Bromwich (1988) and King and Turner (1997) as

$$B = P - E - Q - R,$$  \hspace{1cm} (1)

where $B$ represents total snow depth change, $P$ represents accumulation by precipitation, $E$ represents snow loss from net evaporation (sublimation minus deposition), $Q$ represents snow loss or gain due to the horizontal flux of snow, and $R$ represents the loss of snow from meltwater. The term $P$ corresponds to snowfall from synoptic or mesoscale systems, orographic forcing, or clear sky precipitation (diamond dust) (Bromwich 1988). Net evaporation is defined as snow depth loss from surface sublimation or snow depth gain from surface deposition of hoar frost. Hoar frost, in general, is not a substantial contributor to surface accumulation farther from the coast, so it is apparent that sublimation is the dominating contributor to this term (King and Turner 1997). Melt water runoff is most important in coastal regions during the summer months, but in general is not considered particularly important farther from the coast.

The term $Q$ represents all changes in depth due to the influences of wind, and can be defined as

$$Q = Q_t - Q_s - Q_c,$$  \hspace{1cm} (2)

where $Q_t$ represents the transport of snow particles by wind (represented by either drifting or blowing snow), $Q_s$ represents the net sublimation of the snow particle,
and $Q_c$ represents changes in snow by compaction. Drifting snow occurs when wind speeds are strong enough to cause snow particles to be lifted from, but still remain in contact with, the surface. Blowing snow occurs as wind speeds increase and snow particles are suspended for long periods of time above the surface (Bintanja 1998). Snowdrift sublimation can cause a loss of snow through ventilation of the particles by the wind (Bintanja 2001). Compaction involves the loss in depth over time due to the densification of snow layers through wind or gravity effects.

Of the four terms on the right-hand side of Eq. (1), the largest is precipitation when considering the mass balance of the entire ice sheet, as loss from the other three terms to the ocean and atmosphere is comparatively negligible (Bromwich 1988). When examining the effects of these terms on a more localized scale and focusing on depth rather than mass, other terms may dominate over precipitation. The term $Q$ is particularly important, especially in locations of strong katabatic forcing. When measuring $B$ at the surface from a snow depth change sensor, it is impossible to determine specifically how much of a factor to $B$ any of the terms on the right-hand side of Eq. (1) are from these measurements alone. Using automated surface measurements, the relative influences of $P$ and $Q$, however, can be adequately determined, even if the specific changes in depth cannot. These two terms are important to the surface depth equation and will be the focus of this study.

3. Description of field study

a. Instrumentation

The Antarctic AWS program uses a standard AWS that provides temperature, pressure, wind speed, wind direction, and relative humidity measurements at 10-min intervals. The air temperature, relative humidity (measured with respect to liquid water), wind speed, and wind direction are measured at a nominal height of 3 m above the surface, and the pressure is measured in an electronics enclosure box at 1.75 m. The actual height of the tower depends on the amount of snow accumulation at the base of the unit, although in general each tower is initially set at approximately 3 m above the ground. Each AWS station is powered by 6–12 gel cell batteries, which are charged by 1–2 solar panels, consuming a very low 0.15 W of power (the AWS consume 1300 W h over 1 yr—the equivalent of a 40-W light bulb burning for 1 month). The data collected by the AWS are transmitted in real time to the Argos data collection system (DCS) on polar-orbiting satellites, and the stored onboard data are retransmitted to several ground receiving stations and forwarded to Collecte de Localisation Satellite (CLS) America for archival and processing. A monthly data CD is then provided to the Antarctic Meteorological Research Center (AMRC), which distributes the data.

The sensors added to detect snow depth change at individual sites for this study were acoustic depth gauges (ADGs) (Fig. 2). Snow depth change is measured from the ADG by a series of sonar pulses sent out from the unit, which, upon interacting with the snow surface, reflect a signal back to the ADG, giving the distance to the object. The ADG used was a Campbell Scientific SR50, which has a resolution of 0.0001 m, and an accuracy of $\pm 0.01$ m. The sampling times varied by station—Mary and Windless Bight collected data every 10 min; B-15K, Drygalski, and Nascent every 20 min; and Ferrell and Williams Field every 60 min. Depending on the configuration of the station, the data were either transmitted in real time via the DCS, or stored in memory on the station to be retrieved at a later date.

b. ADG station locations

The placement of the ADGs was chosen for both geographical and logistical purposes (Fig. 3). B-15K, a moving iceberg, was located during this study in the...
southwestern corner of the Ross Sea, in an area of known increased mesocyclone activity (Carrasco et al. 2003). The Drygalski site, located at the tip of the Drygalski Ice Tongue, experiences katabatic wind flow, influences from mesocyclones, and orographic precipitation due to the nearby Transantarctic Mountains. The Ferrell site was chosen for its long climate record of nearly 30 yr. The Mary site, located at the base of Mulock Glacier in the Transantarctic Mountains, was chosen for the effects of katabatic winds and mesoscale vortices on this location. The Nascent site is in an area of little topographic influence, but was of interest because of its proximity to the ice edge. Two logistical reasons for placing an ADG at Williams Field were the close proximity of Williams Field to the McMurdo Station (approximately 13 km) and that it is an airfield for the U.S. Antarctic Program (USAP). Additionally, Williams Field is known to experience strong orographic influences from Ross Island, which is some 10 km north, as well as from other local topographical features (Monaghan et al. 2005). Windless Bight is in a stagnation zone because of its location nestled on the windward side of Ross Island, and was chosen because of known high-accumulation rates at this site from both personal observation and study (Monaghan et al. 2005).

4. Data analysis

a. Categorization of events

For each station, the ADG measurements were examined for events resulting in significant snow depth change. A significant event was defined to be where the maximum snow depth change over a period of at least 30 min was $\geq 0.01$ m (Fig. 4a). Aside from the maximum change, the net change of each event was also determined to identify if the event was an accumulation, ablation, or zero snow depth change event (Fig. 4b). These events were then divided into four categories based on wind speed and temperature data: events due to blowing snow, drifting snow, or precipitation, and a fourth
"unknown" category, for which the cause of snow depth change was not able to be determined directly from these measurements.

The criteria for determining these events were based on a study of wind speed thresholds in western Canada in 1997 (Li and Pomeroy 1997a). This study found that the average threshold for the initiation of blowing snow (as measured at 10 m) was 7.7 m s\(^{-1}\) for dry snow transport and 9.9 m s\(^{-1}\) for wet snow transport. Wet snow was defined as snow that had been subject to temperatures greater than 0\(^{\circ}\)C since the last snowfall, whereas dry snow had never been subjected to temperatures above the freezing point.

To find the appropriate wind speed threshold for the purposes of this study, adjustments were made according to the height of the aerovane at each of the seven Antarctic AWS sites using the log wind profile equation:

\[
U_z = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right),
\]

where \(U_z\) (m s\(^{-1}\)) is the wind speed at height \(z\), \(u_*\) (m s\(^{-1}\)) is the friction velocity, \(k\) is the von Kármán constant.

**FIG. 4.** An example of the raw ADG data from the Mary site during 2005. (a) Fluctuations in data from 1 Feb through 30 Apr 2005. (b) Accumulation, ablation, and zero snow depth change event from May 2005. The vertical axis is in reverse order to give a proper visual look at the data—the ADG measures distance to the snow surface, so accumulation values would appear to decrease with height without changing the axis.
constant (0.4), and $z_0$ is the surface roughness length. Following the methodology of the Li and Pomeroy study, $u_*$ was determined by using $0.5 \times 10^{-4}$ m for $z_0$ and $U_z = 7.7$ m s$^{-1}$ or $9.9$ m s$^{-1}$ for either dry or wet snow transport. From the values of $u_*$, $U_z$ can then be found as the wind speed threshold at the height of the aerovane for each of the Antarctic AWS sites. Drifting snow events were calculated using the same methodology as the blowing snow events, but using $U_z = 4$ m s$^{-1}$ for dry snow and $7$ m s$^{-1}$ for wet snow transport, which was found by the Li and Pomeroy study to be the lowest speed at which snow depth change events would occur. The thresholds for each of the seven sites are given in Table 1.

Precipitation events were categorized to be those events in which blowing or drifting snow was not a factor, and accumulation at the end of the event had occurred. These events were found when wind speeds were below the drifting snow thresholds for both wet and dry snow. This classification system matches the classification system used for precipitation quantification in a study measuring snow accumulation on the Antarctic polar plateau (Braaten 2000), although the drifting wind speeds in the current study were lower than those used in the previous work.

Any events that occurred that did not fit into these categories were placed into the unknown category, meaning that the cause of snow transport in these situations could not be easily identified. The two most common contributions to the unknown category were events that occurred below the drifting snow threshold that did not result in positive accumulation, or situations where the aerovane had frozen and wind speeds were unable to be collected. Since wind speeds are the primary source of categorical interpretation for this study, the lack of wind measurements resulted in an event with no clear cause.

### Additional data

In addition to finding the maximum depth change over an event, net changes over the life of the event were also recorded. Positive net changes were classified as accumulation events, negative net changes as ablation events, and no changes as zero depth change events. As well, seasonality of the net snow depth change during the life of an event, and seasonality of duration and occurrence of event, was also considered. Seasons were distinguished by definitive dates, which are shown in Table 2. For all seasons, the data were normalized for accurate comparison, since all stations operated at different times during the year and for different durations. A full list of the operation times for each of the stations is listed in Table 3.

At four of the seven ADG sites (Ferrell, Mary, Williams Field, and Windless Bight), snow pits were dug to collect measurements of annual accumulation. These measurements were then compared with the ADG data to determine the amount of snow loss over the year at each site. While verification of specific events was not able to be measured through this process, the general accumulation over the period the instrument was in operation was able to be verified. Additionally at these sites, manual measurements of the distance from the ADG to the snow surface were made during two visits to each site, in January 2005 and January 2007. This snow analysis was completed at the Ferrell, Mary, Williams Field, and Windless Bight sites.

### 5. Data issues

Because of differences in operational duration of the stations, sampling rates, seasonality, and therefore meteorological causes of depth change may be biased. For

<table>
<thead>
<tr>
<th>Blowing snow events (dry)</th>
<th>Blowing snow events (wet)</th>
<th>Drifting snow events (dry)</th>
<th>Drifting snow events (wet)</th>
<th>Aerovane height</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-15K</td>
<td>6.7</td>
<td>8.5</td>
<td>3.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Drygalski</td>
<td>7.3</td>
<td>9.3</td>
<td>3.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Ferrell</td>
<td>7</td>
<td>9</td>
<td>3.7</td>
<td>6.4</td>
</tr>
<tr>
<td>Mary</td>
<td>7</td>
<td>9</td>
<td>3.7</td>
<td>6.4</td>
</tr>
<tr>
<td>Nascent</td>
<td>7.5</td>
<td>9.6</td>
<td>3.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Williams Field</td>
<td>6.6</td>
<td>8.5</td>
<td>3.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Windless Bight</td>
<td>6.6</td>
<td>8.5</td>
<td>3.5</td>
<td>6.1</td>
</tr>
</tbody>
</table>

**Table 1.** Blowing and drifting snow thresholds (m s$^{-1}$) for each of the seven ADG sites. Thresholds for both wet events and dry events are shown. The height (m) of the aerovane is also shown.

<table>
<thead>
<tr>
<th>Beginning date of season</th>
<th>End date of season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>1 Oct</td>
</tr>
<tr>
<td>Summer</td>
<td>16 Dec</td>
</tr>
<tr>
<td>Autumn</td>
<td>16 Feb</td>
</tr>
<tr>
<td>Winter</td>
<td>1 May</td>
</tr>
</tbody>
</table>

**Table 2.** Dates for each of the four seasons as defined for this study.
example, katabatic wind flow is most prominent during the autumn and winter months, and stations that operated only during the winter in areas where katabatic winds are dominant will have preference to blowing or drifting snow events. As well, estimations of the precipitation category are also likely to be underrepresented in this study. Those instances where blowing or drifting snow and precipitation were occurring concurrently were not able to be determined using the methodology presented here. Extensive case studies on all events for this study would need to be conducted to achieve this goal, which was not feasible for this work.

For most stations, the sampling rate for the ADGs was 10 or 20 min, while for two the sampling rate was 60 min. The lower temporal resolution at these two locations results in not being able to capture events that last longer than 30 min (which is the minimum for a significant depth change event) and shorter than 60 min. The sampling rates of these two stations have since been changed, but for the data analyzed as a part of this work, the rates remain as such. Consequently, the Williams Field and Ferrell sites will likely have more events in actuality than measured during the study period of this project.

It is important to note that for all cases, the precise cause and magnitude of the snow depth change event could not be determined. Only the fact that each term had some impact on the surface snow depth during a significant event can be determined, but not its extent. With the data available, it was impossible to determine how much the blowing snow contributed to the magnitude of change, the type of snow depth change (accumulation or ablation), and the other potential processes that may also have been a factor. In any of these events, precipitation, sublimation, and compaction may or were assuredly contributors to snow depth change, but without more sophisticated instrumentation, larger power sources, and personnel at each station over longer periods of time, the exact contributions were unable to be determined. These categories merely represent the fact that these contributors were likely the leading factor in change of snow depth at that location and during that time.

6. Results

When the snow depth change events were tallied for all data from 2005 to 2006 for each site, 2710 cases were identified at all seven stations that accounted for a snow depth change of \( \leq 0.01 \) m. Of the 2710 cases identified, precipitation events accounted for 12% of all cases, blowing snow for 37%, and drifting for 35%, with the remaining 16% unknown. Blowing snow was the primary cause of snow depth change at three sites—Mary, Ferrell, and Drygalski—and drifting snow was the primary cause of snow depth change at one site—Windless Bight (Fig. 5). Both the blowing and drifting snow categories were dominant at the Nascent and Williams Field sites. Precipitation was never the primary cause of snow depth change at any site, and the unknown category only dominated at one site—B-15K.

Episodic depth change events varied by month for each of the seven stations. Ferrell and Nascent saw the most events with the greatest magnitude of snow depth change in the month of February. Windless Bight saw increased high snow depth change events during January, and B-15K had the most events to occur during both January and February. Mary and Williams Field saw the largest number of high episodic events during August and June/July, respectively, and Drygalski’s highest number of episodic events was in March.

Most events (87%) lasted between 1 and 10 h, with 63% of those lasting between 1 and 5 h (Fig. 6). Less than 2% of all events lasted longer than 20 h. Three sites—Drygalski, Mary, and Windless Bight—never saw events lasting longer than 1 day, with the Drygalski site not reporting any events longer than 15 h. Summer and winter showed more events that were longer in duration, while spring and autumn showed an increased number of shorter events (Fig. 7).

The majority of snow depth change events (51%) was found to occur during the winter, while 18% and 20% occurred during summer and autumn, respectively. Only 11% occurred during the spring period. Most of the blowing and drifting snow events occurred during the winter and spring seasons, and most of the precipitation events occurred during the summer season (Fig. 8). The unknown category was the highest in summer and winter.

Overall, the percentage of events that resulted in either accumulation or ablation over the event period for
both blowing and drifting snow events was nearly equal. Events that resulted in no snow depth change made up less than 10% of all events. Winter was the month for the highest occurrence of accumulation and ablation events. Five sites (B-15K, Drygalski, Mary, Nascent, and Williams Field) had nearly an equal number of accumulation and ablation events, while Windless Bight had a higher number of accumulation events (Fig. 9). Ferrell was the only site that saw more ablation events. For most sites, the average net snow depth change during an accumulation or ablation event was similar, with the exception of the Mary and Ferrell sites. At these two sites, the net snow depth change for an accumulation event was 0.04 m, and for an ablation event 0.02 m.

Two-year measurements of snow accumulation, as measured from the ADG to the surface, were collected by both manual and automated measurements at five of the seven sites during the period between January 2005 and January 2007 (Fig. 10). The manual measurements collected at Ferrell, Mary, Williams Field, and Windless Bight were made simply by measuring the distance to the snow surface from the base of the ADG with a tape.
measure. The net accumulation over the period was determined by the difference between the initial and final distances measured. The Nascent site was unable to be visited, so the accumulation data at this site are as reported by the ADG only. However, since Nascent remained in operation over the entire period of study (excluding the remaining two months of 2006), these measurements provide an accurate comparison to the other manually measured sites. The remaining two months of data at the Nascent site were able to be determined using trends from the previous year. The B-15K and Drygalski sites, however, did not have a constant ADG record for the 2-yr period and were unable to be visited during this time, so appropriate comparisons at these sites cannot be made. From Fig. 10, it is shown that Windless Bight has the most snow accumulation over

![Image of Fig. 7](image7.png)

**FIG. 7.** Changes in the number of events by season, as defined by the duration of the event. In general, this graph shows that for winter and summer, the number of events increases as the duration increases. For spring and autumn, the number of events decreases as the duration increases. Because data were not continuously available throughout each season, the data are normalized.

![Image of Fig. 8](image8.png)

**FIG. 8.** Seasonality of meteorological cause of snow depth change events. Because data were not continuously available throughout each season, the data are normalized. From this graph, it is seen that blowing and drifting snow events are highest in the winter and spring, while precipitation and unknown events are highest in the summer.
the 2-yr period, at 1.67 m, while Nascent and Williams Field both have the lowest at 0.71 and 0.75 m, respectively.

At Ferrell, Mary, Williams Field, and Windless Bight, snow pits were also dug with the purpose being to estimate how much, if any, snow loss was seen at the surface over time. It was expected that since the manual measurements of net accumulation from the ADG were collected during the same time period and near the location of the ADG, there should be an insignificant difference between the two measurements. Results from this analysis can be seen in Table 4. While Williams Field saw a 2% loss in snow between the two measurements, the Ferrell, Mary, and Windless Bight sites all reported at least a 20% reduction in net accumulation in the snow

Fig. 9. Depiction of the type of snow depth change—either accumulation, ablation, or zero net change—occurring during an event by station. Most stations have a nearly equal number of accumulation and ablation events, but the Ferrell site has more ablation and Windless Bight more accumulation. Because data were not continuously available throughout each season, the data are normalized.

Fig. 10. Two-year snow accumulation totals as measured from the ADG to the surface for five of the ADG locations. For Ferrell, Mary, Williams Field, and Windless Bight, accumulation totals were collected from manual measurements of the difference between the initial and final distance of the ADG to the surface. The Nascent was unable to be visited, so the total is as reported by the ADG. B-15K and Drygalski’s measurements are not shown, as only 1-yr accumulations are available at those locations.
the RAS over the Ross Island region, and consequently one of the three identified strong convergent zones of Ice Shelf. Both the Mary and Ferrell sites are located in varying horizontal distance eastward across the Ross on season, will extend out to the Ross Sea and to some the Ross Sea (Parish et al. 2006). The RAS, depending onantarctic Mountains, and is driven by synoptic effects in the Transantarctic Mountains (O'Connor et al. 1994). The Mary and Windless Bight sites had an equal or nearly equal percentage of events influenced by both blowing and drifting snow (38% versus 42%, respectively, for Nascent, and 33% for both for Williams Field). Increased winds from the RAS can spread to the Nascent site on the Ross Ice Shelf, which would increase the number of blowing and drifting events at this site. The Nascent and Williams Field sites had an equal and only 18% and 7% to drifting snow and precipitation, respectively. Despite being located nearly 200 km apart, the two sites are affected by similar meteorological regimes. The Mary site is influenced by katabatic wind flow due to the station’s proximity to the Transantarctic Mountains (approximately 40 km) (Bromwich 1989). The Ferrell site is also influenced by katabatic flow from the Transantarctic Mountains, although not as strongly as the Mary site because of its location farther east. At the Mary site, 53% of events were influenced by wind speeds of higher than 10 m s\(^{-1}\), as compared with only 21% at Ferrell. Ferrell is more directly affected by the topographical regime of Ross Island and nearby Minna Bluff (just south of the White and Black Islands; see Fig. 3), which serves to maintain the katabatic flow from the Transantarctic Mountains (O’Connor et al. 1994).

Influences from the Ross Ice Shelf airstream (RAS) can also be seen at these two sites. The RAS is largely controlled by a barrier wind that flows along the Transantarctic Mountains, and is driven by synoptic effects in the Ross Sea (Parish et al. 2006). The RAS, depending on season, will extend out to the Ross Sea and to some varying horizontal distance eastward across the Ross Ice Shelf. Both the Mary and Ferrell sites are located in one of the three identified strong convergent zones of the RAS over the Ross Island region, and consequently are influenced by increased wind speeds (Fig. 11). Additional effects, such as mesocyclones as described by Carrasco et al. (2003) or a topographically enhanced “wave of energy” as described by Adams (2005), both of which track past the Mary and Ferrell sites, are also presumed to affect blowing and drifting snow at these sites, although the extent to which is unknown.

The Drygalski site was also dominated by blowing snow events (39%), which likely was a consequence of its location at the base of the Drygalski Ice Tongue. Katabatic wind flow from David Glacier is prominent at this location, although not as strong as the flow spilling onto the Ross Ice Shelf (Bromwich 1989). Influences from mesocyclones, which are most prevalent in this corner of the Ross Sea, are also likely to contribute to increased blowing snow events at this site (Carrasco et al. 2003).

The Nascent and Williams Field sites had an equal or nearly equal percentage of events influenced by both blowing and drifting snow (38% versus 42%, respectively, for Nascent, and 33% for both for Williams Field). Increased winds from the RAS can spread to the Nascent site on the Ross Ice Shelf, which would increase the number of blowing and drifting events at this site. The RAS at the Nascent site, however, is weaker than at other locations on the Ross Ice Shelf, which was reflected in the decreased number of wind transport events at Nascent versus sites located in strong regions of the RAS. Wind roses for Williams Field indicate that the site is dominated by south-southeasterly flow from White Island (Fig. 12). As flow converges on the lee side of White Island, localized high winds occur, which will impact Williams Field and increase blowing and drifting snow events, which can be severe (Monaghan et al. 2005).

Blowing and drifting snow events accounted for only 17% and 26%, respectively, of snow depth changes at the B-15K site, and were not the dominant category at this location. Katabatic wind flow from the Transantarctic Mountains can be seen to extend to Franklin Island at times, influencing the B-15K site (Bromwich 1989). In comparison to the Drygalski site, which was closer to the Transantarctic Mountains, B-15K had a much lower number of horizontal transport events. Only 5% of the events at B-15K experienced wind speeds greater than 10 m s\(^{-1}\), compared to 22% at Drygalski—a result of weakened katabatic flow at this station due to increased distance from the katabatic origination. Synoptic and mesoscale systems also likely contribute to blowing and drifting snow events at this location (Carrasco et al. 2003).

At the Windless Bight site, 41% of all events were from drifting snow, while 23% were from blowing snow. These results are particularly interesting as Windless Bight is, as the name implies, in a region of very little strong wind flow—less than 5% of events at this station

<table>
<thead>
<tr>
<th>Site</th>
<th>Measured accumulation from ADG</th>
<th>Measured accumulation from the snow pit</th>
<th>Percent loss</th>
<th>Snow loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrell</td>
<td>0.8955</td>
<td>0.6137</td>
<td>31.468</td>
<td>0.141</td>
</tr>
<tr>
<td>Mary</td>
<td>1.0654</td>
<td>0.8382</td>
<td>21.325</td>
<td>0.114</td>
</tr>
<tr>
<td>Williams Field</td>
<td>0.7523</td>
<td>0.7406</td>
<td>1.555</td>
<td>0.006</td>
</tr>
<tr>
<td>Windless Bight</td>
<td>1.6726</td>
<td>1.2954</td>
<td>22.551</td>
<td>0.189</td>
</tr>
</tbody>
</table>

7. Discussion

a. Horizontal snow transport

It is clear from these results that blowing snow events had the greatest influence at the Mary and Ferrell sites, where 75% of the events were related to blowing snow, and only 18% and 7% to drifting snow and precipitation, respectively. Despite being located nearly 200 km apart, the two sites are affected by similar meteorological regimes. The Mary site is influenced by katabatic wind flow due to the station’s proximity to the Transantarctic Mountains (approximately 40 km) (Bromwich 1989). The Ferrell site is also influenced by katabatic flow from the Transantarctic Mountains, although not as strongly as the Mary site because of its location farther east. At the Mary site, 53% of events were influenced by wind speeds of higher than 10 m s\(^{-1}\), as compared with only 21% at Ferrell. Ferrell is more directly affected by the topographical regime of Ross Island and nearby Minna Bluff (just south of the White and Black Islands; see Fig. 3), which serves to maintain the katabatic flow from the Transantarctic Mountains (O’Connor et al. 1994).

Influences from the Ross Ice Shelf airstream (RAS) can also be seen at these two sites. The RAS is largely controlled by a barrier wind that flows along the Transantarctic Mountains, and is driven by synoptic effects in the Ross Sea (Parish et al. 2006). The RAS, depending on season, will extend out to the Ross Sea and to some varying horizontal distance eastward across the Ross Ice Shelf. Both the Mary and Ferrell sites are located in one of the three identified strong convergent zones of the RAS over the Ross Island region, and consequently

The Drygalski site was also dominated by blowing snow events (39%), which likely was a consequence of its location at the base of the Drygalski Ice Tongue. Katabatic wind flow from David Glacier is prominent at this location, although not as strong as the flow spilling onto the Ross Ice Shelf (Bromwich 1989). Influences from mesocyclones, which are most prevalent in this corner of the Ross Sea, are also likely to contribute to increased blowing snow events at this site (Carrasco et al. 2003).

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At the Windless Bight site, 41% of all events were from drifting snow, while 23% were from blowing snow. These results are particularly interesting as Windless Bight is, as the name implies, in a region of very little strong wind flow—less than 5% of events at this station
experienced wind speeds $>10 \text{ m s}^{-1}$. The site is located in a stall region on the southern side of Ross Island where blocking effects from the island cause cold air to build on the windward side, forcing flow to travel around the island (Adams 2005; Monaghan et al. 2005). As a consequence, high–wind speed events are rarely seen at this location.

b. Precipitation

B-15K had the highest percentage of precipitation events of all sites (27%), which is not surprising because of the station's location in the Ross Sea. B-15K and Drygalski (where precipitation accounted for 14% of all events) were the two sites farthest north in this study, and experienced the highest temperatures and highest number of wet blowing and drifting snow events of all stations. Precipitation at this location likely occurred not only from mesoscale cyclones, but also because of orographic effects. It was presumed that for both of these locations the number of “combined” events (those that experience both snow transport and precipitation) was high, but this cannot be determined at this time.

Windless Bight saw the second highest number of precipitation events, at 16%. The relative low number of precipitation events is surprising, as studies have shown increased precipitation on the windward side of Ross Island (Monaghan et al. 2005). Additionally, anecdotal observations at this location have shown snow at this site to be much less dense as compared to other AWS sites. Further examination of the events indicates a lower average snow depth change during a precipitation event than in blowing and drifting snow events (0.02 versus 0.03 m), indicating that it is not a small number of events with large accumulations that is a contributor. One possible explanation for this might be that snow at this site may appear to be precipitation but is actually snow that falls during blowing snow events when the flow is stopped.

FIG. 11. The extent of the RAS from the southern edge of the Ross Ice Shelf north. The Mary and Ferrell sites are located in an identified confluence zone of the RAS, which is shown in the circle (from Parish et al. 2006).
by Ross Island. Also, it is unclear how many of the 21% of unknown cases are influenced by precipitation. Furthermore, it may be that more of the blowing and drifting snow events are also influenced by precipitation than other sites, a fact that cannot be fully understood with automated instruments alone.

The Nascent and Williams Field sites saw 8% and 10%, respectively, of precipitation events at these locations. Williams Field is not in an area that is known to be a particularly high-precipitation location, so these results are not unexpected (Monaghan et al. 2005). The Nascent site, despite being near the ice edge, has a predominantly southerly wind direction from flow off the dry southern Ross Ice Shelf, which results in a lack of available moisture in the region to produce precipitation. Additionally, a flat topography in this region yields little opportunity for forcing mechanisms to generate precipitation. The Nascent site is also in a location where mesoscale and synoptic systems are not as frequent (Carrasco et al. 2003; Simmonds et al. 2003). Those systems that do affect this location are also likely to experience horizontal snow transport as well, and would thus be included in the horizontal transport categories.

By far, the Ferrell and Mary sites experienced the lowest number of pure precipitation events. Given the vast number of blowing snow events at these sites it would be rare for a pure precipitation event to occur at these locations. It is surmised that mesoscale and synoptic-scale systems are responsible for much of the precipitation at Ferrell rather than orographic forcing. At the Mary site, orographic precipitation enhanced by synoptic systems that produce a barrier wind at this location is likely responsible for most precipitation events. It is likely that the majority of precipitation at these sites occurs concurrently with blowing and drifting snow.

c. Unknown

While the specific causes of snow depth change at all of these sites are not able to be fully explained with the data available, it was only at B-15K where the unknown category dominated all others at 30%. There are likely many reasons for the high unknown category, not the least of which was that the site was located on a moving iceberg in the Ross Sea. Dynamical processes surrounding the movement of the iceberg as well as effects of the acceleration of winds around the sides of the iceberg are not fully understood. Since the location of the AWS was approximately 3 km from the ice edge on the iceberg, there were likely numerous dynamical effects on the site that are not fully captured. One interesting result from this site was the high number of precipitation events that occurred, given that the station was only operational during autumn and winter. Since precipitation dominated the summer season at other stations, it is unclear why B-15K was different. Further analysis and data are needed to adequately explain the discrepancy at this site.

d. Net snow depth change

While most sites experienced a nearly equal amount of accumulation and ablation events, two sites, Ferrell and Windless Bight, did not. Windless Bight had 179 cases, or 58%, of all net snow depth change events that resulted in accumulation, compared to only 128 cases, or 41%, that ended in ablation. Ferrell site had 21 cases, or 38%, of all net snow depth change events that resulted in accumulation, and 32, or 57%, of events that ended in ablation. Anecdotal observations by the authors have confirmed Windless Bight to be a site of high accumulation based on the speed at which the AWS towers are buried on a yearly or biyearly basis, as well as the soft-packed snow at the surface. In addition, the ADG at Windless Bight measured the highest accumulation of all sites.

More surprising, however, is the fact that ablation events dominate the landscape at the Ferrell site. While seeing a high number of ablation events at a site with high wind speeds is not surprising, ablation events that are the most prominent at the site imply that the surface should be bare or in a blue ice zone, which is not the case at Ferrell. Furthermore, anecdotal observations prove there is at least some accumulation on site, as the AWS tower generally needs to be raised every 4 yr, in addition to a general upward accumulation trend as measured from the ADG. One possible reason for this could be the time of year that the data at Ferrell were collected.
8. Conclusions

Ferrell was primarily only in operation at the end of the summer and beginning of autumn seasons. It is highly likely, given the katabatically driven winds at this site, that more accumulation events occur during the winter season, when katabatic winds dominate and station data were not available.

e. Snow loss

The results of the snow loss study were a bit surprising for all four locations. It was expected that there would be a minimal snow loss between the ADG and snow pit measurements, as the two measurements were taken over a similar time span, as well as a fairly close distance. While it is expected that a significant reduction in snow would occur over time because of compaction, snow setting, and sublimation when compared to a short-term event, the losses between the two measurements during a similar time span are worthy of note.

Some possible reasons may have to do with the tower on which the ADG rests. In some locations, snow drift at the base of the tower could impact snow accumulation measurements made by the ADG. While most sites did not appear to have significant snow drift, this could nonetheless contribute to the ADG reporting a higher snow depth than the snow pits. As well, it is possible that the proximity of the tower can result in less-compact snow near the ADG than in the snow pit, which was generally taken anywhere between 3 and 6 m from the ADG site. When blowing snow reaches the tower, turbulence effects around the tower could cause the snow to fall to the surface as a “simulated” precipitation, much like in the stagnation zone near Windless Bight.

Interestingly, comparisons of the annual total loss of snow at these sites to a study of snow loss due to latent heat fluxes on the Ross ice shelf show much higher losses of snow (0.04–0.08 m yr\(^{-1}\) for some sites) (Stearns and Weidner 1993). Reasons for these discrepancies are likely varying locations (the areas in this study were in higher wind regimes), and variations of years, as the Stearns and Weidner study looked at years in the mid- to late 1980s. Further observations will need to be collected in subsequent seasons to determine if the 2005–06 season was anomalous.

8. Conclusions

This work documents a field campaign in operation between January 2005 and October 2006 in which seven acoustic depth gauges were placed on automatic weather stations across the Ross Ice Shelf and Ross Sea regions of Antarctica to measure changes in snow depth at these locations. The measurements of snow depth change were then compared to wind speed and temperature data from the AWS to determine four categories of the causes of snow depth change: those caused by blowing snow, drifting snow, and precipitation, and a fourth “unknown” category that describes those events not able to be determined using this method. While a determination of how much snow depth change was caused by each of these terms could not be made, a comparison of the data to the meteorological data of the AWS could describe whether or not advection or precipitation played a role in changes in snow depth at the surface. It was found that blowing snow made up the majority of events at 37%, drifting snow at 35%, precipitation at 12%, and unknown at 16%. This dataset was further expanded to show the geographic and seasonal dependence of the events.

This work highlights some of the important limitations in measuring snow depth change in the polar regions, and specifically, Antarctica. From the surface AWS and ADG measurements, an assessment of whether horizontal snow transport or precipitation affected the snow depth at a particular site was possible, but determining the extent to which these factors changed the depth was not. Other contributions to snow depth change, including compaction or sublimation, could not be identified directly using this method, although they are certainly a part of snow depth change. Measurements of precipitation were also only able to be collected when winds were below the drifting snow threshold, and those events in which winds were above the drifting threshold and precipitation was occurring were not able to be determined. In addition, 16% of the cases could not be determined using these methods at all, and the climatological importance of those cases remains unknown.

As the network of automated snow accumulation measurements expands across the Antarctic, so does the opportunity for validation of satellite efforts made through the IPWG. Staffing more stations across the continent with increased power capabilities and more accurate precipitation gauges that can discount the influences of horizontal snow transport is not feasible at this time. Continued expansion of this network will provide improved estimations of snow depth change across a broader area of the continent over concurrent seasons so as to begin to understand the changes in snow depth on a localized scale. Using automated surface measurements in conjunction with model output, reanalysis data, and satellite observations can provide not only validation of the spaceborne and model-generated data, but also a more accurate depiction of the meteorological causes of snow depth change through data assimilation into models with enhanced blowing snow parameterizations.

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REFERENCES


