Estimation of snow accumulation in Antarctica using automated acoustic depth gauge measurements

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Summary Measurements of Antarctic precipitation are important to further the understanding of climate change, mass balance of ice sheets, and the global water cycle. Currently, Antarctic precipitation measurements are largely absent due to the many complexities of measuring precipitation in high latitudes. While many of these issues have yet to be overcome, measurements of snow accumulation and partitioning the causes of these changes are an important beginning. With the use of automatic weather stations and acoustic depth gauges along with visual stratigraphy and snow density observations, preliminary measurements and causes of snow depth change across the Ross Ice Shelf were taken during a period of 2003-2006. The effects of topography as well as maritime influences were also considered. A net accumulation was found at all sites, and precipitation was shown to be the primary cause of positive snow depth change. Topographical influences were found to be more significant than maritime influences.

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Introduction

Antarctica is known for having the most extreme weather on earth, from high wind speeds to bitterly cold temperatures. Measurements of this harsh weather are made in real-time by automatic weather stations (AWS), which are located in many different locations across the Antarctic continent. These weather stations take basic meteorological measurements, such as temperature, pressure, wind speed and direction, relative humidity, and vertical temperature difference. However, one measurement the AWS are unable to acquire is that of precipitation. There has yet to be developed a low-power system that can accurately measure precipitation by removing other extraneous influences, such as blowing snow. Precipitation measurements across the continent are therefore taken with a very high spatial and temporal discontinuity, and only as part of small field campaigns or at manned stations.

The ultimate goal of this project is to produce an accurate continent-wide map of Antarctic precipitation derived from observations. To do this, measurements of snow accumulation at the surface will be needed, and depth changes occurring from both blowing snow and precipitation will need to be determined. Acoustic depth gauges (ADGs), commonly used for taking measurements of accumulation in the Arctic, have been implemented in Antarctica as part of the instrument suite on board the AWS. The ADGs provide the only automatic real-time accumulation measurements in Antarctica at this time.

This project focuses on the first step of this problem – observing accumulation at the surface from ADGs. In this paper, preliminary results from the observations of the ADGs and AWS will be used to determine the partitioning of accumulation on the ground for snow depth change cases. In addition, observational validation for modeling studies indicating that topography is the primary forcing mechanism of precipitation is explored. This information will provide a starting point for future study into the amounts and origins of precipitation across the continent.

Data Acquisition and instrumentation

In order to produce snow accumulation measurements and deduce the origin of the changes in snow depth, several types of instruments were needed to both measure the snow depth change and the meteorological factors present that contributed to this change. The AWS and ADGs were the two instruments used in this effort.

AWS are located throughout the Antarctic continent, with the stations' primary purpose being to take unmanned meteorological measurements with little or no need for human interaction. Initially developed by Stanford University, the U.S. stations were first placed in Antarctica in 1979 on an expanded project already being developed at the University of Wisconsin. Approximately 100 stations have been deployed to Antarctica in the period from 1980-2006, with approximately 60 stations currently active. Some of these stations are placed in the harshest areas of the continent, allowing for an examination of weather data during all types of weather events.

The sensors used to detect depth change at a point site for this study were acoustic depth gauges (ADGs). Snow depth change is measured from the ADG by a series of sonar pulses sent out from the unit, which, upon interacting with an object (such as the snow surface), will reflect a signal back to the receiver within the ADG unit. When snow accumulates or disperses from beneath the ADG, the change in distance to the snow surface can be determined.

Two other sets of data were used in order to determine the cause and amount of net accumulation – visual stratigraphy and snow density measurements. Visual stratigraphy measurements are commonly used to look at seasonal or yearly changes in snow depth through the examination of horizontal snow layers in a snow pit (Schwerdtfeger, 1984, Braaten, 1997 and others). Accumulation is estimated by evaluating the characteristics of each snow layer to determine if depth change was due to blowing snow or precipitation. Measurements of the weight of the snow were also taken in the snow pits in each accumulation layer, which were then converted into measurements of the density of the snow. The density of the snow is highly variable – it can change once the snow is lofted into the air, and after it has been packed down at the surface.

Field campaign

In order to acquire measurements of accumulation and ablation at the surface in Antarctica, ADGs were deployed at several locations across the Ross Ice Shelf. Additional data were also collected at several sites across the Ross Ice Shelf and West Antarctica manually from snow pits. Deployments of personnel and instrumentation to Antarctica, and manual measurement of data occurred during four field seasons between 2003 and 2007. Eight ADGs were placed at Williams Field, Windless Bight, Mary, Ferrell, B-15A, B-15K, Nascent, and Drygalski (Fountain) (Figure 1). Data for Drygalski, B-15A, and B-15K were only used when these stations were located south of the Drygalski Ice Tongue.

These particular AWS sites were selected for various reasons, both scientific and logistical. An ADG was placed at Williams Field due to its close proximity to McMurdo, and the fact that there is a major landing strip at this site. Windless Bight was chosen due to its geography; as the name implies, very little wind is seen at the surface at that location, and allows for a view of site that has less influences from blowing snow. Mary site was chosen for its proximity to the Transantarctic Mountains – at the base of the mountains, this station not only experiences influences from orographic precipitation and katabatic winds, but also other influences still being researched (Adams, 2005). Ferrell site was chosen for climatological purposes, as the AWS at this site has a long history. B-15A, B-15K, Nascent, and Drygalski were all chosen due to each station's proximity to the ocean. Drygalski is also in close proximity to steep geography, and experiences katabatic wind influences as well.

The ADGs were placed at these stations largely during the first two years of the project. During the latter years, data was collected from the stations, and snow pits were dug in order to collect visual stratigraphy and snow density measurements. Snow pits were dug at each of the AWS that had an ADG, with the exception of B-15A, B-15K, and Drygalski, which were not dug due to logistics. In addition, several other snow pits were dug at other locations on the Ross Ice Shelf and in West Antarctica, including Kominko-Slade, Harry, Siple Dome, Linda, Laurie II, Swithinbank, and Byrd (Figure 1). The data at these locations allowed for a comparison between sites with ADGs and those without, and for differing geography.

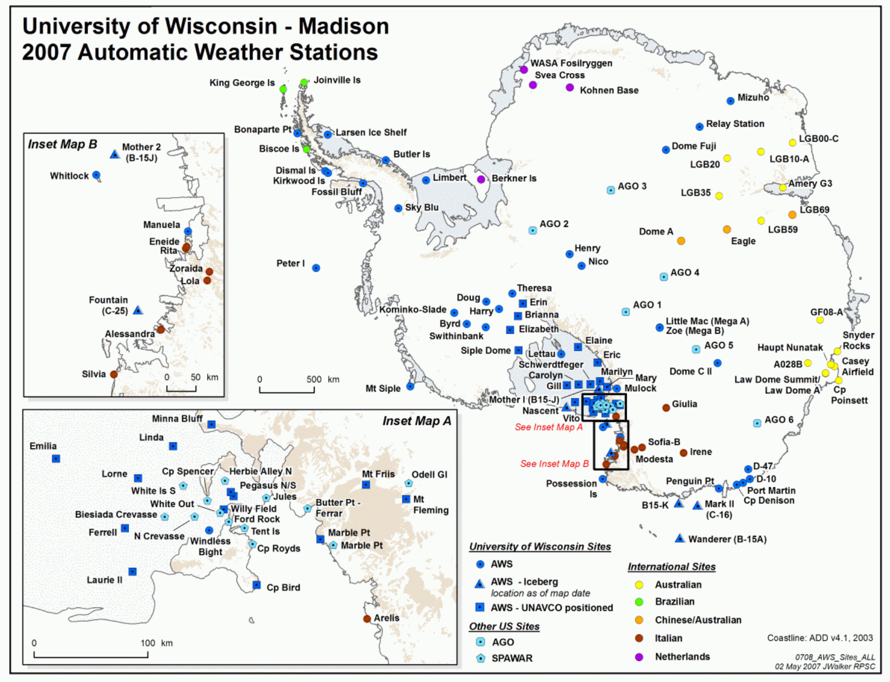

Figure 1. Locations of AWS sites across the Ross Ice Shelf and the Ross Sea. Current as of 2007.

Data analysis

Changes in snow depth result from the influence of some external factor on the surface layer of snow – precipitation, blowing snow, a combination of blowing snow and precipitation, sublimation, humans or animals, and potentially many others that are not generally even considered. For this study, precipitation and blowing snow were the only two factors examined for potential causes of snow depth change. Sublimation was not considered in this preliminary analysis, as it is beyond the scope of this project. Influences from humans and animals are anticipated to be minimal, and therefore not of concern for this work. Precipitation and blowing snow will have a much larger affect on changes in snow depth than other factors, and consequently were the only two factors studied.

For each station each year, ADG measurements were plotted and examined for any significant changes. These events have no upper or lower limit of accumulation or ablation in order to be singled out as a depth change event, but events not significant enough to be seen on a yearly plot were not used. The time span of the events was also not a factor in whether or not the event was identified – all events, no matter how short in duration, were classified. After these events were identified, plots were made focusing on the particular days snow depth change occurred. Measurements from the ADGs were then plotted against wind speed and relative humidities. From these plots, five categories of depth change were named – precipitation, blowing snow, combined (blowing snow and precipitation), undetermined, and unexpected.

Precipitation events were identified using relative humidities – if a relative humidity sensor indicates a constant profile of high values over time, there must be some moisture source causing this increase. Since the relative humidity sensor is at the top of the AWS (approximately 3-4 meters), the constant profile was assumed to be from precipitation falling from above. Blowing snow would produce a highly variable profile, and would not be expected to be a factor in this situation.

The blowing snow category describes events of snow depth change due to high wind speeds. The blowing snow threshold used in this case was 10 m/s – the approximate middle ground of the blowing snow threshold studies (Li and Pomeroy, 1997, Budd et al., 1966, King and Turner, 1997, and others).

The combined category describes events that occur due to both blowing snow and precipitation. The unexpected category identifies events that were not anticipated – either there was snow depth change when it was unexpected or there was no snow depth change when conditions were ideal. The undetermined category describes events that occurred with snow depth changes but no apparent reason why. These categories were tallied and are provided in the graphs in the following section.

Preliminary results

The ADG data collected has provided some interesting results, confirming some of the previously assumed characteristics of the snow pack, and providing some surprising findings. When the snow depth change events were tallied for the years from 2004-2006 for each site, precipitation events accounted for 15% of all cases, blowing snow for 6%, combined for 7%, undetermined for 32%, and unexpected for 39%. It was found that precipitation was predicted to be the primary cause of snow depth change (more than blowing snow or the combined cases) for every station but Mary site (Figure 2).

Net accumulation at all sites for this project was shown to be positive (Figure 3). Windless Bight was shown to have the highest accumulation rate, while Nascent the smallest. This matches well with informal observations taken at Windless Bight (for example, the frequent burying of AWS towers). Drygalski was also found to have a high accumulation rate. This was anticipated, as there are many influences at this site (such as maritime, katabatic, and increased cyclonic activity) that can contribute to high positive accumulation rates (Bromwich, 1989, Monaghan, et al., 2005). Accumulation at Mary site was expected to be one of the highest accumulation sites, but instead ranked in the middle of the eight sites. This indicates that the effect of blowing snow might be negative, offsetting any contributions from precipitation.

Influences of topography and the ocean were also considered. Generally, it was found that sites located close enough to a significant topographical region (such as Mary, Drygalski, Williams Field, or Windless Bight) had much greater accumulation rates over time due to the effects of orographic precipitation and katabatic wind flow than did sites anticipated to be influenced by increased cyclone activity from the nearby Ross Sea (B-15A, B-15K, Drygalski, Ferrell, and Nascent). This corroborates with modeling results, indicating that precipitation, and therefore accumulation, is higher in regions influenced by topography than those that are not (Monaghan, et al. 2005).

For the surface density measurements, it appears that, in general, the Ross Ice Shelf had densities higher than sites in West Antarctica. West Antarctica is a known area of high accumulation, in large part due to affects from increased cyclonic activity over this region, but relatively little extreme wind flow (such as from katabatics). The Ross Ice Shelf, on the other hand, has many locations with high wind speeds. Informal observations by the authors and others at these sites, particularly at Ferrell, Laurie II, and Linda sites, shows the layers of snow in this area to be quite compact and hardened by constant winds traveling over the region.

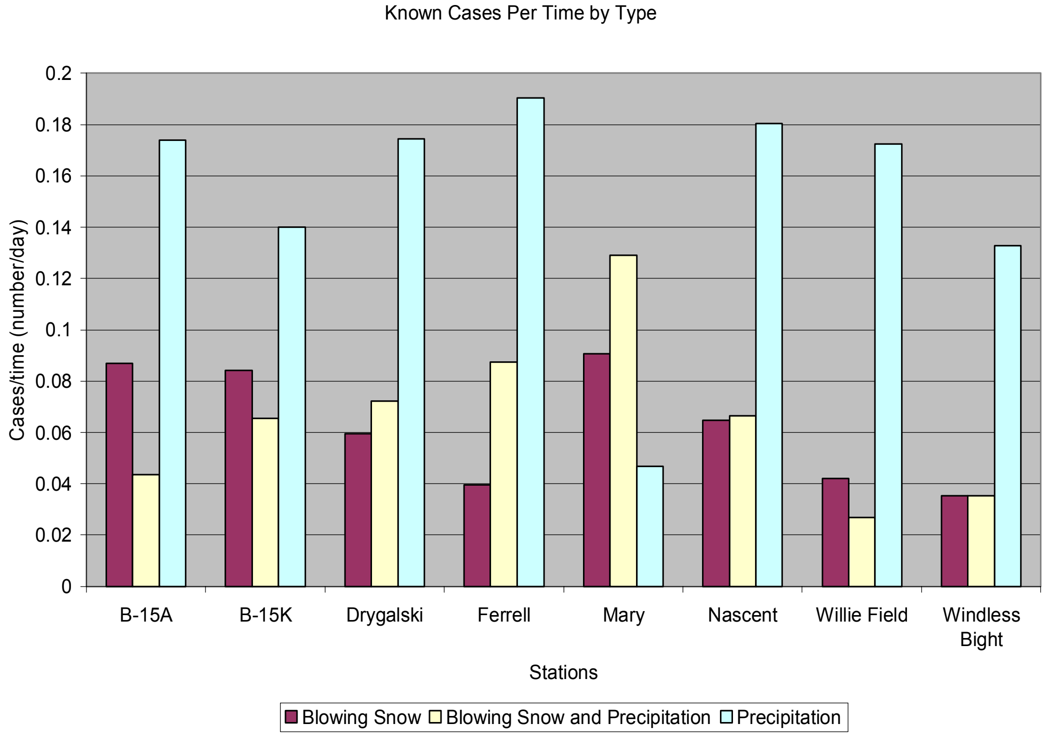

Figure 2. Plot of ADG data from 2004-2006 depicting all the known cases of snow depth change (changes due to precipitation, blowing snow, and combined events) per day. Each plot is normalized for the amount of time the station was in operation for accurate comparison.

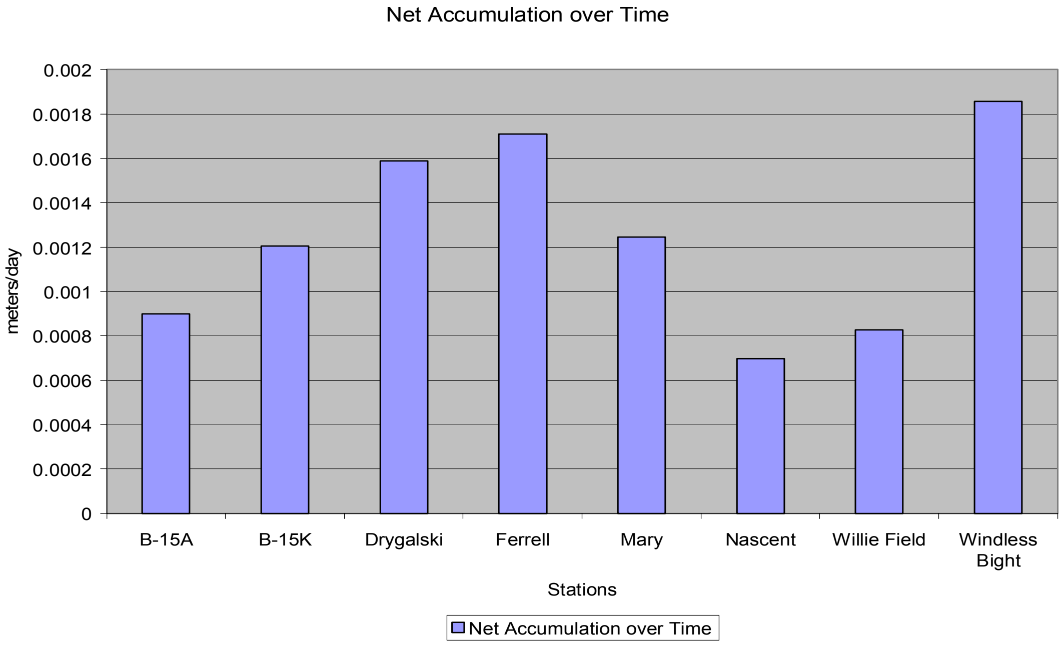

Figure 3. Net accumulation per day for each station as observed by the ADG. Stations are normalized for the time of operation.

Comparisons between the snow density data and event type case can be shown as well (Figure 4). Generally, lower snow densities should be found with precipitation events, and higher densities with blowing snow events. Only 2005 data is shown, as this was the year where nearly all stations had both ADG data and snow density data. Case events were only used from 2005, which has similar results to the combined 2004-2006 data. For 2005, snow densities were highest at Mary site, which was also shown to have the most blowing snow events. During 2005, Nascent had the most precipitation events, which correlated well with the low density data at this site.

In conjunction with snow density measurements, visual stratigraphy was performed at each site with an ADG during the 2005-06 season with the exception of Mary which was visited during the 2006-07 season. At each site, net accumulations matched up well between the ADGs and the observed layers of the snow pits. For example, at Ferrell site during 2005, measurements from the snow pit are similar to the accumulation seen from the ADG (.386 m vs. .305 m).

The most interesting result from the ADG data is how little is understood about the processes resulting in the observed depth changes. As shown earlier, there are more cases where the cause of snow depth change is unknown (undetermined or unexpected) versus known (blowing snow, precipitation, or combined). This shows that with these measurements, there is still much that is not fully understood about accumulation in Antarctica.

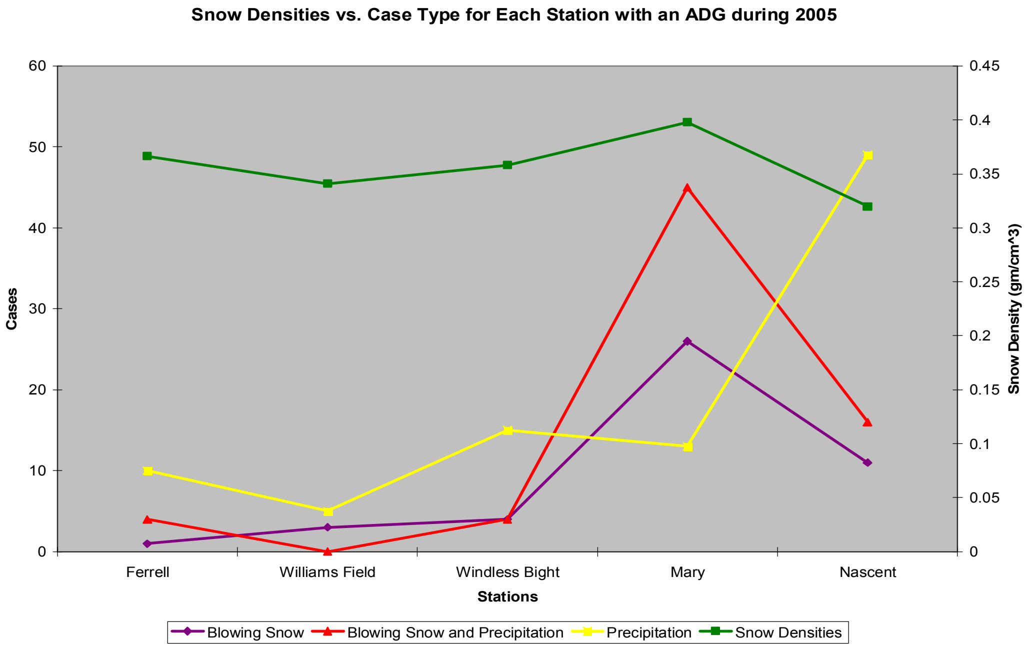

Figure 4. Snow densities for 2005 as collected from snow pit measurements versus event case type. The green line shows snow densities for each site, while the purple line shows the number of blowing snow events, the red shows the number of combined blowing snow and precipitation events, and the yellow shows the number of precipitation events.

Conclusions

For this study, the quantification and causes of snow depth change across the Ross Ice Shelf and portions of West Antarctica were undertaken using AWS and ADGs, and to a smaller degree, visual stratigraphy and snow density. The data collected was partitioned into categories as follows: precipitation, blowing snow, combined, undetermined, and unexpected. From this data, it was shown that precipitation constitutes the majority of snow depth change events. However, it was also shown that the amount of cases that fall in the unknown categories (undetermined and unexpected) were far greater than any of the known categories.

From this, it is clear that for the majority of the cases, the cause of depth change is unknown. This suggests that an overall classification of the causes of snow depth change solely from AWS equipped with ADGs is not feasible. To understand the observations, one must use the ADG observations for what they are – as a measurement of accumulation only. Then methodologies must be developed to determine the unknowns (such as sublimation or runoff) if an estimation of precipitation is to be made. This may be accomplished by using a cloud resolving mesoscale model simulation of Antarctic flow and the associated blowing snow at the surface. If this could be done, it would offer the potential for such a model to assimilate the ADG observations directly. Then the assimilated analysis would provide estimates of all of the terms that are consistent with the ADG observations. This provides the hope that ADG observations combined with all other observations through data assimilation can enable precipitation measurement in Antarctica.

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