ESTIMATION OF SNOW ACCUMULATION IN ANTARCTICA USING AUTOMATED ACOUSTIC DEPTH GAUGE MEASUREMENTS

by

Shelley L. Knuth

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science
(Atmospheric and Oceanic Sciences)

at the

UNIVERSITY OF WISCONSIN-MADISON

2007

APPROVED: ______________________________ DATE: ________________________

Dr. Gregory J. Tripoli, Academic Advisor

Abstract

Antarctica is a continent of many meteorological unknowns, the most significant of which is the temporal and spatial distribution of precipitation. Traditional methods of quantifying precipitation, such as estimates from microwave sounders, snow gauges, or radar are not feasible or not available in Antarctica at the present time. Consequently, the amount of accumulation at a given site, whether by blowing snow or falling precipitation, remains largely unknown. Acoustic depth gauges (ADG) provide the only concrete real-time information for accumulation in Antarctica. However, ADGs only measure snow depth change and not precipitation. The real issue is determining the influence of precipitation on snow depth change as observed from the ADGs.

The focus of this project is to evaluate the usefulness of continuous automated snow depth measurements for the purpose of measuring precipitation. There are two specific goals of this work – 1) to determine if the accumulation of snow at a given observation site is significantly affected by the horizontal transport of snow; and 2) to determine if measurements of snow depth change are sufficient to define precipitation patterns. This project, lasting from 2003-2006, resulted in the placement of eight ADGs mounted onboard automatic weather stations (AWS) at several locations across Antarctica. Using information from the AWS, ADG, and other data collected, preliminary studies on expected causes of accumulation at each station were conducted. The results suggested that observation of snow depth change alone was not sufficient to determine precipitation. However, closer examination of the measurements suggested that when depth observations were combined with other measurements, the potential exists to accurately estimate the contribution of precipitation to depth change.

Acknowledgments

I would first like to thank Dr. Gregory Tripoli, my advisor, for all his assistance on this project. Greg challenged me to give more than I knew I had, to "look outside the box" and question science as I knew it instead of just accepting it, and gave me confidence to assert myself when I truly believed in the research I was performing. Greg also instilled in me a fascination in field work research, first as an undergraduate when I accompanied him to Steamboat Springs, CO to complete a field experiment, and later on many storm chasing trips over the years. Greg has been an important influence on this project and my role as a scientist, and I owe him a debt of gratitude for all he has done for me over the years.

I also owe a big thanks to Dr. Charles Stearns, the principal investigator of the AWS project. Chuck gave me a job fresh out of college and opportunities to go places and do research that I could have never dreamed of. I also am thankful to the other members of the AWS project – Jonathan Thom, George Weidner, Linda Keller, and Matthew Lazzara - for all their assistance with this project. In particular, much of this work wouldn't have been possible without the help of Jonathan. I would especially like to acknowledge Jonathan for all his help with configuring the ADGs to work with the AWS units, for digging snow pits during the 2006-07 field season when I didn't deploy, for helping me understand the data and explaining to me what I was seeing, and for keeping me laughing when things got crazy. I owe much more to him than these few words alone can express. I would also like to thank George for teaching me so much about Antarctic weather, for his never-ending knowledge of Antarctica and his willingness to share it, and for being the brains behind how to read accumulation layers in the snow. George was extremely helpful when collecting snow density measurements and digging snow pits during the 2005-06 field season, and kept that field season light and funny (stay away from the pork!). Linda was of invaluable assistance in helping me when quality controlling the data, and also gave me many helpful suggestions on ways to improve my project. Linda was a sounding board when I needed to talk out the various aspects of this project, and she, with her vast knowledge of Antarctic weather and of the sometimes peculiarities of the AWS data, was of great assistance to me. Matthew was also an excellent sounding board and gave me many helpful hints on how to focus this topic. He also took on a lot of the time-consuming tasks in the office so that I could finish this thesis, and I am very grateful to him for that.

There are also several people who helped with some of the logistical portions of this project, including Dr. Gordon Hamilton from the University of Maine who assisted greatly by providing the five ADGs that were used for the majority of data collection for this project. Dr. Douglas MacAyeal of the University of Chicago supplied considerable support by offering the ADG and snow pit data from his iceberg sites, as did Katie Leonard for her Nascent and Mary snow pit data. Mark Seefeldt of the University of Colorado also facilitated a great deal of this project by deploying several of the ADGs during the 2004-05 field season. Additionally, Connie Linehan was very helpful with the logistical portions of submitting this thesis. Also, I would like to thank my two readers, Dr. Pao Wang and Dr. John Young, for their excellent suggestions when reading over my thesis.

I would also like to thank my friends, specifically Kris Wile, Steve Jaye, Jessica Staude, Nick Biermann, Heather Woods, Abby Fontaine, Sarah McDonald, and everyone else who has helped me throughout the years. The memories I have of spending time with you during graduate school are memories I will keep for a lifetime. In particular, Amanda

Adams helped me a great deal by talking me through a lot of my project and helped me to understand it better. I owe so much to her not only for this project but in shaping me as a scientist.

My family has also played an important role in molding me for my future and helping me reach this point. My parents, Charles and Susan Langfeldt, have been the fundamental, consistent role in my life in getting me to where I am today. They always believed in me, always encouraged me to go farther, and never let me hold myself back. My brother, Chuck, is also someone special to me, who has always pushed me to never settle for less.

And finally, but most importantly, I want to thank my husband Paul, who has never let me down, has never doubted me, and has been there for me through it all. Paul has been there when I thought I couldn't go on, when I suffered failures, and when I enjoyed great successes. He has always been supportive of my many adventures, and he is someone who I am lucky to have in my life. He is my rock, my one and only, and I love him now, and always.

Table of Contents

1. Introduction

Antarctica is known for having the most extreme weather on earth, from high wind speeds to bitterly cold temperatures. Until recently in history, however, real-time measurements of these conditions were unavailable, largely due to the inaccessibility of many of the remote areas of the continent. With the introduction of unmanned automatic weather stations, and the placement of manned field camps around Antarctica, daily measurements are now taken in real-time at various locations. The number of manned stations are extremely limited over many parts of the continent, with distances upwards of 1300 kilometers from station to station (Figure 1). In contrast, unmanned automatic weather stations (AWS) across Antarctica are much more abundant. In 1980, when the Antarctic Automatic Weather Stations (AAWS) program was born, less than ten stations were put out across Antarctica (Figure 2). In 2006, there were over sixty stations reporting.

While the AAWS program provides valuable weather information for many remote locations, one important part of the measurement puzzle is still missing – precipitation. At the present time, measurements of precipitation in real-time are minimal, and where there are observations collected, great biases can occur. Real-time precipitation measurements are only made at the manned Antarctic stations, where personnel, with high turnover rates, collect observations. The unmanned AWS cannot take precipitation measurements as there has yet to be developed a low-power system that can accurately measure precipitation by removing other extraneous influences. Models, such as the Antarctic Mesoscale Prediction System (AMPS), have made a first attempt at mapping precipitation across the continent but have yet to produce verifiable results due to lack of measurements on the ground (Bromwich,

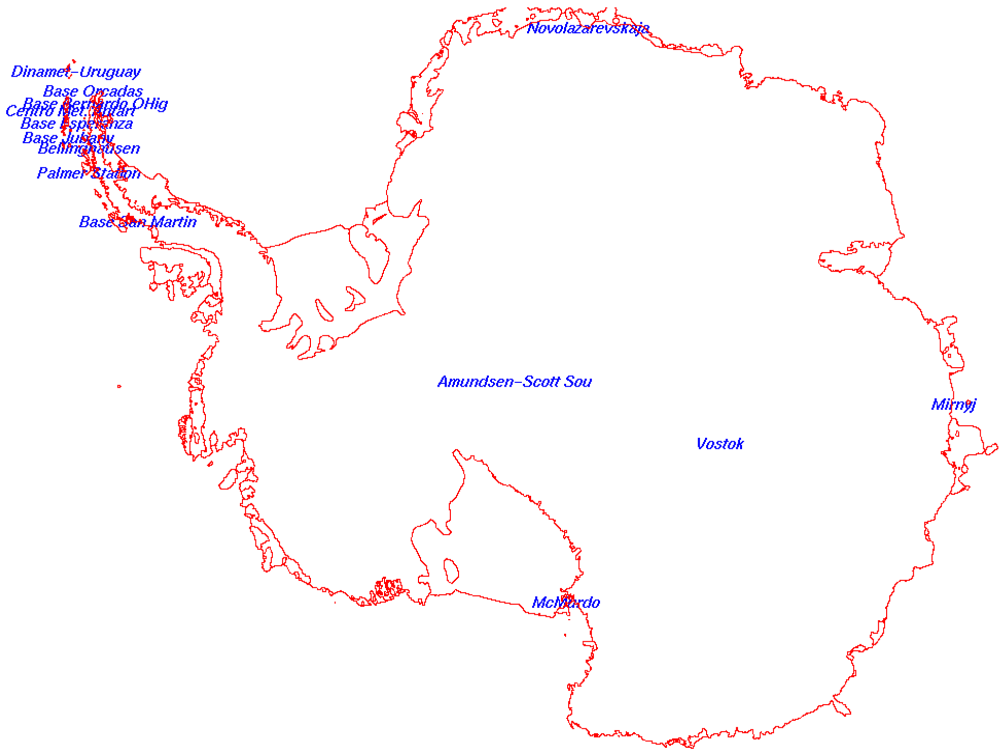


Figure 1. Map of manned stations that measure precipitation across Antarctica. Current as of 2005.

2003). Reanalysis data, while valuable, are still not actual measurements, but rather model results derived from assimilated data. Snow stakes are commonly used at manned stations, but are not available automatically or in real-time. Ice core data is currently the only available means of which to track precipitation across the continent, but this data is not available in real-time, has high spatial variability, and is only a measure of depth change. Further information is required to quantify the changes in depth prompted by precipitation.

The lack of precipitation measurements in polar regions, and specifically the Antarctic, are due to a combination of many factors. Blowing snow, issues with using microwave satellite imagery, logistics, and extreme weather are just a few challenges researchers face when quantifying precipitation. Blowing snow is arguably the most

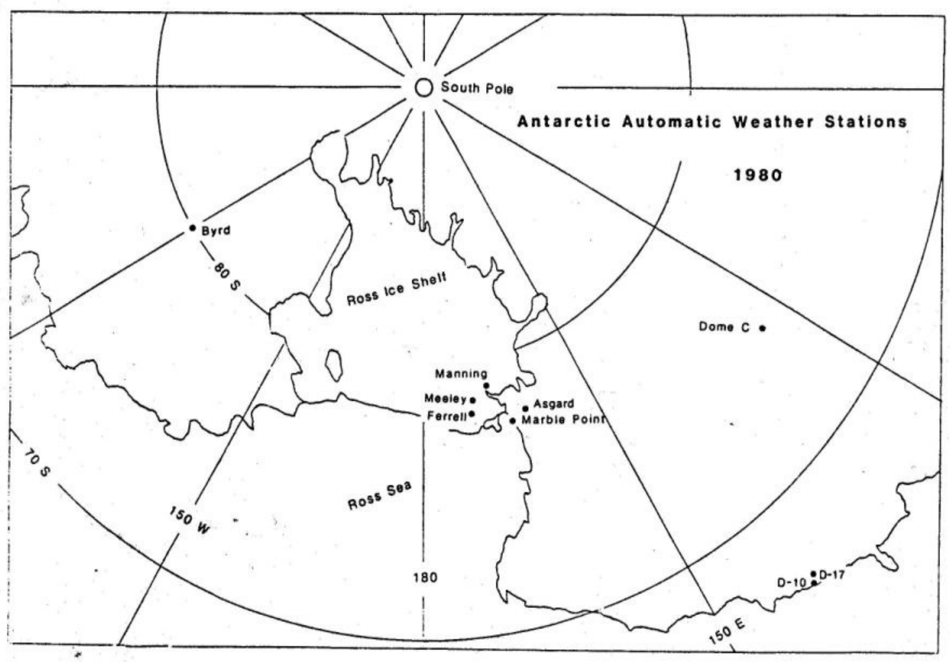


Figure 2. Map of Antarctica centered on the Ross Ice Shelf, depicting the 9 stations deployed during the first year of the Antarctic Automatic Weather Stations Project.

formidable of these challenges to overcome, as high and near constant wind speeds continuously transport snow vast distances over the unimpeded landscape. Blowing snow can add or remove snow from an area, even dominating the overall depth change in some regions. Cyclones that typically bring precipitation tend to have high speeds that blow snow, further complicating the situation.

Acquiring accurate measurements of Antarctic precipitation is important to developing a further understanding of how weather processes affect precipitation distribution and amount. Antarctica represents one of the least understood parts of the global water and energy cycle, and knowledge of the affects of precipitation on this cycle is necessary to understand the processes resulting in climate change. Assessing the water energy cycle of Antarctica is a key component of understanding the mass balance of ice sheets, potential glacier melting, and imbalances in the Earth system that may develop by adding freshwater to the ocean.

The end 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 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 already been implemented in Antarctica as part of the measurement ensemble on board the AWS. The ADGs provide the only automatic real-time accumulation measurements in Antarctica at this time.

The effects of blowing snow and precipitation on the amount of snow accumulation or ablation in a region is a consequence of topography. Topographical influences, specifically the Transantarctic Mountains and Ross Island, have two important affects. First, orographic lifting affects focus snowfall onto the windward slopes. Secondly, strong winds are generated which blow the snow accumulated along the slopes out onto the ice shelf. A variation of the equation given by Bromwich, 1988, finds the total depth change at a particular site to be:

$$\dot{D} = \left(P + B - S - R + G\right) / \rho_s \tag{1}$$

where $\dot{D}$ is the snow depth accumulation rate $\left(\mathrm{m\ s^{-1}}\right)$, P is the precipitation mass accumulation rate $\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right)$, B is the accumulation of blowing snow $\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right)$, S is net mass sublimation rate $\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right)$, R is the rate of run-off of meltwater $\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right)$, and G is the net loss or gain of snow mass due to glacial drift $\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right)$. B is given by:

$$B = \int_0^{z_b} \nabla Q dz \qquad (2)$$

where Q is the horizontal flux of blowing snow $\left(\text{kg m}^{-2}\ \text{s}^{-1}\right)$ and z_b (m) is the depth of the layer containing blowing snow. S, R, and G, as well as variations in snow density, are ignored in this study as it is beyond the scope of this project and generally assumed to be small in comparison to the P term. The snow density ρ_s $\left(\text{kg m}^{-3}\right)$ is simplified here to be a constant but in fact varies throughout the depth of the snow layer. While large variability in snow density can be found as a snow particle moves throughout time and space, this project is only concerned with snow density values as compared to other stations.

It is anticipated that the P term will dwarf all other terms in Equation 1 when averaging accumulation across the entire continent (Bromwich, 1988). In some localized regions, however, the B term may have just as much if not more of an impact on D. Modeling studies suggest that it is likely that in regions along mountain slopes ∇Q is negative while along the ice shelf, in regions prone to katabatic flows, ∇Q is positive, and may even exceed P (Monaghan, 2005, Bromwich, et al, 2004, and others). The challenge of understanding the water budget cycle is to determine ∇Q, S, and most importantly P, by measuring D.

The acoustic depth gauges measure D, which is determined by both P and B. However, there are no measurements in real-time currently available for either P or B, and only preliminary observations available (through the efforts of this project) for D. Distances between observation point sites can also be large, and consequently it is challenging to measure accumulation patterns across the entire continent. It is anticipated that satellite and model data can provide information that will aid in estimating the relationship between B and P. In fact, models simulating both B and P could be designed to assimilate depth change, and so partition D between B, P, and even S.

Precipitation can be quantified across Antarctica, but measurements from ADGs can only provide a part of the answer. A combination of methods, including surface measurements, satellite data, and model output, will all contribute to the estimation of Antarctic precipitation. This project focuses on the first step of this problem – observing accumulation at the surface from ADGs (term D). 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 main contributor of precipitation is explored. This information will provide a base for future study into the amounts and origins of precipitation across the continent. In particular, this paper is based on the following hypotheses:

1) Snow accumulation at a given site is significantly affected by the horizontal transport of blowing snow

2) Accumulation measurements alone are not sufficient to define precipitation patterns

This thesis will describe the results of this campaign. Chapter 2 will cover general information on Antarctica, as well as background information and previous research for both precipitation and blowing snow. Chapter 3 will go over the instrumentation used in this project, including an overview of the AAWS program, information regarding the ADGs, and an overview of the other data collected during the course of this project. Chapter 4 will provide descriptions of the data types and collection methods, including work completed during field seasons. Chapter 5 will discuss the results of this project, and chapter 6 will provide conclusions and information on future work.

2. Background Information

Antarctica is a continent of many meteorological unknowns. The extreme weather, elevation, and remoteness of the region make it challenging to take accurate and continuous meteorological measurements, especially in the interior of the continent. Because of this, many scientific issues are left poorly understood. The temporal and spatial distribution of precipitation and the effects of blowing snow on measuring precipitation are some of these misunderstood phenomena. This section will provide a background on completed work regarding precipitation in Antarctica, issues with blowing snow, and general information regarding the Antarctic continent.

2.1 General Antarctic Information

The most hazardous weather on earth can be found in Antarctica, the southernmost land in the world. The lowest recorded temperature on earth, -89.4°C, was recorded at Vostok station on the Antarctic plateau in July 1983 (Aguado, 2001). Across Antarctica, temperatures can average -4°C on the coasts, or up to -55°C in the interior of the continent, and wind speeds can average up to 20 m/s in certain areas (King and Turner, 1997).

Antarctica is comprised of three specific geographical regions – East Antarctica, West Antarctica, and the Antarctic Peninsula (Figure 3). East and West Antarctica are separated by the Transantarctic Mountain range. East Antarctica has the largest area of the three, covering 10.35×10^6 km^2 (King and Turner, 1997). This region is also characteristically cold and high in elevation, and is where the coldest temperatures on the continent are typically found. In general, the elevation of the polar plateau, a major portion of East Antarctica, is above two km, with areas even above four km. The polar plateau is also one of the largest deserts in the world. There are several manned stations in East Antarctica from various countries, including Vostok Station (Russia) and Dome Fuji (Japan) (King and Turner, 1997).

West Antarctica has the second largest area at $1.97x10^6$ km^2 and an average elevation of 850 m (King and Turner, 1997). West Antarctica, due to its lower elevation, is generally warmer than East Antarctica. There are also several manned stations located in West Antarctica, including Siple Dome (U.S.) and the West Antarctic Ice Sheet station (WAIS) (U.S.). The most under-represented section in Antarctica in terms of data collection is located in West Antarctica, approximately between 75 and 80°S and 90 and 145°W.

The Antarctic Peninsula is a narrow strip of mountainous land surrounded by ocean and is the only part of the Antarctic continent that is partially located outside of the Antarctic Circle. For these reasons, the Antarctic Peninsula region is generally the warmest part of the continent, earning the nickname, "The Banana Belt". The Antarctic Peninsula has the smallest area of the three at $0.52x10^6$ km^2.

Another geographical feature that is quite important to Antarctic weather is the ice shelf. The biggest ice shelf on the continent is the Ross Ice Shelf, located between West Antarctica and the Transantarctic Mountains, just off of the Ross Sea (Figure 3). The Ross Ice Shelf is a large floating piece of ice approximately the size of Texas. Ice rivers flow from higher elevations through the valleys of the Transantarctic Mountains and the Siple coast, forming an "ice lake", which is the Ross Ice Shelf. When the ice shelf reaches its maximum arbitrary size, large tabular icebergs calve into the Ross Sea. Accumulation from P and B also can assist in ice growth leading to calving. The largest calving event seen by satellite resulted in the B-15 iceberg, which broke from the Ross Ice Shelf in 2000 and was approximately 10,000 km^2 (Arrigo, et al, 2002). These large floating icebergs can disrupt local weather and ocean currents.

Figure 3. Map of Antarctica depicting various geographical locations (Adams, 2005).

Most of the Antarctic continent is covered with ice, and holds about 90% of the world's freshwater (King and Turner, 1997). Less than 3% of the surface has no ice cover for at least part of the year (Schwerdtfeger, 1984). The Antarctic ice sheet is thickest over East Antarctica, but West Antarctica is home to many ice floes, which can move as fast as 500 m/year (King and Turner, 1997).

2.1a Antarctic Weather Features

There are several key climatological weather features across Antarctica, as exhibited in mean sea level pressure charts and geopotential height fields (King and Turner, 1997). It should be noted that surface sea level pressure in the interior of Antarctica is generally around 600 mb due to elevation. In mean sea level charts, several features are distinct - a circumpolar trough of low pressure surrounding Antarctica at a mean latitude of 66°S, a weak surface anticyclone over the continent, and departures within the circumpolar trough in the form of low pressure systems (Figure 4). The circumpolar trough is strongest and closest to the continent during spring and autumn (King and Turner, 1997).

In addition to these features, there are also others that are observed in the geopotential height fields. Specifically, in the summer and winter there is a trough with several cutoff lows located over the Ross Ice Shelf region at 500 mb. At higher geopotential height levels the vortex shifts to be located more centrally over the continent (Figures 5 and 6).

In general, many of the extreme wind speeds in Antarctica are largely controlled by topographical influences, and katabatic winds are among the most intense. Katabatic winds are density driven currents, in which colder air that forms on higher elevation areas drains to lower elevation areas. The cold dome that forms in these higher elevation areas forms a localized high pressure region, while the lower elevation area has a localized low pressure region. The pressure gradient force between the two areas produces down slope sub-Rossby radius scale katabatic accelerations. In the presence of topographical features, such as mountain valleys or chutes, the focused katabatic winds can reach extreme speeds.

These katabatic winds are important to the Antarctic climate, in part because of their ability to transport snow, both falling and on-the-ground, vast distances. It is not unusual to

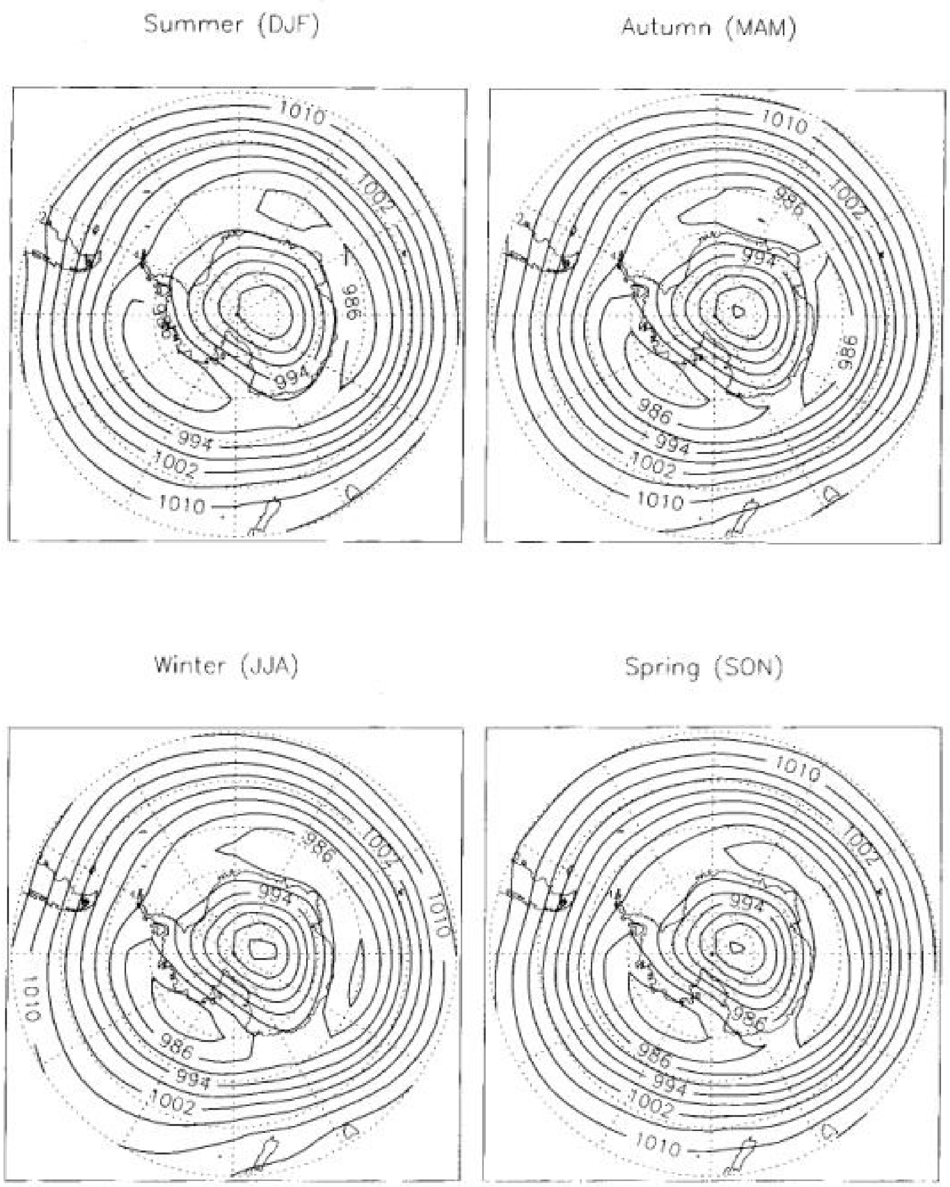


Figure 4. Seasonal average mean sea level pressure, from analyses by the Australian Bureau of Meteorology for 1972-91. From King and Turner, 1997.

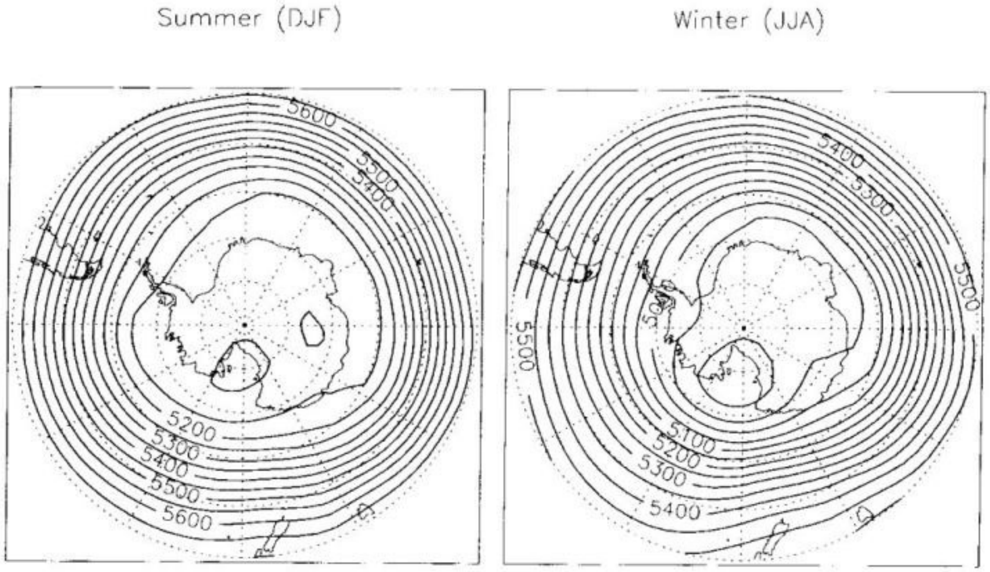


Figure 5. The average 500hPa geopotential height in the summer and winter months from analyses from the Australian Bureau of Meteorology (1972-91). From King and Turner, 1997.

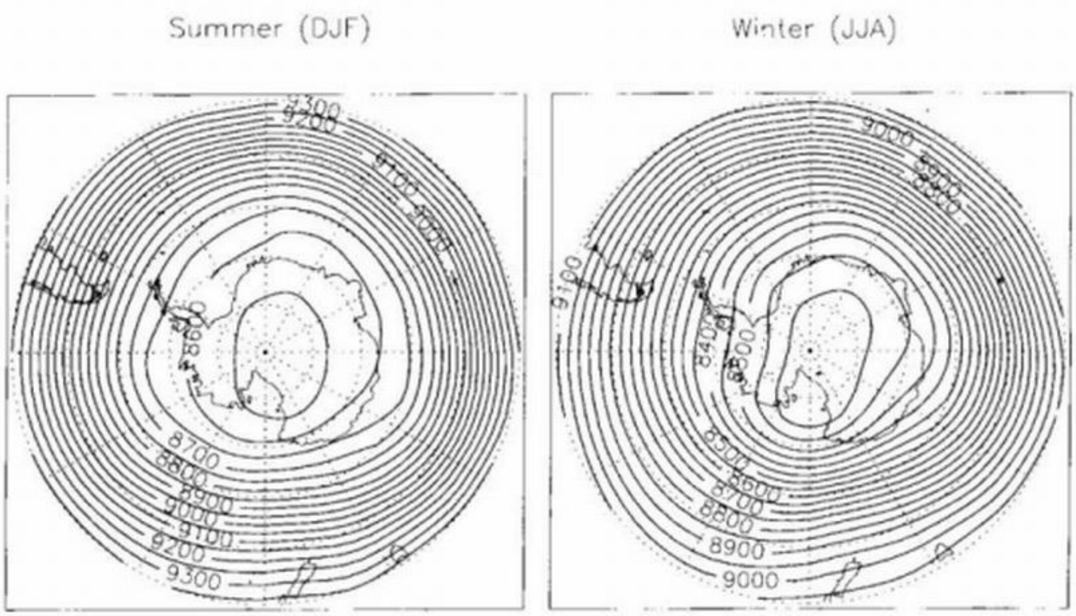


Figure 6. The average 300hPa geopotential height in the summer and winter months from analyses from the Australian Bureau of Meteorology (1972-91). From King and Turner, 1997.

observe mean katabatic wind flow from the Transantarctic Mountains to be in excess of 20 m/s or more (King and Turner, 1997). The katabatic winds of most interest to this project are those that drain from the polar plateau to the Ross Ice Shelf through the valleys of the Transantarctic Mountains. To a limited degree, katabatic influences from regions near Terra Nova Bay, and specifically David Glacier near the Drygalski Ice Tongue will also be explored (Figure 7).

The two places of greatest interest to this study, the Ross Ice Shelf and to some extent, West Antarctica, are two of the most meteorologically interesting on the continent. The Ross Ice Shelf in particular consists of an area dominated by low pressure, high radiation losses to space, and extreme winds. It is anticipated that there is less precipitation on the Ross Ice Shelf near the coast than surrounding areas due to the lack of topographical lifting, but as the topography increases inland the precipitation increases. Accumulation on the Ross Ice Shelf can be high due to blowing snow from katabatic wind flows or cyclonic activity.

Unlike the Ross Ice Shelf, West Antarctica sits atop a rugged landscape, and has many more variations in topography. Because of this, there is generally increased accumulation in certain areas, most likely due to precipitation influenced by a combination of local topography and local wind patterns that displace the snow from where it initially falls. The increased topographical influences also have an affect on increased cloud cover. The International Satellite Cloud Climatology Project (ISCCP) has shown there to be more cloud cover over West Antarctica than other areas of the continent (Schiffer and Rossow, 1983 and Schwerdtfeger, 1970). It has also been determined that cyclone activity onto the continent from the ocean is more frequent in both West Antarctica and the Ross Ice Shelf/Ross Island regions than surrounding areas (Carrasco, et al, 2003). This increased cyclonic activity is likely responsible for increased accumulations due to the ability of the cyclone to transport moisture from the Antarctic ocean inland and then lift that flow both dynamically and with the assistance of topographic barriers.

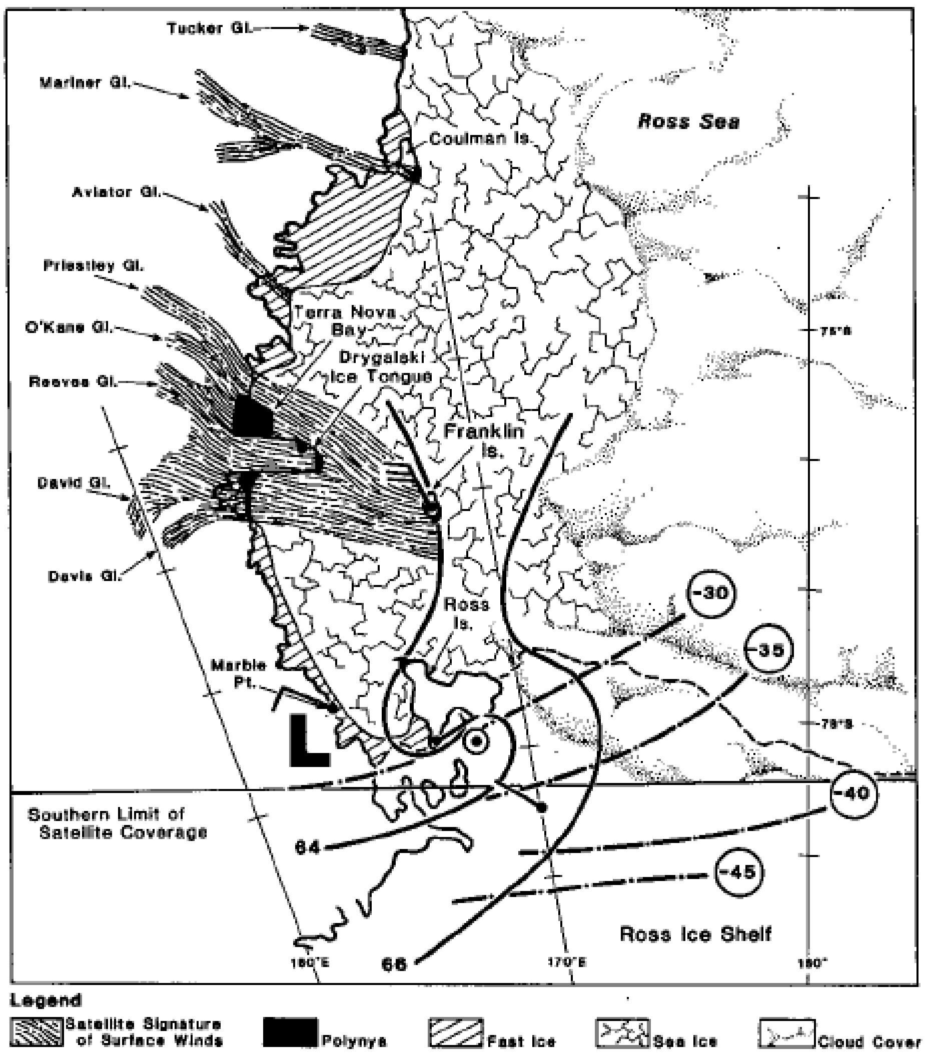


Figure 7. Depiction of influence of wind flow on the Drygalski Ice Tongue and areas to the west of Franklin Island (Bromwich, 1989).

2.2 Precipitation in Antarctica

Precipitation is an important part of depth change at the surface, as it represents the input of snow from the atmosphere onto the continent. At present, estimations of the general snowfall accumulation across the continent from precipitation have been largely assumed from ice cores, remote sensing techniques, or assimilated analyses. Real-time direct measurement of precipitation across much of Antarctica has not been a realistic option. Many issues, most importantly the extreme weather across the continent, prevent sound and accurate measuring of precipitation at this time.

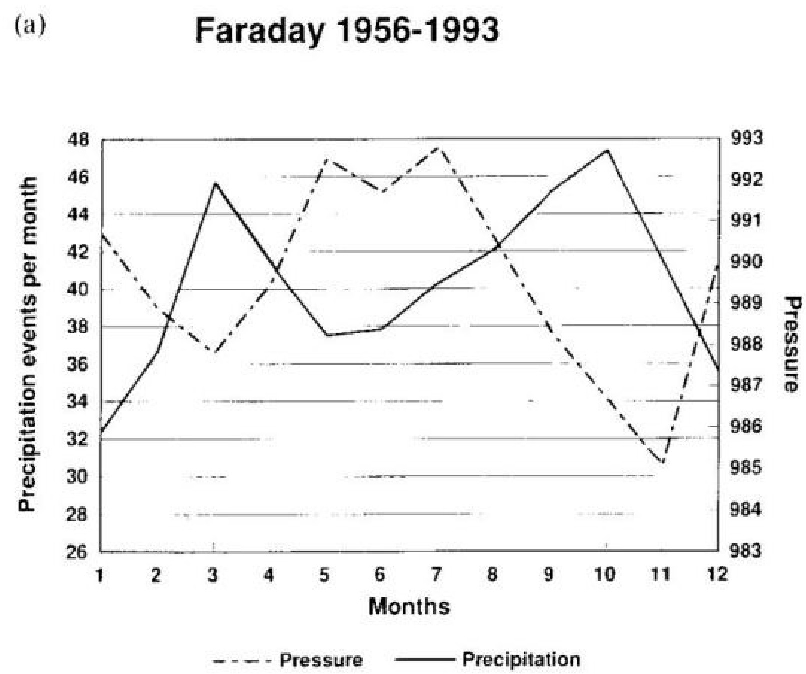
Nonetheless, the general climatology of Antarctic precipitation is understood at some level from the current data available. It is believed that the coastal regions tend to receive more snowfall than the interior of the continent. Precipitation in these areas is enhanced due to the proximity of the warmer ocean waters, coupled with higher moisture values and more cloud condensation nuclei (CCN) from the salty water. Also, the ice edge of Antarctica tends to be quite steep and topographical regions influenced by cyclonic activity entering the continent from the broad ocean waters increases precipitation in these areas. The Antarctic Peninsula (also a coastal region) generally has the greatest precipitation amounts due to the inception of moist flow from the oceans as well as typically having the warmest temperatures on the continent. Temperatures in this region average -5°C in the winter and 0°C in the summer (King and Turner, 1997). The highly variable topography of the Antarctic Peninsula also contributes to increased precipitation from upslope flow.

The interior of the continent, and in particular the high polar plateau, sees very little if any precipitation. Cyclones rarely reach this far inland and away from baroclinic forcing. If any circulation does penetrate onto the high plateau, little moisture is left for it to produce precipitation. Precipitation on the high polar plateau, including near the South Pole, comes largely in the form of "diamond dust", which is precipitation that falls from the clear sky as radiation cools the air to extremely cold temperatures forcing even small amounts of moisture in the air to nucleate onto tiny ice crystals.

The West Antarctic and Ross Ice Shelf regions have varying precipitation rates. As mentioned earlier, the Ross Ice Shelf is anticipated to have less significant precipitation than other areas, due to the flatness of the area and lack of topography. However, this area is near the coast and does experience many cyclones that traverse the area and produce precipitation. As discussed earlier, increased cyclone activity over West Antarctica leads to larger precipitation values for this region. Topography in West Antarctica also leads to increased precipitation in that region.

The importance of topography in precipitation accumulation cannot be overstated. In particular, the southern edge of the Transantarctic Mountains and the windward side of Ross Island see increased precipitation due to orographic effects (Monaghan, 2005). Precipitation is also shown to fall on the leeward side of the island – however, this is largely due to cyclonic activity in the Ross Sea as well as eddy shedding of vortices that split as they travel around Ross Island.

Seasonally there are variations in the amount of precipitation, largely due to the amount of cyclonic activity that reaches the coasts of the continent from the ocean (Figure 8). Spring and autumn receive the most precipitation on the coast, as more cyclones are generated by the variations in weather during these volatile seasons (King and Turner, 1997). Precipitation rates in the interior of the continent, specifically on the polar plateau, are not expected to have great variations as cyclones have a difficult time overcoming elevation



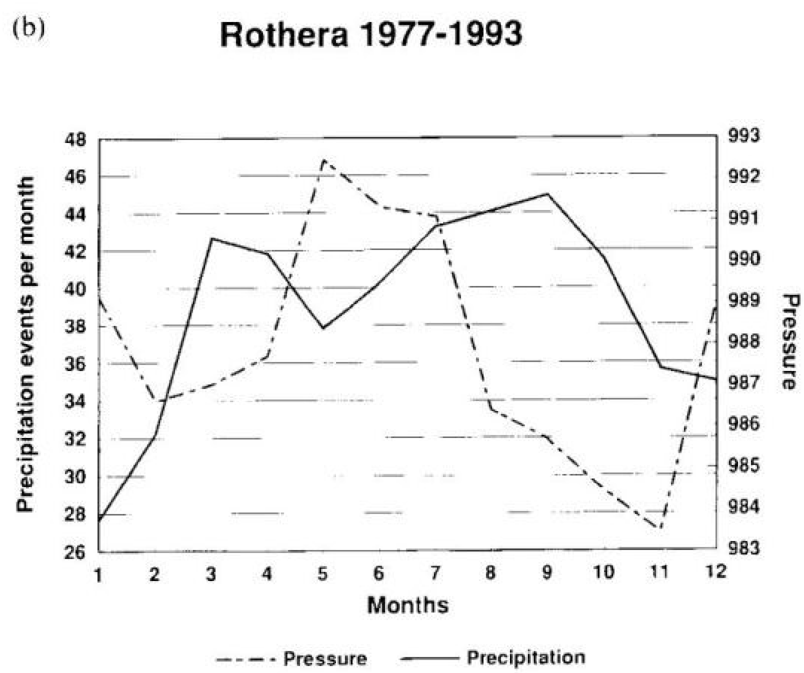


Figure 8. Monthly mean sea level pressures and comparative precipitation events at a) Faraday and b) Rothera. From King and Turner, 1997.

obstacles, and rarely reach the far interior of the continent. Also, low moisture contents in these areas prevent much precipitation from falling at any time of the year.

General accumulation rates across the continent can be seen in Figure 9, and are assumed to be precipitation rates, which is only a fair estimation in the interior of the continent. Accumulation rates from this study are representative of the observed general climatology of Antarctica.

There has been some recent work on attempts to quantify precipitation using the European Center for Medium Range Forecasts (ECMWF) reanalysis data (Briegleb and Bromwich, 1998, Cullather, et al, 1998, Bromwich et al, 1998), but these methods are not foolproof as the reanalysis is also extrapolated numerical "data". One such study, Massom, et al, 2004, compares the reanalysis data to in situ AWS and passive microwave remote sensing data to examine the amount of precipitation falling over the East Antarctic due to penetrating cyclone events. While this study has some good first results, the authors note that further research is needed, namely on the ground measurements, to provide a more complete understanding of the dynamical processes and true surface precipitation amounts.

Another project using reanalysis data to quantify precipitation, as described in Bromwich, et al, 2004, is important, as it has provided the first attempt at continent-scale mapping of precipitation. This study uses the Antarctic Mesoscale Prediction System (AMPS), a fifth generation version of the MM5 modeling system, to measure the temporal and spatial variability of accumulation due to precipitation across the continent. The study, using a "dynamic retrieval method" which utilizes dynamic variables within the atmospheric model to predict precipitation, compares simulations to climatological analyses of accumulation and reanalysis datasets. The analysis of precipitation is then compared with snow drift effects by using wind variables in the model.

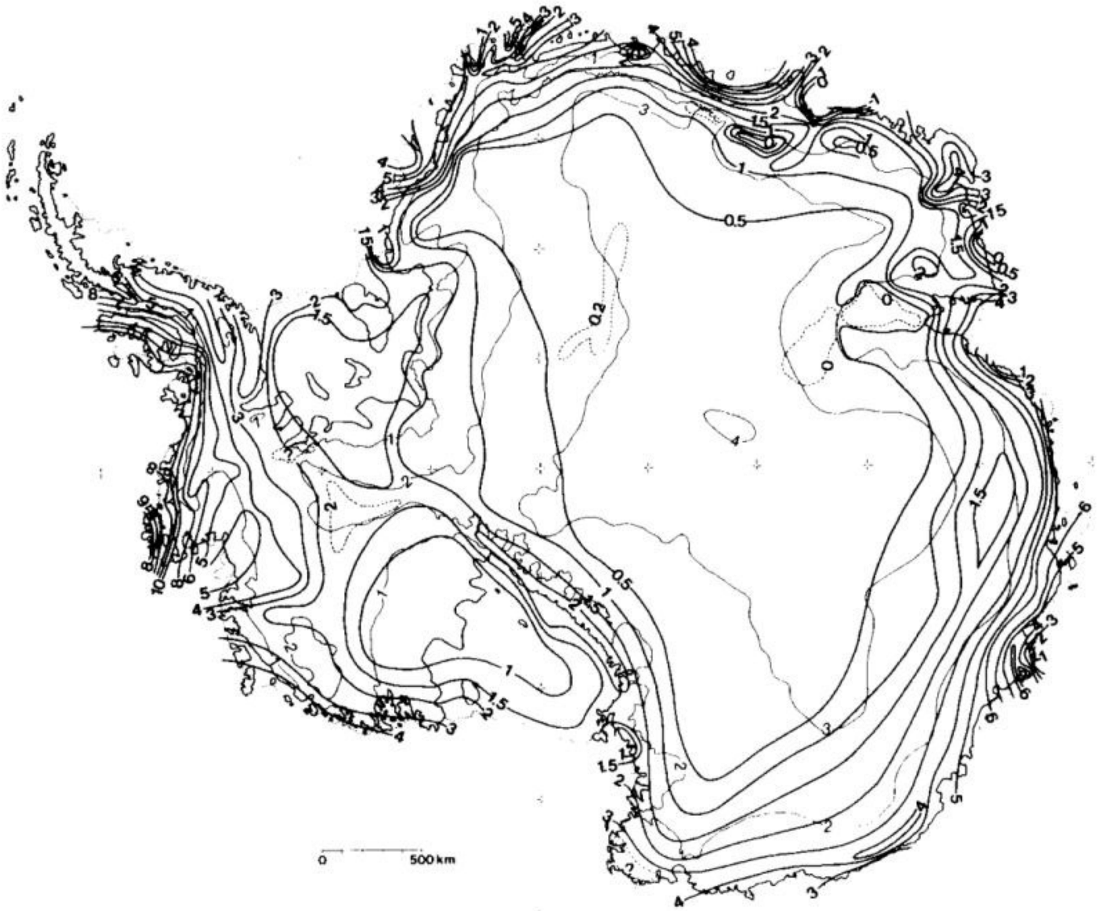


Figure 9. Estimated accumulation over Antarctica. Light solid lines are elevation in km, and heavy solid lines indicate accumulations of 100 kg m^{-2} yr^{-1}. (From Bromwich, 1988).

While the simulations seem to match well with the climatological and reanalysis data, the project is not without its flaws. The model finds it difficult to match simulations of the spatial distribution of precipitation minus evaporation (sublimation) with accumulation maps in certain areas of the continent, especially in some areas with strong katabatic winds or low accumulation rates. It is anticipated that the coarse resolution of the model (the simulations in the innermost grid were at 60 km) was also the cause of poor comparisons in coastal regions and parts of the interior. It is generally found that the AMPS model is overestimating accumulation in the coastal regions and underestimating accumulation in the interior near severe topographical regions. The AMPS model estimates precipitation over the entire continent to average 215 mm/year.

An important study conducted by Monaghan, et al, 2005 produced the first ever climatology of the McMurdo region. Using a high resolution 3.3 km version of the AMPS model, Monaghan found that topography led to a precipitation maxima along the southwestern slopes of the Transantarctic Mountains, as well as the southern slope of Ross Island. This study, however, was conducted using model output alone – observations depicting the value of D from Equation 1 were not available for validation.

Further preliminary studies by the author have also shown precipitation to be concentrated in highly topographical regions (Figure 10). Several case studies of significant snow accumulation events, as detected by the acoustic depth gauges, were consistent with precipitation being focused along the slopes of the Transantarctic Mountains and Ross Island areas.

2.2a Precipitation Measurement Challenges

Measuring snow is very challenging, and Antarctic precipitation is especially complicated. There are many factors that prevent accurate precipitation measurement, including issues preventing measurement from microwave satellites, logistical problems,

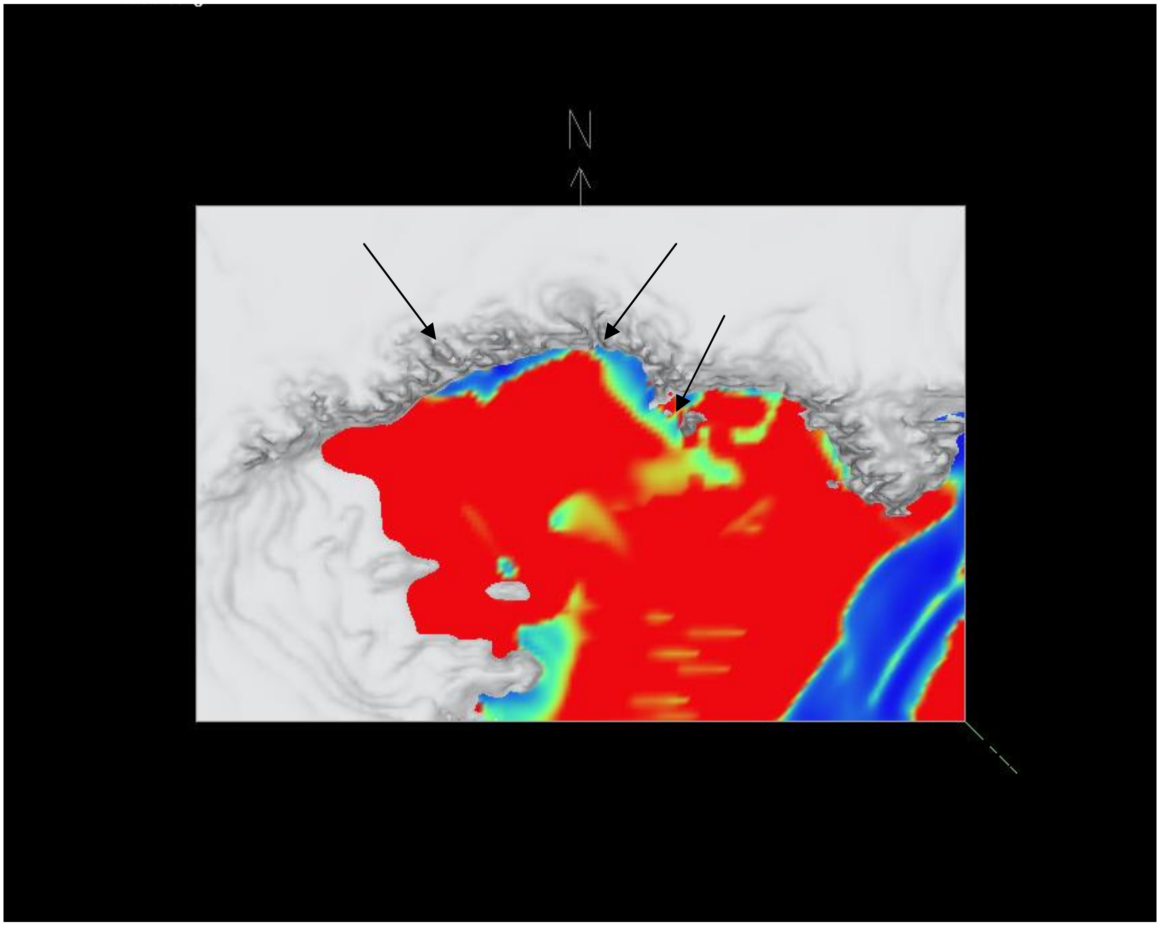


Figure 10. Image from the University of Wisconsin Nonhydrostatic Prediction Model showing precipitation focused along the Transantarctic Mountains and the windward side of Ross Island (indicated by arrows). Output from 26 April 2004.

extreme weather conditions, and most importantly, blowing snow. Microwave satellites have been proven to be reliable estimators of precipitation in the tropic regions, especially over ocean areas, but the technology is not yet in place to make these instruments accurate estimators of precipitation over polar regions (Todd, et al, 2001). Conventional measurement techniques break down when measuring snow because small snow particles are poor scatterers of the conventional microwave frequencies, and falling snow contrasts poorly against a surface snow cover background. Also, microwave satellites do not distinguish between blowing snow and falling precipitation, and thus can suffer from the same blowing snow limitations as surface measurements.

In most mid-latitude regions, weather and logistical issues play a relatively small role in inhibiting accurate and frequent measurements of meteorological conditions, but in the Antarctic this is one of the largest contributors to poor measurement coverage. Weather in Antarctica is the harshest on earth, making measurement of weather variables a logistical challenge. Automatic weather stations have partially alleviated this problem in many parts of the continent, as these stations provide real-time weather information for remote locations all year round and do not require on-site personnel to take measurements.

The most troublesome component to measuring precipitation, above all of these, is blowing snow. Traditional measurement techniques designed to detect P directly, such as snow gauges, snow stakes, or snow fences, are at present not plausible for use in Antarctica as snow blows into and out of these measurement areas, making it extremely difficult to be able to determine what snow has fallen into the gauge as precipitation and what has merely been advected in from another location. Additionally, high wind speeds and high accumulation rates can sometimes cause these devices to be blown away by the wind or covered by snow before it is feasible for personnel to reach the site. Cyclones, which often are the contributors of precipitation, especially toward the coastal regions of the continent, are typically also accompanied by high wind speeds. Topographical influences, which also contribute to Antarctic precipitation, can also have high wind speeds associated with these areas as wind rushes from higher elevations to lower. The unimpeded landscape of Antarctica, in particular on the Ross Ice Shelf, can cause snow to be transported great distances from where the snow initially falls as precipitation.

Other types of data, such as satellite or ice core data, have been used to quantify seasonal snow depth changes, but these methods cannot separate B from P. Satellite data can only measure the change in surface height, and displaced snow at the surface that does not actually accumulate on the ground can be misinterpreted in the data (Bromwich, et al, 2004). Ice core data is expensive to recover and is only located in a few key areas, so continent-wide mapping is not plausible.

2.2b Precipitation Measurement Processes in Antarctica

For these reasons, attempts at measurement of precipitation in Antarctica are taken regularly only at certain manned stations. For the United States program, this is McMurdo Station, Palmer Station, and South Pole Station. At McMurdo Station, precipitation is measured from the top of Building 165, or the "MacWeather" building. A large white metal canister is taken up to the roof where snow is collected. Every six hours, an observer goes to the top of the roof, and when precipitation is available to be measured, brings the white canister inside. Hot water is poured along the sides of the white canister to melt the snow within. Once the snow is entirely melted, the remaining liquid is poured into a giant black container with a standing ruler, and the amount of the liquid equivalent is measured.

Palmer Station uses a method similar to McMurdo Station, using a rain gauge to collect precipitation. The rain gauge is made by the NovaLynx Corporation and is surrounded by a wind screen to reduce evaporation and sublimation, as well as blowing snow out of or into the gauge. Measurements are taken on a flat, rocky surface at ground level. Any solid precipitation is electronically heated and melted, and the liquid equivalent measured. The gauge is a tipping bucket, where the bucket tips for every 0.01" of liquid precipitation measured. Measurements are transmitted on the PalMOS system, and are taken every 2 minutes.

South Pole in general does not take a precipitation measurement. Since South Pole receives little precipitation over a yearly basis, the meteorology observers simply report this precipitation as a “trace”. This accounts for diamond dust or any other precipitation that would be seen at the station.

2.3 Quantifying Blowing Snow Across Antarctica

Blowing snow is a vital component of the weather in Antarctica. It is important for aircraft visibility, for tracking wind movement, and in determining the mass balance of the ice sheets (Holmes et al, 2000, Vaughn et al, 1999, Gallée, 1998). Blowing snow also accounts for a large portion of the accumulation or snow removal at point sites across the continent. Blowing snow can have an affect on the local climate by transporting precipitation to other areas of the continent than where it had fallen (King and Turner, 1997). Recent work has shown that blowing snow may alter katabatic winds by increasing moisture levels in the wind layer (Wendler, et al, 1993 and Gosink, 1989). Acquiring accurate measurements of the amount of snow that is being lofted from place to place is important, as blowing snow (along with precipitation and sublimation) is one of the largest factors contributing to snow accumulation (Bromwich, 1988). In Antarctica, blowing snow is a very common phenomenon, as wind speeds are quite high in many parts of the region.

2.3a Blowing snow

Blowing snow represents the mass of snow that is advected away from or onto a location during periods of strong winds (King and Turner, 1997). There are two types of mass transport of snow – drifting and blowing. Drifting snow occurs when light winds – between 5 and 10 m/s – carry snow particles to a level only slightly above the surface (Schwerdtfeger, 1984). Blowing snow is stronger – snow particles are lifted from the surface to two to hundreds of meters in the vertical, greatly reducing visibility. Schwerdtfeger also points out that availability of snow is imperative. While in Antarctica, this is never a problem, there does need to be fresh snow at the surface which is easily movable and not as likely to remain on the ground. Snow is less likely to move after several days of light winds and no precipitation because of a thin crust that will form on the surface and impede movement.

The dynamical processes behind the effects of blowing snow are quite simple. When the wind stress on a snow surface becomes too large, snow grains will be lifted and blown through the air at a level above the surface. The ability for the particles to be lifted from the snow surface is, in part, dependent on friction velocity, which is further dependent on the snow surface, and the age of the snow.

If a particle returns to the surface, only to be lofted again, it will take with it several more snow granules. This process is referred to as saltation (King and Turner, 1997). Once elevated from the surface, these particles can be lifted further into the atmosphere by turbulent eddies, depending on how fast the wind speed is. At this point, the particles reach a state of suspension, and do not return to the surface for some time. In this situation, the upward lifting of the particles by turbulent diffusion is balanced by gravity, allowing the particles to remain aloft.

Attempts at calculating a benchmark wind speed for blowing snow, below which snow would remain at the surface and above which snow would be lofted in the vertical, have been well documented. King and Turner, 1997 and Schwerdtfeger, 1984 use a blowing snow threshold of 10 m/s for the Antarctic, based on comparisons of several studies. Li and Pomeroy found threshold wind speeds in the western Canadian prairies to be between 7 and 17 m/s for dry snow, as measured at 10 m. Budd, et al, 1966 found much higher threshold wind speeds, at 14 m/s, for areas of Antarctica with extremely cold temperatures. The threshold wind speeds are related to conditions of the snowpack, as related to snow particle bonding, cohesion, and kinetic properties which are a function of snow temperature (Li and Pomeroy, 1997).

There have been some important field campaigns conducted in which real-time blowing snow measurements were acquired. The Byrd Snow Drift Project, conducted during 1962-1963, is an important landmark study of in situ blowing snow measurements (Budd et al, 1966). This project coupled snow drift gauges at varying levels above the snow surface with wind speed measurements at Byrd Station in West Antarctica (approximately 80˚S 119˚W) with the purpose being to measure snow accumulation as related to wind speed. Some key findings from this study include the affects of snow roughness on blowing snow transport, the drift density profile, and snow particle distribution. Most importantly, it was found that significant blowing snow was confined to the lowest 10 meters of the boundary layer.

A more recent study at the South Pole, combining ground based infrared and lidar data with measurements from ground personnel has developed a climatology of blowing snow at this location (Mahesh, et al, 2003). One surprising finding from this study was that the surface layer of drifting particles was several meters thicker than previously thought by scientists.

Another recent field campaign was conducted by Braaten, 2000, which involved documenting snow accumulation at a point site on the Antarctic polar plateau using three types of surface measurements – an ADG, snow stakes, and snow tracers. The ADG measured snow accumulation by calculating the distance to the snow surface. Five lines of snow stakes were placed at the site (53 bamboo poles total) as part of the measurement collection. The snow stakes were intended to acquire a good characterization of the spatial variability of the snow accumulation at the site. Microsphere tracers of varying colors were dispersed by an automatic device meant to trace snow accumulation with much greater time resolution. Four different colors were used over the 12-month collection cycle, with each color being dispersed every 14 days for 3 months. The tracers were collected by digging snow pits at various distances from the dispersive source and melting the ice at specific depth levels in the lab.

The ADG observed only a few accumulation events, but these events totaled up to 88% of the total accumulation. Comparisons to satellite data showed no single meteorological pattern for the accumulation events, but measurements at the nearby AGO-2 site indicated wind speeds below the blowing snow threshold, indicating that precipitation was the main cause of accumulation. However, the ADG can only measure a small area at the site, so these measurements compared to the snow tracer and snow stake measurements were vital. The snow tracer data indicated several more accumulation events at varying distances from the ADG. Microsphere tracers, unlike the ADG, could not give an accurate time estimate of the accumulation event, except to note that the event must have occurred during the 14 day period in which the tracers had been dispersed. This study is particularly important as it depicts actual surface measurements using differing methods at a particular point site, similar to the methodology of this project.

When precipitation falls, it typically (although not always) is accompanied with a storm system which also produces strong winds. Winds were shown to be produced by a topographically trapped Kelvin wave effect along the Siple coast that creates flow surges that may exceed the strength of the katabatic winds (Adams, 2005). Modeling evidence suggests that snow produced along the slopes of the Siple coast and Transantarctic Mountains from orographic uplift can then be driven out onto the Ross Ice by these surges of strong flow. Consequently, in order to make an accurate determination of the amount of precipitation that falls at any given location, one must also be able to accurately partition accumulation between P and B.

3. Data Acquisition and Instrumentation

Without instruments, data collection would be impossible. In Antarctica, scientists rely on automated instruments to provide key data that would not otherwise be collected, as extreme conditions and the remoteness of the continent prevents observers from continually reaching certain locations. For this study, instruments and the data collected from these instruments are vital to understanding the weather and its effect on precipitation measurement. This section will discuss the instruments and data collected that are important to this study, namely the AWS, and the corresponding instruments located on board these stations, specifically the ADGs.

3.1 Antarctic Automatic Weather Stations

Automatic Weather Stations (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 produced by Stanford University, the U.S. stations were first placed in Antarctica in 1980 on a project developed by Dr. Charles Stearns at the University of Wisconsin-Madison. During the first year there were only nine stations largely located in areas along the coast of the Antarctic continent. In 2006, there were approximately 60 stations actively operating, with some of the original stations from the early 1980s still active (Figure 11). Approximately 100 stations have been deployed to Antarctica in the period from 1980-2006. 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.

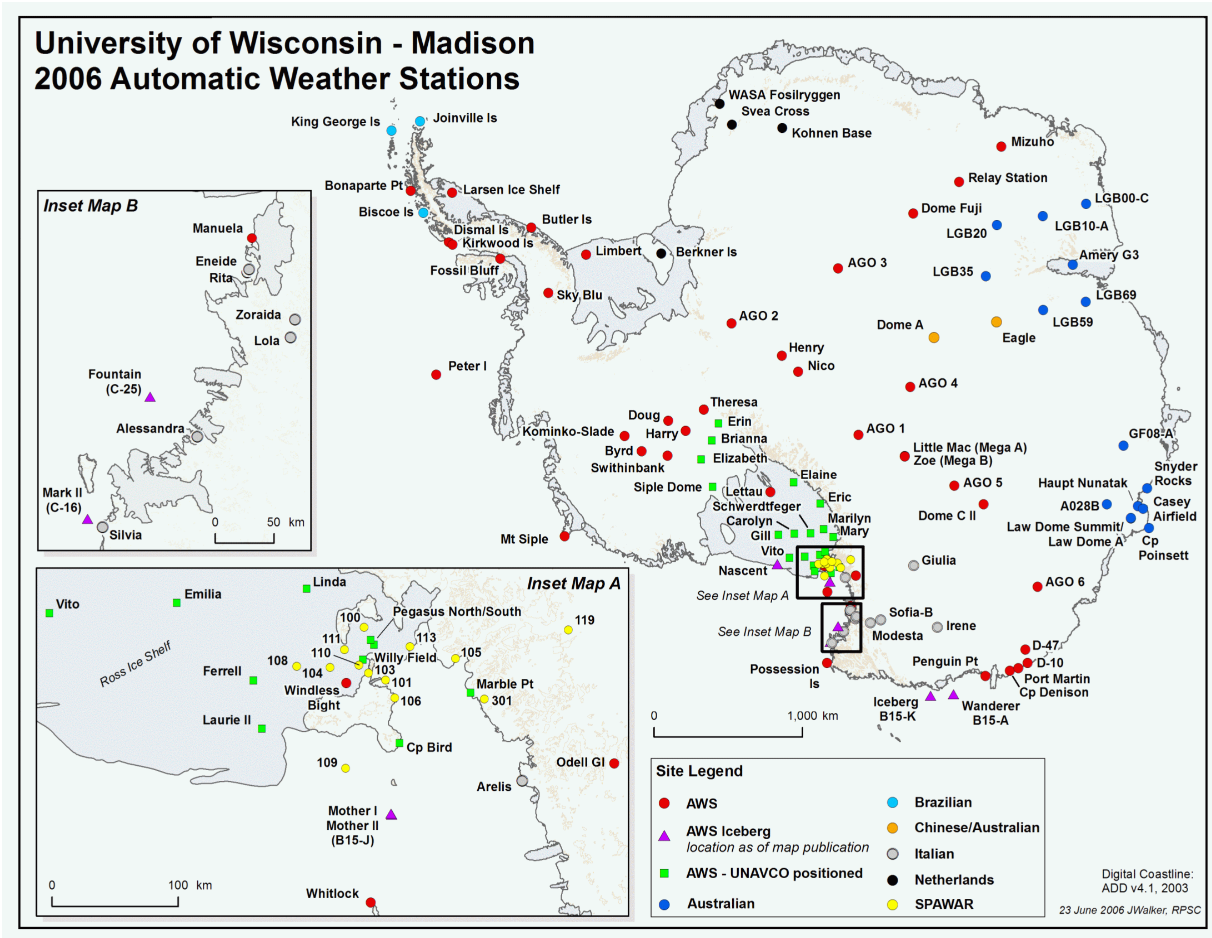


Figure 11. Map of the Antarctic continent depicting the locations of all operating AWS units. Current as of 2006.

The AWS units take basic meteorological measurements, including air temperature, pressure, wind speed, and wind direction. Newer AWS units also measure relative humidity (with respect to liquid water) and vertical temperature difference. The air temperature, relative humidity, wind speed, and wind direction are measured at a nominal height of three meters above the surface, and the pressure is measured in an enclosure box at 1.75 meters. Vertical temperature difference is measured from three meters to .5 meters above the snow surface. The height of the tower depends on the amount of snow accumulation or drifting at the base of the unit, but each tower is generally three meters. Temperature profiles can also be placed within the snow surface to measure snow temperature at various depths (Figure 12).

The data collected by the AWS is both stored on a data logger on board the unit as well as transmitted via the Service ARGOS data collection system (DCS). The ARGOS DCS are on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series. The data is transmitted from the AWS units to the ARGOS DCS system, which is then sent via direct broadcast to various ground stations. The data can only be transmitted via ARGOS DCS when the satellites are within view of the AWS unit, which occurs approximately once every hundred minutes per satellite (Stearns et al, 1993). At any given time, there are two ARGOS satellites in orbit.

The stations are powered year-round by solar panels and batteries. Six 12-volt gel-cell batteries and one solar panel are sufficient to power the stations near McMurdo, but twelve gel-cell batteries and two solar panels are required for areas near South Pole. Occasionally, the station will stop transmitting due to lack of power as battery capacity decreases with time, but in general this system is sufficient for uninterrupted operation.

3.2 Acoustic Depth Gauges

The sensors used to detect depth change at a point site for this study were acoustic depth gauges (ADG) (Figure 13). 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. The amount of

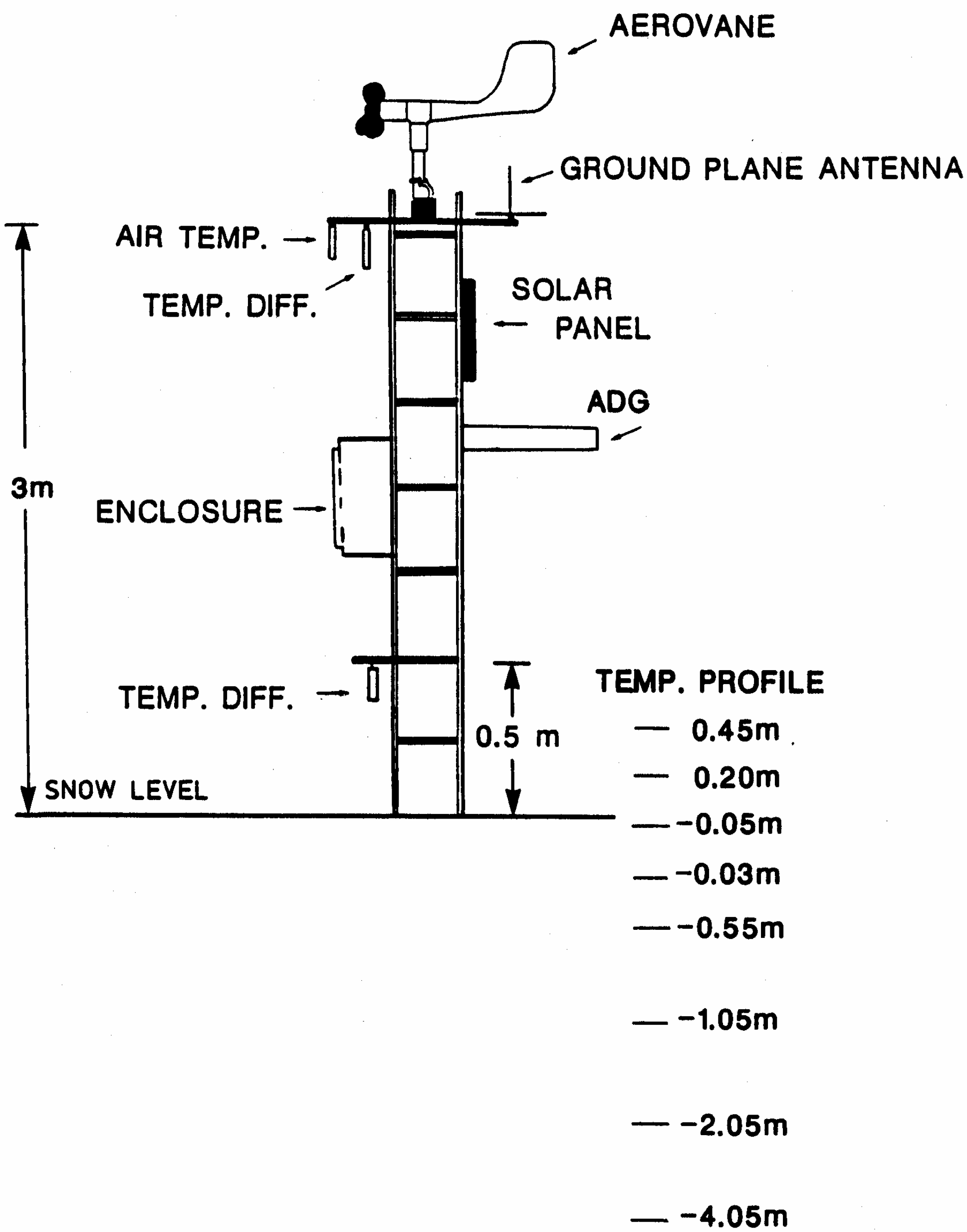


Figure 12. Depicts a schematic drawing of a typical AWS unit in Antarctica. Temperature, wind speed, and wind direction are measured at a nominal height of three meters at the top of the tower. Pressure is measured in the enclosure box, located at approximately 1.75 meters above the snow surface. The temperature difference is measured between 3 meters and .5 meters above the surface.

Figure 13. Image of the Campbell Scientific ADG, model SR50.

time it takes for the signal to transmit and then return to the ADG is the distance to the object. Each unit was placed onboard an AWS at varying heights, with the ADG facing the snow surface. When snow accumulates or disperses from beneath the ADG, the distance to the snow surface can be determined. The ADGs were mounted on board AWS at specific sites, relaying information about snow accumulation or ablation at the particular site.

The type of ADG used for this project was developed by Campbell Scientific, Inc., model #SR50. The SR50 acoustic depth gauges were supplied by Gordon Hamilton from the University of Maine, and were formerly used in the International Trans-Antarctic Scientific Expedition (ITASE) project. Four of these ADGs were placed at Williams Field, Windless Bight, Mary, and Ferrell. Four additional SR50 ADGs provided by Dr. Douglas MacAyeal of the University of Chicago were installed at B-15A, B-15K, Nascent, and Drygalski. This model requires 9-16 volts of D.C. power, and consumes 250 mA of power at its peak, and are typically active for approximately .6 seconds (Campbell Scientific, 2003). Its resolution is .1

mm, and is 31 cm long, has a diameter of 7.5 cm, and weighs approximately 1.3 kg. The SR50 units can be used within the temperature range of -45°C to -50°C. Depending on the configuration of the station, the data is either transmitted in real-time via the ARGOS system, or stored in memory on the station to be retrieved at a later date.

Each ADG is placed on a boom that extends out from the tower of the AWS. The base of the sensor faces the snow surface. On each tower the ADG hangs from an arbitrary level, based on the preferences of the deployment team. The beginning height of the ADG can vary from station to station with no influence on the end data result, as comparisons in changes of height, not absolute height, are considered. Table 1 gives the distances from the sensor to the snow surface at the time of the installation.

AWS Sites	Lat/Lon	Distance to Surface at Install Time
B-15A	73.74°S 170.66°E (variable)	3.72 m
B-15K	76.36°S 167.18°E (variable)	2.01 m
Drygalski	75.54°S 165.60°E	2.332 m
Ferrell	77.87°S 170.82°E	1.06 m
Mary	79.30°S 162.97°E	1.04 m
Nascent	78.1°S 178.5°E	4.75 m
Williams Field	77.87°S 166.98°E	1.52 m (2003) 0.56 m (2005)
Windless Bight	77.73°S 167.70°E	1.19 m

Table 1. Names and locations of the eight AWS sites with ADGs located on board. Each location is approximate, since many of these sites move each year with the moving ice floes. B-15A and B-15K move more dramatically since both are moving icebergs in the Ross Sea.

3.3 Visual Stratigraphy and Snow Density Measurements

Manual measurements of snow depth change were taken at various AWS sites across the Ross Ice Shelf and West Antarctic via visual stratigraphy and snow density measurements. Visual stratigraphy measurements are commonly used in order to look at 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 (Figure 14).

The cause of snow accumulation can be determined by the crystallization of the snow within differing layers. Accumulation layers due to precipitation tend to have a lighter, fluffier appearance, while accumulation layers due to blowing snow tend to be hard packed. The determination of layers that are caused by a combination of blowing snow and precipitation are more ambiguous, but it is anticipated that these layers would have a harder texture due to the fractured ice crystals resulting from the blowing process. The layered structure typically indicates the beginning of a summer season layer by a shallow horizontal layer of ice that is formed when the sun warms up the snow layer while a warm wind blows across the surface.

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. This information is valuable, since it can provide insights into whether snow was lofted from one location to another. In general, snow densities are higher for aged snow and snow that is hard-packed. Wet and fresh snow have lower densities. Densities also increase with depth in a column of snow (Schwerdtfeger, 1984).

Figure 14. Image of horizontal accumulation from a snow pit as taken at Ferrell site on the Ross Ice Shelf in January, 2006.

4. Collection of Field Observations

In order to acquire measurements of accumulation and ablation at the surface in Antarctica, instrumentation that quantifies depth change was deployed at several locations across the Ross Ice Shelf. Additional data was also collected at several sites across the Ross Ice Shelf and West Antarctica manually from snow pit data. Deployments of personnel and instrumentation to Antarctica, and manual measurement of data occurred during the 2003-04, 2004-05, 2005-06, and 2006-07 field seasons. The following chapter will describe the efforts undertaken during these field seasons, and descriptions of the methods of collecting the observations used for this project.

4.1 ADG Site Selection

The ADGs were installed at eight AWS sites near McMurdo and across the Ross Ice Shelf – B-15A, Williams Field, B-15K, Nascent, Mary, Ferrell, Windless Bight, and Drygalski (Figure 15). B-15A and B-15K are located on moving icebergs. The Drygalski site was located on the edge of the Drygalski Ice Tongue when deployed. In March 2006, an iceberg containing the AWS broke off the ice tongue, and began to float northward out of the Ross Sea. The latitude and longitude locations of each ADG site can be seen in Table 1.

These particular AWS sites were selected for various reasons, both scientific and logistical. Since one challenge facing scientists working in Antarctica is logistics (for example, having the time, the cooperation of the weather, and the air power to be able to visit a particular station), working with other projects can help immensely when placing instruments. B-15A, B-15K, Drygalski, and Nascent are four such sites. The "Earth's

Largest Icebergs" project, led by Dr. MacAyeal, had already placed ADGs on B-15A and B-15K in 2003 for use on that project. In 2004 and 2005, Dr. MacAyeal's group had planned to place two additional ADGs at the Nascent and Drygalski sites, and agreed to share the data collected there.

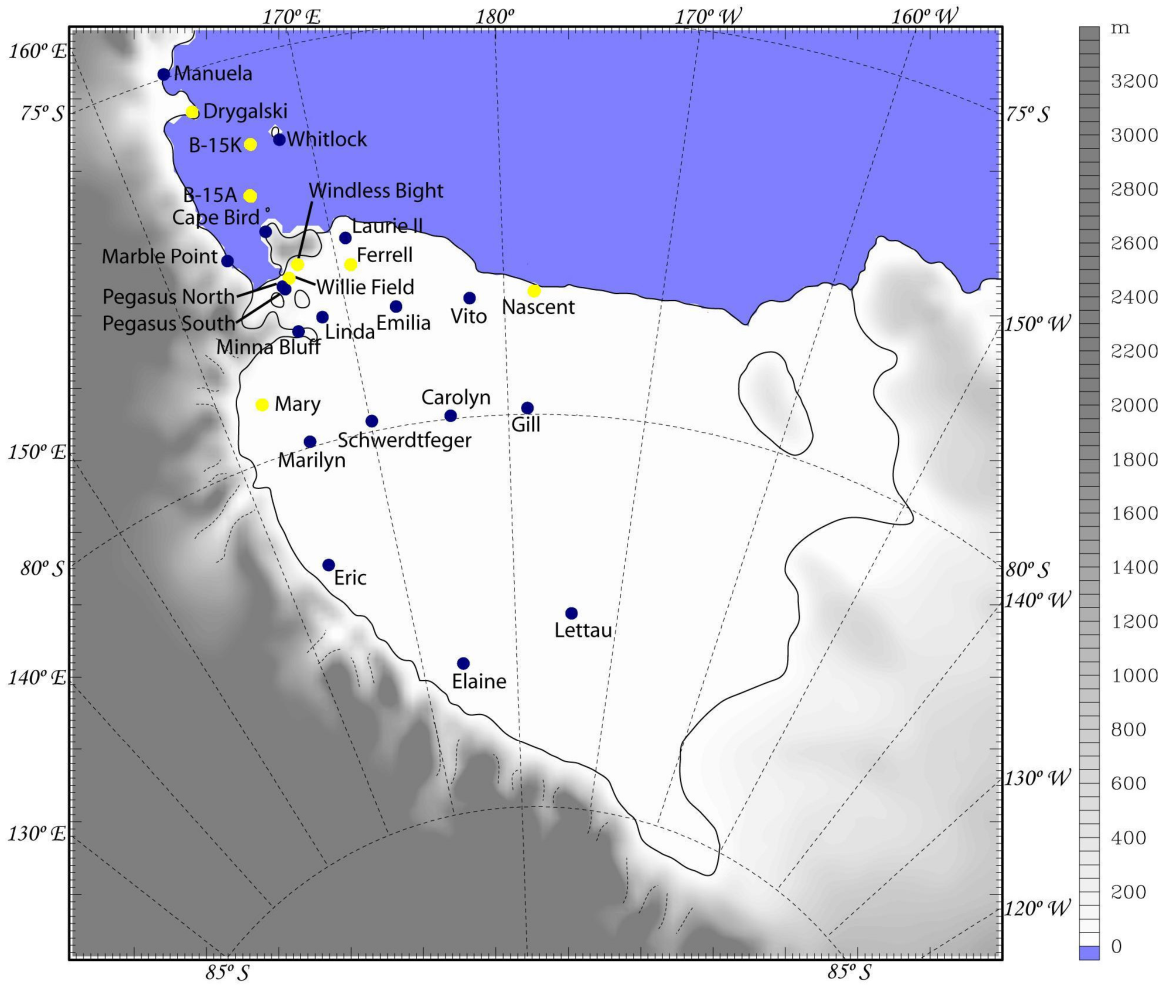


Figure 15. Locations of AWS sites across the Ross Ice Shelf and the Ross Sea. The yellow dots indicate AWS stations with ADGs. Current as of December 2006. *Image courtesy of Mark Seefeldt, University of Colorado.*

These four sites are good locations for scientific reasons as well. B-15A and B-15K, being in the Ross Sea, provide a good setting to compare the differences in precipitation at an ocean site versus a land site. The Nascent site, located on the Ross Ice Shelf, is the only site with an ADG located in the great expanse of the shelf, in an area expected to have larger precipitation due to its proximity to the ocean, but also greater dispersion due to higher wind speeds. The Drygalski site was an excellent location to study the affects of topography and katabatic wind flow. Cyclonic influences were also anticipated to affect accumulation due to the sites' proximity to the Ross Sea.

The placement of ADGs at Mary, Ferrell, Windless Bight, and Williams Field were intended to create an eventual precipitation measuring network near McMurdo Station. Because of the close proximity of Williams Field to McMurdo Station (approximately 13 km), the placement of an ADG was useful logistically. In addition, there is a landing strip close by, and acquiring precipitation measurements in this area would be useful to determine whether there are any implications for landing aircraft. The Williams Field site is also useful for placement of an ADG because there was brief interval in the mid-1990s during which an ADG was taking measurements of accumulation at that site.

Ferrell site was chosen due to its long climate record of thirty years. There is also known accumulation to occur at this site from informal observations over the years by AWS support personnel who have had to repeatedly raise the tower to keep it from being buried. Mary site was chosen due to the possibilities of upslope precipitation occurring in this area. It was also chosen for logistical reasons – Mary site was erected for use by another project studying the Ross Air Stream, and that team placed the ADG at that site while visiting.

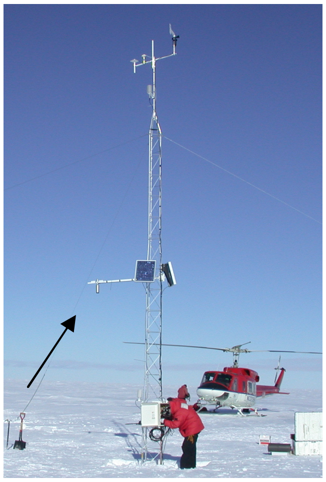
Windless Bight site was chosen particularly due to its lack of wind at that site, allowing for more precipitation measurements due to light winds. See Figure 16 for images of these sites.

4.2 Geography of Sites

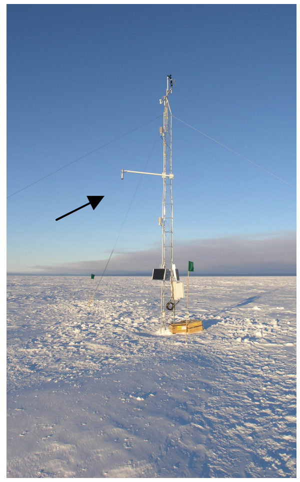
Geographically, each site provides an interesting look at different features of Antarctic landscape and climate regimes. Nascent and Ferrell are located on the flat expanse of the Ross Ice Shelf, affected by little topography. Several other sites - Ferrell, Nascent, and Drygalski - are located within relative close proximity to the ocean – Ferrell within about 30 km, Nascent is within about 10 km, and Drygalski within 1-2 km. The iceberg sites – B-15A and B-15K - are affected by maritime influences since they are on icebergs floating in the Ross Sea.

In addition to being affected by oceanographic influences, the Drygalski site (located on the Fountain AWS) is also influenced topographically. The Drygalski site is located at the base of the Drygalski Ice Tongue, a piece of ice that flows out from the valleys of the Transantarctic Mountains. Katabatic wind flows are prominent in this region, and are not an uncommon occurrence (Figure 17). Mary site is also influenced by topography, as it is near the base of the Mulock Glacier in the Transantarctic Mountains. Mary site also is affected by katabatic wind flow.

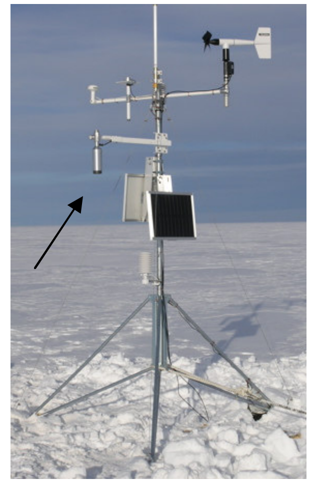
Williams Field and Windless Bight are also influenced by topography. Williams Field, while located on the Ross Ice Shelf, is still in close proximity to Ross Island (approximately 10 km). Windless Bight is also affected by topography, as it is located near the base of Mt. Erebus. Being in this location, Windless Bight rarely sees high wind speeds as it is nestled in the wake of the active volcano.



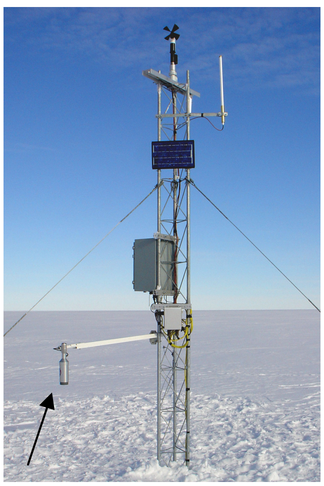
a) B-15A, Oct. 2003



b) Nascent, Oct. 2004



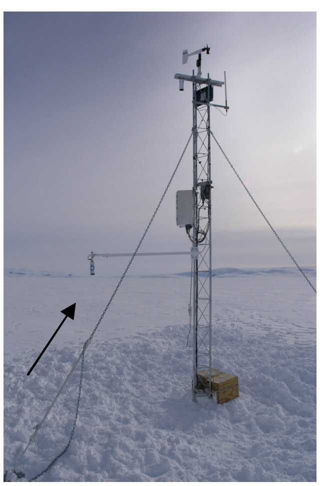
c) B-15K, Oct. 2004



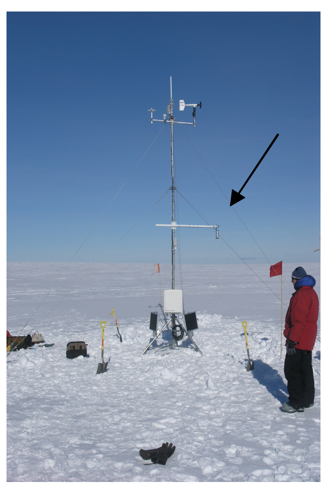
d) Mary, Jan. 2005

e) Williams Field, Feb. 2005

f) Ferrell, Feb. 2005



g) Windless Bight, Jan. 2006



h) Drygalski, Nov. 2005

Figure 16. Images from each of the AWS sites with ADGs. Arrows point to the location of the ADG.

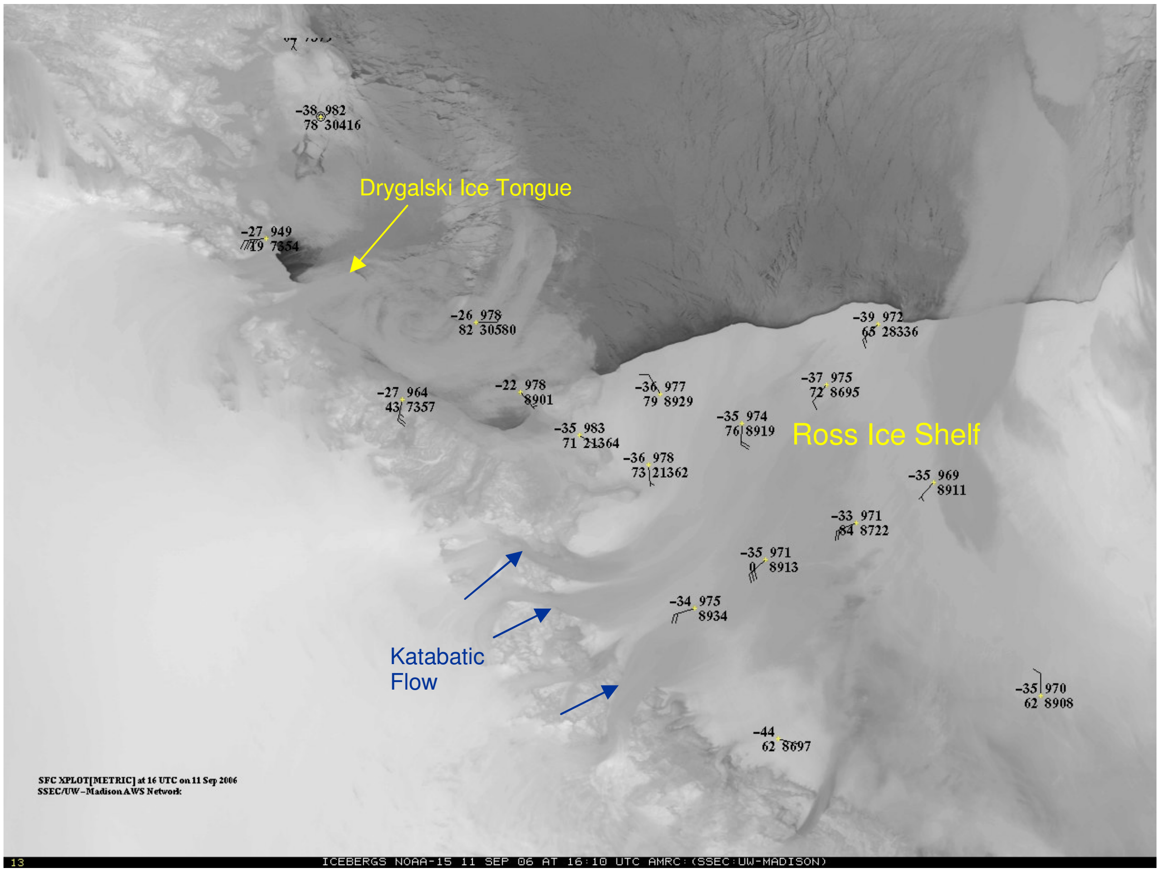


Figure 17. Infrared satellite image from September 2006 showing katabatic flow from the Transantarctic Mountains, across the Ross Ice Shelf and the Drygalski Ice Tongue. Plots on the map are from AWS.

4.3 Field Seasons

There were three field seasons during which deployments of the ADGs occurred, the first of which was in October 2003. During this time, two ADGs were deployed to Williams Field and B-15A, with the ADG at B-15A deployed by a team led by Dr. MacAyeal, and the ADG deployed at Williams Field by Jonathan Thom of the University of Wisconsin. The Williams Field ADG reported data beginning in late January of 2004 but stopped in late May of 2004, assumed to be due to a loss of power at the site. The ADG at B-15A began reporting usable data in July 2004 and is still active.

The second deployment field season occurred during late 2004 and early 2005. One ADG was deployed at the Nascent Iceberg site and another at B-15K site in October 2004 by a team led by Dr. MacAyeal. The second set of ADGs were deployed by Mark Seefeldt of the University of Colorado in January and February 2005. Four acoustic depth gauges were deployed at Windless Bight, Ferrell, Mary, and a replacement at Williams Field. The ADGs at Ferrell and Williams Field were not able to transmit in real-time via ARGOS as Mary, Windless Bight, B-15K, and Nascent were, due to the fact that the two stations at these sites were older and could not be configured properly with the newer Campbell Scientific system required to be used for the ADGs. The third deployment field season occurred during late 2005, when a team lead by Dr. MacAyeal deployed one ADG at the Drygalski site. An SR50 ADG was deployed, and configured to transmit in real time. The site began transmitting in November 2005, and is still active.

There were also three field seasons in which data was pulled from the dataloggers onboard the AWS units, and the units were visited and maintained if needed. The first of these occurred during the October 2004 deployment season. Data was acquired from Williams Field (data from B-15A had been sent via ARGOS). The second field season occurred in early 2006. In January 2006, the author and George Weidner of the AWS project at the University of Wisconsin pulled data from data loggers onboard the stations at Ferrell and Williams Field. The data from Windless Bight, Mary, B-15K, and Nascent was sent via ARGOS. The third season occurred during October and November 2006, when data was collected from the Ferrell and Williams Field sites. The Drygalski data had been sent via ARGOS.

During the 2005-06 field season, it was determined that the ADGs at Ferrell and Williams Field had stopped reporting partway through the previous year. Measurements were taken only from 29 December 2004 to 29 May 2005 for Ferrell and from 28 December 2004 to 27 May 2005 for Williams Field. The software programs required for operating the ADGs were re-downloaded onto the Campbell Scientific systems at each site, and data was flowing through the system once again.

General maintenance to all ADGs at each site was conducted. At some locations, the booms holding the ADGs had to be raised to avoid being buried by snow accumulation during the following year. This was especially true at Windless Bight, as high snow accumulations in previous years had threatened to bury the ADG in the upcoming year. At times, upon visiting these sites, the ADG was already buried in the snow, and data collected during this time was skewed. Also at these AWS stations, as well as many others visited across the Ross Ice Shelf and West Antarctica that did not have ADGs on board, snow pits were dug and measurements of the density of the snow and visual stratigraphy were taken. These results and the implications will be discussed in the upcoming chapters.

4.4 Visual Stratigraphy and Snow Density Measurements

Each AWS site that had an ADG on board was visited during the 2005-06 or 2006-07 Antarctic field seasons, and information about the accumulation at each site was deduced through measurements from snow pit data. At each site snow pits were dug to the previous two years' accumulation. In general, two layers were sought – one for the 2005 summer season, and one for the 2004 summer season. Only two seasons were chosen because the

ADGs had only been placed out for one (at most locations), and an extra year was chosen for comparison.

Visual stratigraphy was performed at these sites, which consisted of looking for each summer's layer, the layers in between, and measuring the depth of each layer and the snow type (hard packed, soft, etc.) (Schwerdtfeger, 1984). At some locations, the layers for the summer season were depicted by a hard ice layer, while at other locations there was no distinct hard layer, but rather a clear change in the density and texture of the snow. In general, soft granular layers exist between these layers. Multiple layers occurred at some sites, and the depth of these layers varied along with location.

At each site visited, measurements of the weight of the snow were also taken in order to later determine the density of the snow at each site. After finding the location of the past two years' accumulation, samples of snow were taken within the pit by a plastic cylinder that was open on both ends. Whenever possible, samples were taken from the soft granular layers in between two consecutive years' layers. If the layers were hard-packed instead of soft, samples were taken of the harder layers.

Visual stratigraphy and snow density measurements were also collected at some sites in West Antarctica. While there were no ADGs at any of these locations, these measurements were taken as part of a "mission of opportunity" when these sites had to be visited as part of general maintenance for the AWS project. Having measurements at these sites also provides the chance for comparisons between snow accumulation on the Ross Ice Shelf and in West Antarctica.

5. Results

For over three years, ADG data was acquired from each of the eight AWS discussed above. Analysis was done on this data depicting specific information about the accumulation and ablation changes at each site. The ADG data at each site was compared to other sites, analyzed by region type, and compared to other types of data available. The following chapter will describe the data collected from these ADGs.

5.1 Availability of Data

Before discussing the analysis of data, it is important to note the amount of time each station was transmitting usable data. Each site had some issues throughout the three years of this project, with some gaps in data collection during this time. There were many reasons the sites stopped operating, such as failure of instruments or the burying of the ADG. However, each site produced enough data to be viable. Graphs depicting information about event type are normalized for the amount of time the station was in operation.

Nascent site was the only site that remained operational during the entire three years of data collection - a total of 1033 days, while Ferrell had the shortest availability of data – only 217 days (Figure 18). The iceberg sites all remained operational for approximately the same amount of time – around 450 days, with B-15K operational at a little less time. The decreased amount of data at these sites was likely due to the movement of the icebergs on which these stations were deployed. The locations of these icebergs vary throughout time dramatically, and since the ADGs were originally placed onboard the stations, the icebergs have traveled from the Ross Sea (approximately 77°S 167°E) to just off the coast of Wilkes

Land (67°S 157°E) in East Antarctica. Since this project is primarily focused on quantifying precipitation on Ross Ice Shelf, data from the icebergs is not considered when out of range of the shelf. Consequently, no data was used after the icebergs moved north of the Drygalski Ice Tongue in the Ross Sea – after 1 May 2005 for B-15A and after 10 October 2005 for B-15K. During the time of this project, the ADG at Drygalski also calved from the Drygalski Ice Tongue, forming the C-25 iceberg. However, as soon as the iceberg calved it began to move north, so no data from this station was used after 29 March 2006.

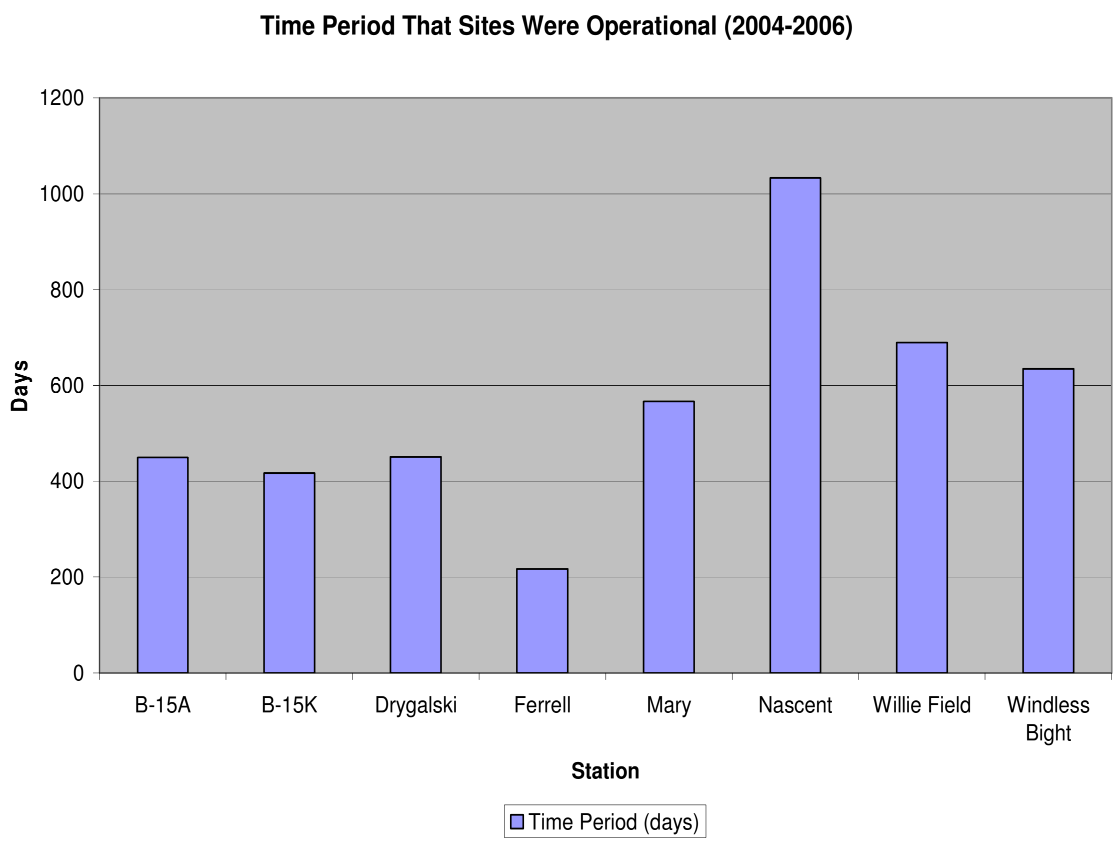


Figure 18. Period of time that stations were operational. Time is measured in days.

5.2 Data Analysis

The ADGs measure the distance to the surface of the snow, so that measurements reflect snow depth change, which can be either due to accumulation or ablation. As distances to the snow surface decrease, accumulation is occurring at the surface, and vice versa. This study is only concerned with relative changes – absolute changes are not considered. Changes in snow depth are caused by the influence of some external factor on the 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 are not of concern for this work.

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 were 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 (term P), blowing snow (term B), combined (blowing snow and precipitation) (B plus P), 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 is clearly some phenomena causing a moisture increase. Since the relative humidity sensor is at the top of the AWS (approximately 3-4 meters), the constant profile could be due to precipitation falling from above. While snow particles can be lofted from the surface to the level of the relative humidity sensor, it is expected that the profile in this case would be much more variable. Precipitation might not be the only phenomena that produces a high and constant relative humidity profile, but it would not be able to be identified without this availability of moisture, so for this preliminary analysis, increases in accumulation during periods of high and constant relative humidity profiles are considered to be precipitation.

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 discussed earlier. Since there has been no definitive study showing blowing snow thresholds in Antarctica from observations, this quantity may or may not be accurate. Also, snow surface characteristics vary by year and location, so one specific threshold is difficult to assume. However, blowing snow thresholds for solid precipitation have been found to be anywhere between 6 and 14 m/s, so the selection of 10 m/s for this study was not unreasonable.

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. This category would also include situations where relative humidity profiles were constant or wind speeds greater than 10 m/s and there was no snow depth change. The undetermined category describes events that occurred with snow depth changes but no apparent reason why. An example of the plotted data and separation of categories is provided in Figure 19. These categories were tallied and are provided in the graphs in the following sections.

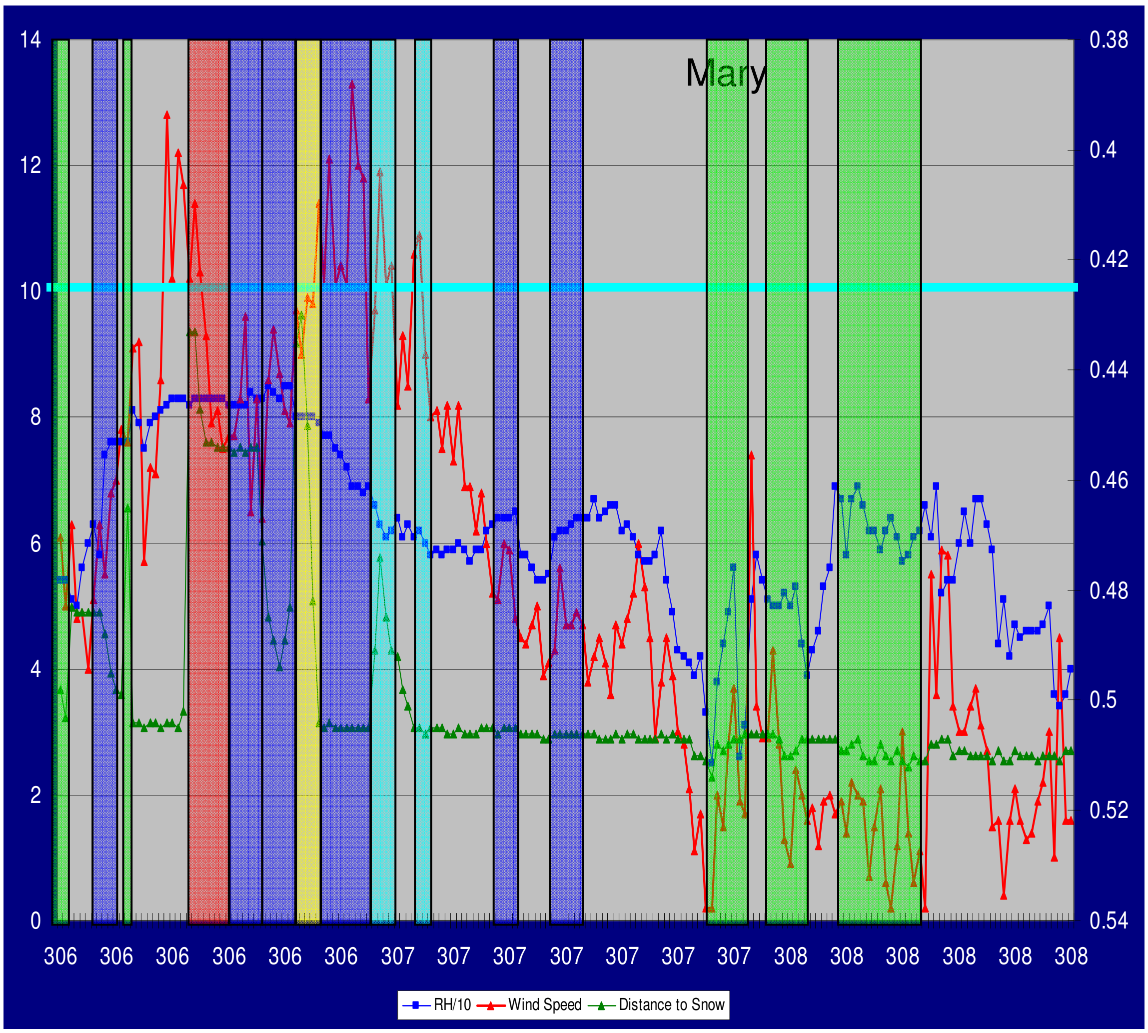


Figure 19. Sample of data from Mary site from November, 2005. The red line on the left axis shows wind speed, the blue line on the left axis shows relative humidity, and the green line on the right axis shows distance to the snow surface. The blue horizontal line depicts the blowing snow threshold. Categories are defined as follows: green – undetermined, blue – unexpected, red – combination, yellow – precipitation, and light blue – blowing snow.

5.3 Data Issues

There are some issues with the data that should be noted. For example, as mentioned earlier, the blowing snow wind speed threshold is assumed to be 10 m/s, which may or may not be accurate. Also, wind speeds are measured at the top of the tower, and readings of wind speeds at the surface are not available, so that there may be some discrepancies between wind speeds at the top of the tower versus the bottom. As well, other contributors to constant relative humidity profiles, including fog or moist air masses, could also cause high and constant values of relative humidity but are not considered here.

Furthermore, the ADG requires temperature measurements due to the fluctuations of the speed of sound with temperature. Since the temperature measurement is at the top of the tower, there may be some issues created with this measurement. At times the ADG measurements appear to fluctuate with the temperature signal. While every effort has been made to screen out this data, this may not be true for all cases. Also, the sampling time of the data is not constrained, nor is the magnitude, so small changes in snow depth for a short amount of time might be false data. Some of the unexpected and undetermined case events can be explained by knowing some of the biases of the data.

5.4 Preliminary Results

The ADG data over the past three years have provided many interesting results, confirming some of the previously assumed characteristics of the snow pack, as well as providing some surprising findings. When the snow depth change events were tallied for all 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 20).

Ferrell and Nascent sites had the highest rate of precipitation cases per day of all, at .19 and .18 respectively. Without further analysis, the reasons for this cannot be fully understood, but it is anticipated that the close proximity to maritime influences as well as cyclone activity in this area may have an affect on the amount of precipitation events. Mary site has less precipitation events per day than any other site – at .04. This indicates that orographic precipitation or precipitation from cyclonic activity might not be a large factor in accumulation for this area.

Three sites – B-15A, B-15K, and Williams Field, have more blowing snow events than combined. This follows well for B-15A and B-15K with studies by Bromwich, 1989, describing the extent of katabatic wind flow into the Ross Sea. Bromwich indicates katabatic affects originating in Terra Nova Bay can be felt as far out as Franklin Island in the Ross Sea, which is near the area where the icebergs were located during the length of this study (Figure 7). It is also expected that the stations that are floating in the middle of the Ross Sea (B-15A and B-15K) have a higher amount of combined events due to increased cyclone activity in the southwestern part of the Ross Sea (Carrasco, 2003). However, parts of the Ross Sea are covered in ice for much of the year, making moisture levels less relevant in these partially covered areas, which most likely is partially accountable for lower combined events than blowing snow.

Wind profiles for Williams Field indicate that the prominent wind direction for this site (for wind speeds greater than the blowing snow threshold) is from the south (Figure 21).

Williams Field is located downwind of White and Black Island, a known area of extreme wind speeds (Figure 22). Monaghan, 2005 says that wind speeds race down the lee slopes of Black and White Island, which corresponds well with the observed accumulation at Williams Field. In this area, term B is assumed to be larger or at least on par with term P in Equation 1.

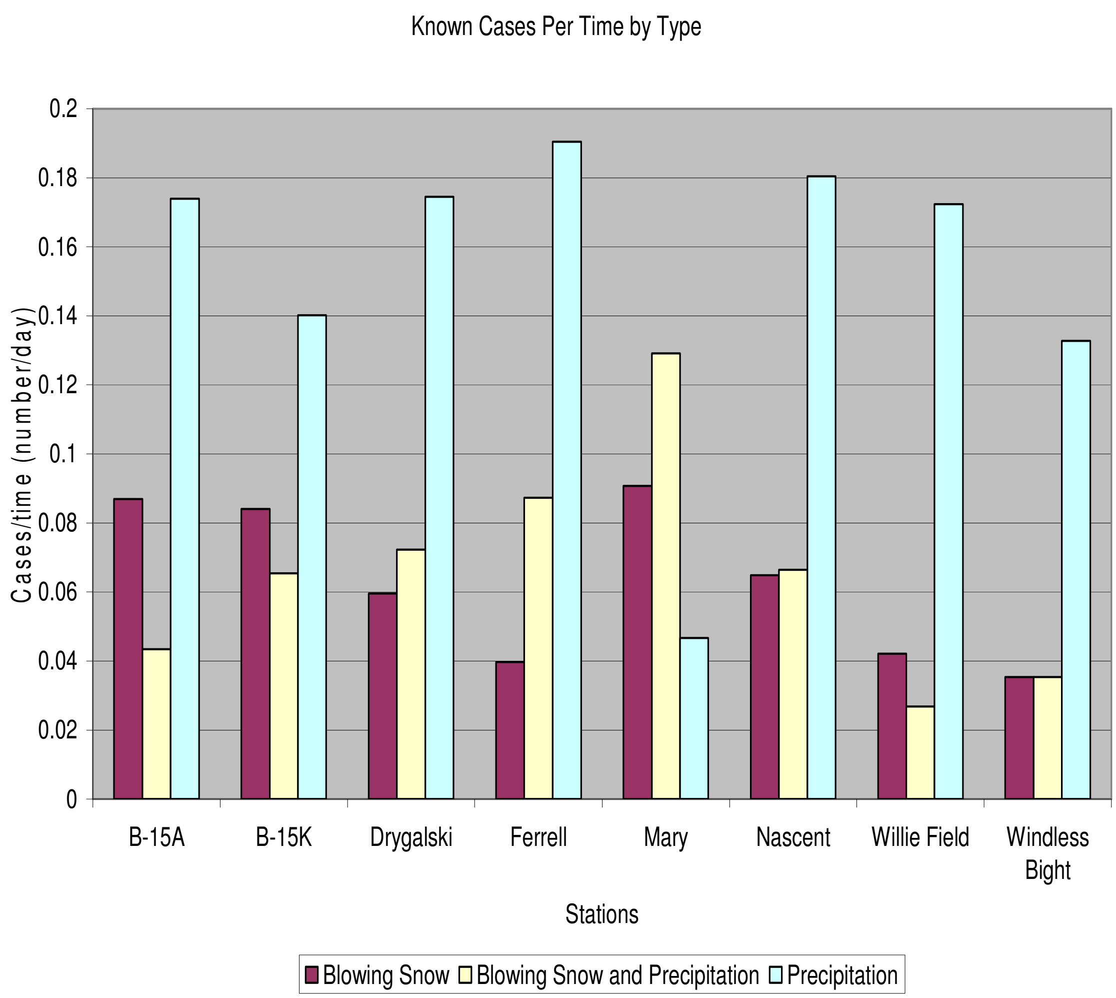


Figure 20. Plot of ADG data from 2004-2006 depicting all the known cases of snow depth change (changes due to precipitation, blowing snow, and combined events) per day. Each plot is normalized for the amount of time the station was in operation for accurate comparison.

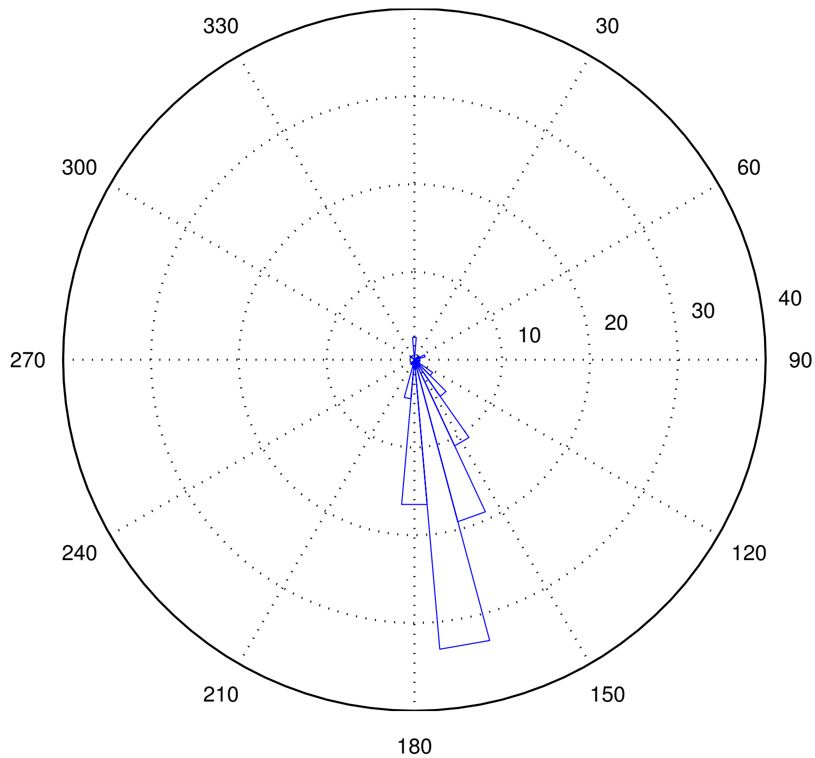


Figure 21. Prominent wind direction for wind speeds greater than 10 m/s for data from 2004-2006 for Williams Field. North is at 0˚and south at 180˚.

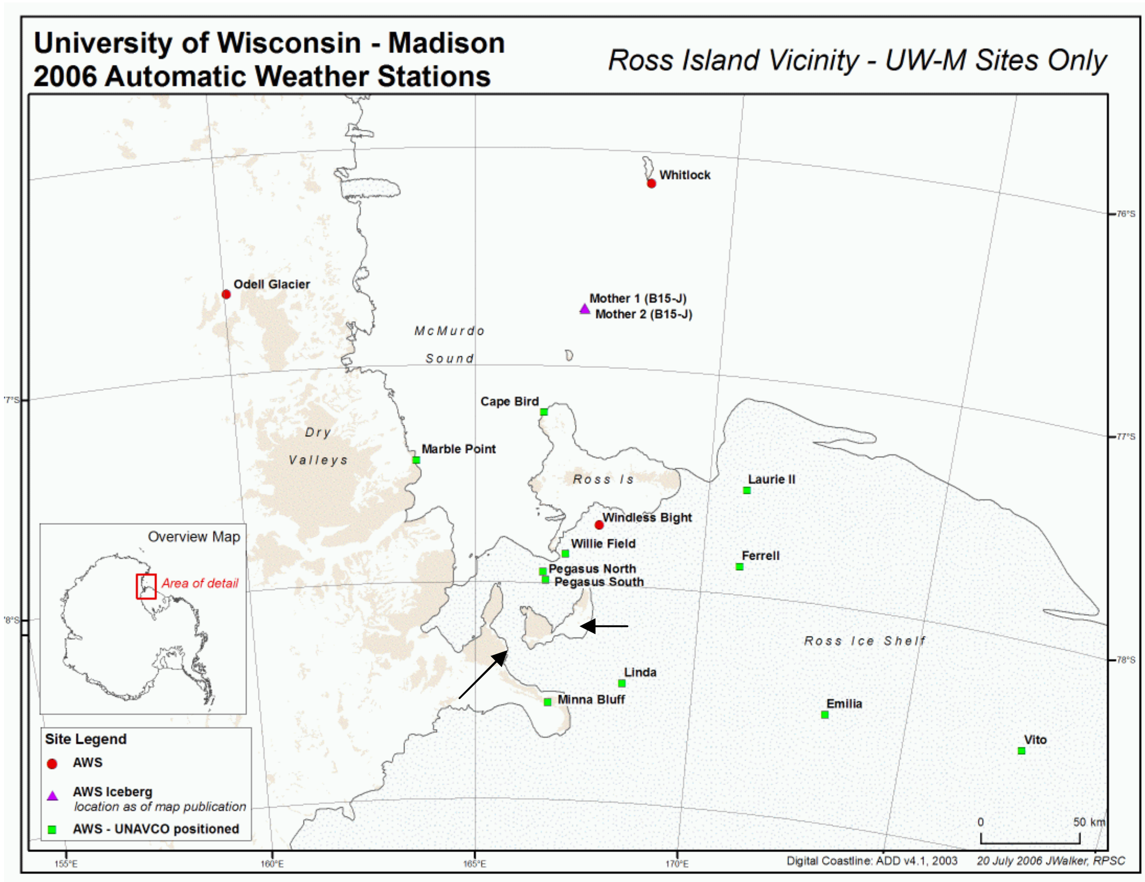


Figure 22. Map depicting AWS locations near Ross Island. The arrows indicate White and Black Island.

Drygalski, Ferrell, Mary, and Nascent have more combined events than only blowing snow events (Windless Bight has an equal amount of blowing snow and combined events). Wind profiles for Ferrell and Nascent are shown in Figure 23 and 24. Prominent wind directions (for wind speeds greater than 10 m/s) are from the south-southwest, following well with influences from katabatic flow from the Transantarctic Mountains, as described by Bromwich, 1992.

Windless Bight has the least number of blowing snow events for all the stations, which is in concert with expected results. Very few situations occurred over the course of the three years of data in which wind speed data was greater than 10 m/s, due to the enclave that the station is located in, making it a relatively wind-free location. The Drygalski site had fewer blowing snow events than anticipated, suggesting that perhaps katabatic flow does not play a large role in positive or negative accumulation at the station site. An examination of prominent wind direction for this site indicates that wind speeds greater than 10 m/s tend to flow down the David Glacier. Consequently, the result of only a few blowing snow events is curious, as many previous studies have indicated that wind speeds from the Scott Coast will flow at relatively high wind speeds (Bromwich, 1989, King and Turner, 1997).

Mary site had the highest number of blowing snow events of all stations, which is in accordance with the station location. At Mary site, combined events of blowing snow and precipitation are the primary cause of snow depth change. The topography in the vicinity of Mary site, namely being at the base of the Mulock Glacier and within range of known high wind speeds from Byrd Glacier, have significant influences on accumulation at Mary site.

Mary's proximity to the Transantarctic Mountains indicates that accumulation from blowing snow as caused by katabatic flow as well as upslope precipitation both are expected to contribute to significant snow depth change. As Monaghan, 2005 points out, significant precipitation due to orography occurs in the upslope region of the Transantarctic Mountains. Additionally, as Adams, 2005 shows, a "wave" of energy flows from the Ross Sea past Siple Dome and follows the southern edge of the Ross Ice Shelf, turning along the Transantarctic Mountains and heading north toward Ross Island, and eventually, the Ross Sea. This wave flows past the Mary site, and will also have unforeseen implications on changes in snow depth. As well, prominent wind speeds are shown to be from the direction of katabatic flow

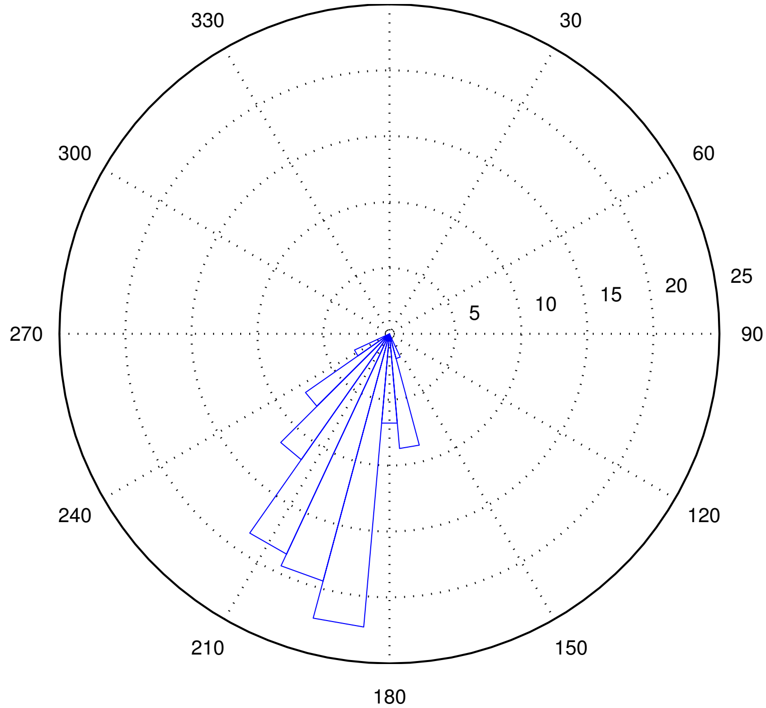


Figure 23. Prominent wind direction for wind speeds greater than 10 m/s for data from 2004-2006 for Ferrell site. North is at 0˚and south at 180˚.

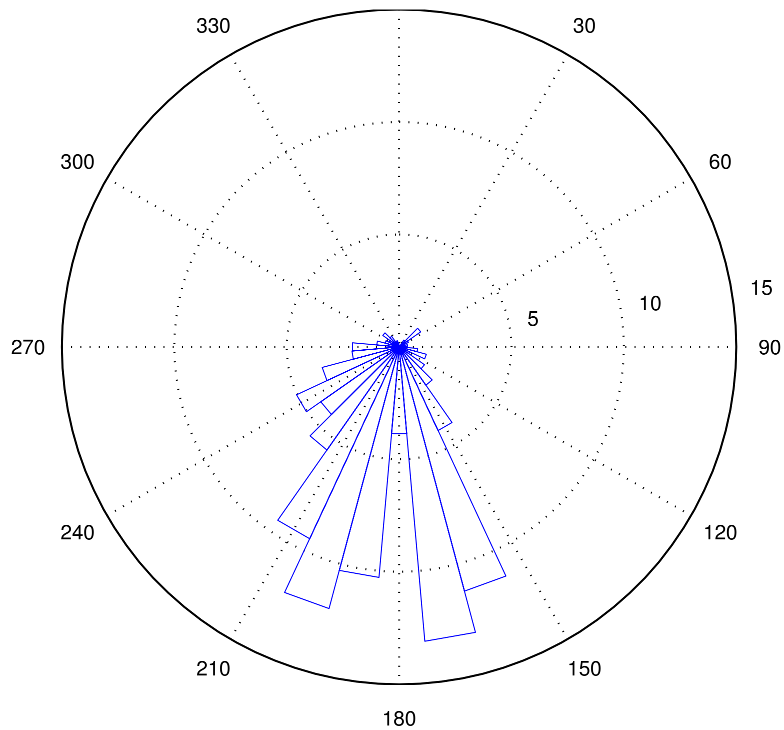


Figure 24. Prominent wind direction for wind speeds greater than 10 m/s for data from 2004-2006 for Nascent. North is at 0˚and south at 180˚.

down the Transantarctic Mountains which assuredly has implications on snow depth change (Figure 25).

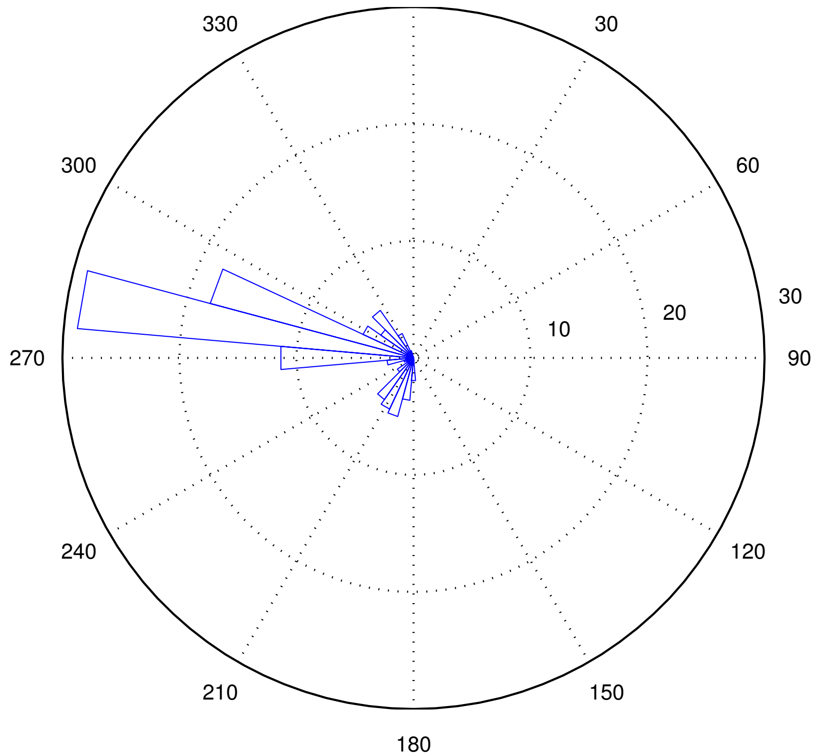


Figure 25. Prominent wind direction for wind speeds greater than 10 m/s for data from 2004-2006 for Mary. North is at 0°and south at 180°.

Net accumulation at all sites for this project was shown to be positive (Figure 26). 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 an expected result, 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, 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 B term in Equation 1 might be negative, offsetting any contributions from P.

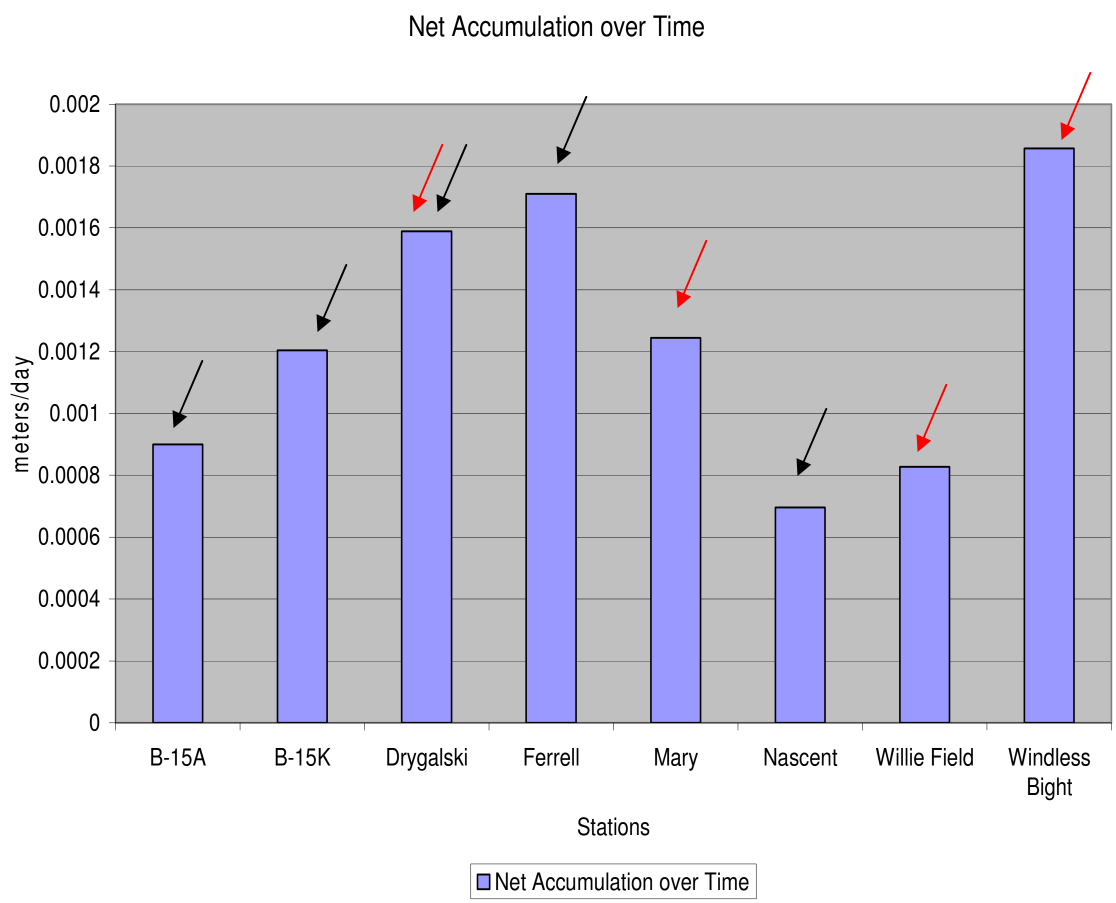


Figure 26. Net accumulation per day for each station as observed by the ADG. Red arrows indicate topographically influenced stations, while black arrows indicate maritime influenced stations. Stations are normalized for the amount of time operating.

In general, previous theory indicates that P is the primary contributor to accumulation (D) (Bromwich, 1988, King and Turner, 1997, etc.). This claim is demonstrated well for Windless Bight and Ferrell, as these sites had a higher number of precipitation events contributing to high accumulation rates (D). Since Ferrell is located at the northern edge of the Ross Ice Shelf, mass transport of snow from the south is greater due to a greater fetch. However, this theory was not corroborated at Nascent site. Wind profiles for Ferrell and Nascent are shown in Figures 23 and 24. Prominent wind directions (for wind speeds greater than 10 m/s) are from the south-southwest, following well with influences from katabatic flow from the Transantarctic Mountains. One potential for the discrepancy at Nascent site might be that the value of B might be greater than P at this site. In other words, B has a greater magnitude than term P in Equation 1, due to an increase in Q, and thus dwarfs the P term. One aside to this is that all sites (with the exception of Mary) have more precipitation cases than either blowing snow or combined events, and all sites produce a positive net accumulation, which shows that in general this theory is correct.

Influences of topography and the ocean were also considered (Figure 26). 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 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 the previously mentioned modeling results, indicating that precipitation, and therefore accumulation, is higher in regions influenced by topography than those that are not.

Comparisons of the ADG data to snow density measurements were also made. Snow density measurements were taken at several sites across the Ross Ice Shelf and West Antarctica during the 2005 and 2006 field seasons. All of the ADG sites, as well as Laurie II and Linda, are located on the Ross Ice Shelf, while Siple Dome, Kominko-Slade, Byrd, Harry, and Swithinbank are in West Antarctica. Every site with an ADG, with the exception of the two iceberg sites and Drygalski, had a snow pit dug and density measurements taken. At the surface, Ferrell had the highest snow density, with Laurie II close behind (see Figure 11 for locations of sites) (Figure 27). Swithinbank, Harry, and Byrd had the lowest snow densities at the surface.

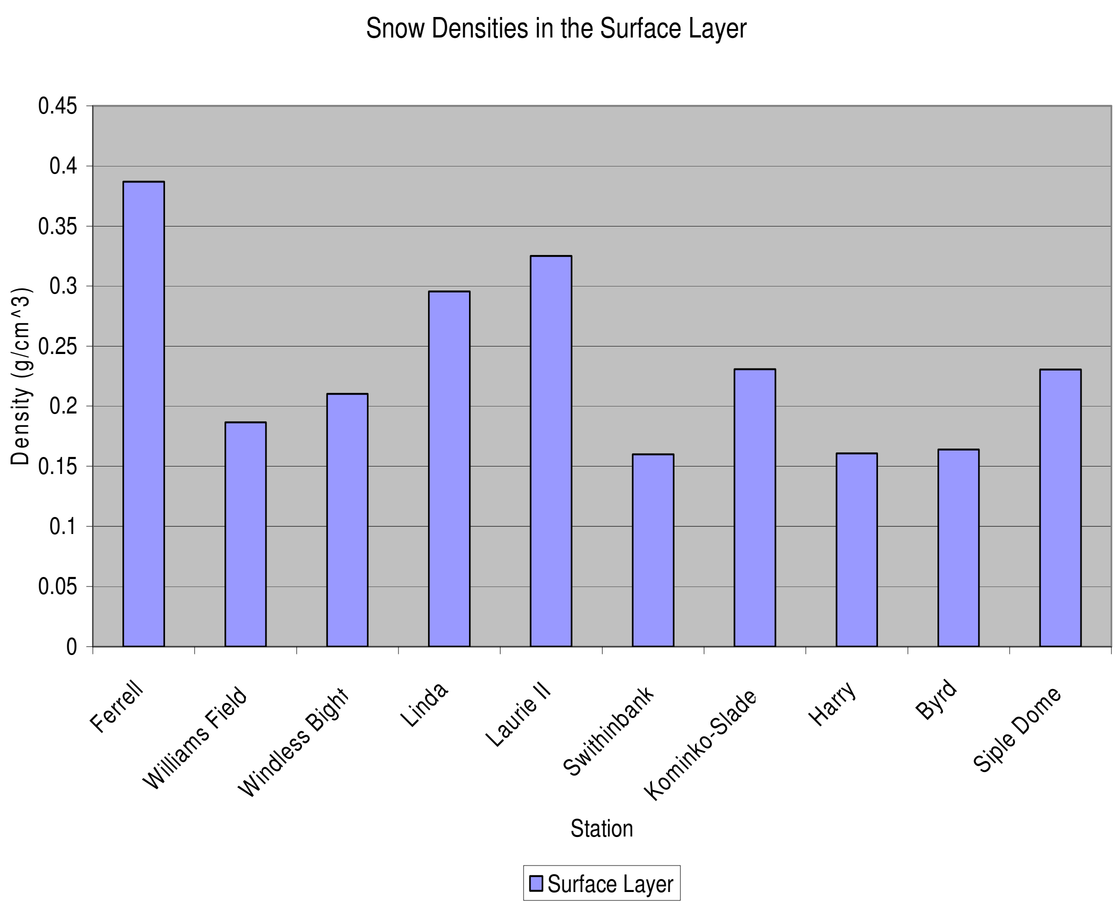


Figure 27. Densities of snow in the surface layer at several locations across the Ross Ice Shelf and West Antarctica.

For the surface measurements, it appears that, in general, the Ross Ice Shelf had densities higher than sites in West Antarctica. As mentioned earlier, 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 layer of snow in this area to be quite compact and hardened by constant winds traveling over the region.

As density measurements are collected further down from the surface, there is a relative constancy to many of the measurements, with perhaps the exception of Linda site (Figure 28 and 29). Data at this site may be spurious, so additional measurements at this site will need to be taken. However, the observed hardness of this layer in the snow pit may very well make this reasonable data. Mary has the second highest density in the previous two years' layers. However, these measurements were taken by different personnel through a different method, so it is unclear if a complete comparison can be made with this site and the others.

Comparisons between the snow density data and event type case can be shown as well (Figure 30). Generally, lower snow densities should be found with precipitation events, and higher densities with blowing snow events. Only 2005 data is shown below, 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

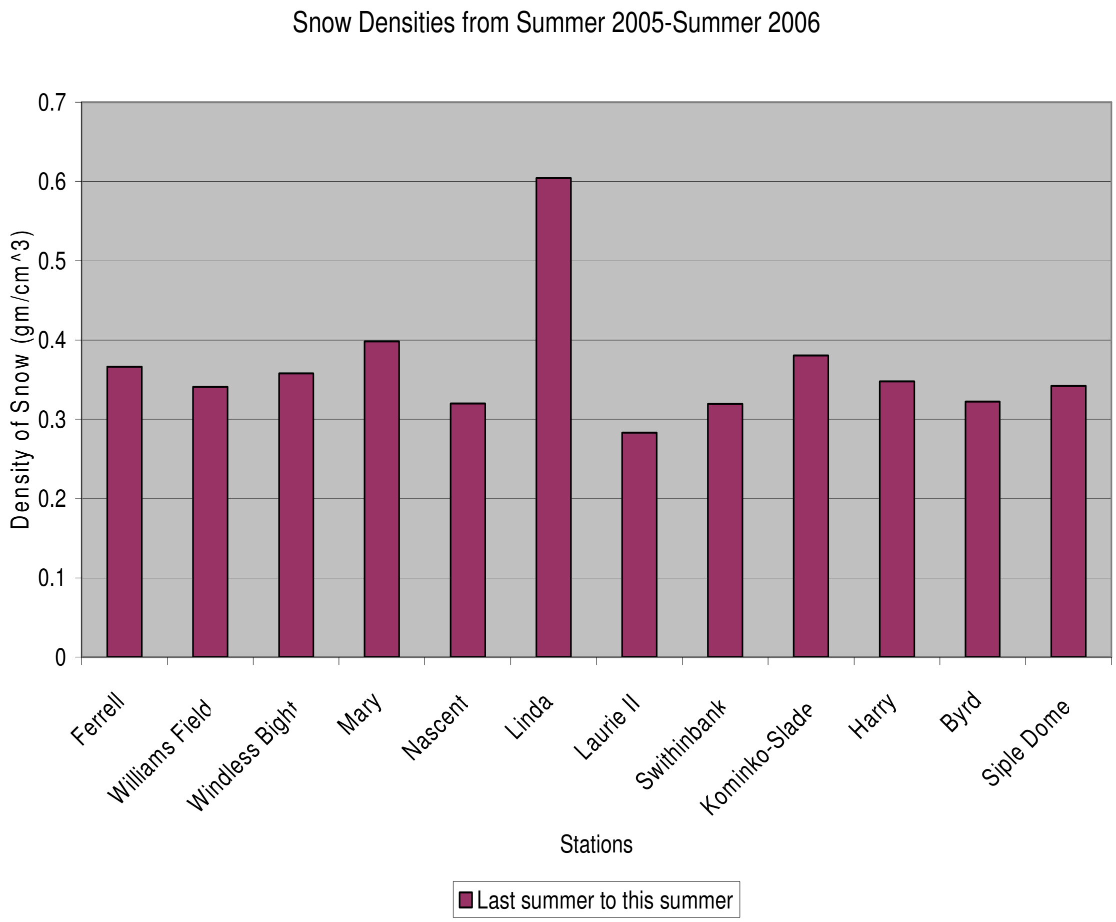


Figure 28. Densities of snow in the layer from summer 2005 to summer 2006. Stations are located on the Ross Ice Shelf and in West Antarctica.

each site with an ADG during the 2005-06 season with the exception of Mary which was visited during the 2006-07 season. An example of this data can be seen in Figure 31. The visual stratigraphy shows that there was .305 meters of accumulation during the beginning of the summer of 2005-06, through the time the site was visited (approximately 7 January 2006). During the time the ADG was operating at Ferrell during 2005 (approximately 109 days) the net accumulation shown from the ADG was .106 m. By extrapolating this for the rest of the year, the accumulation seen from the snow pit dug is similar to the accumulation seen from the ADG (.386 m vs. .305 m).

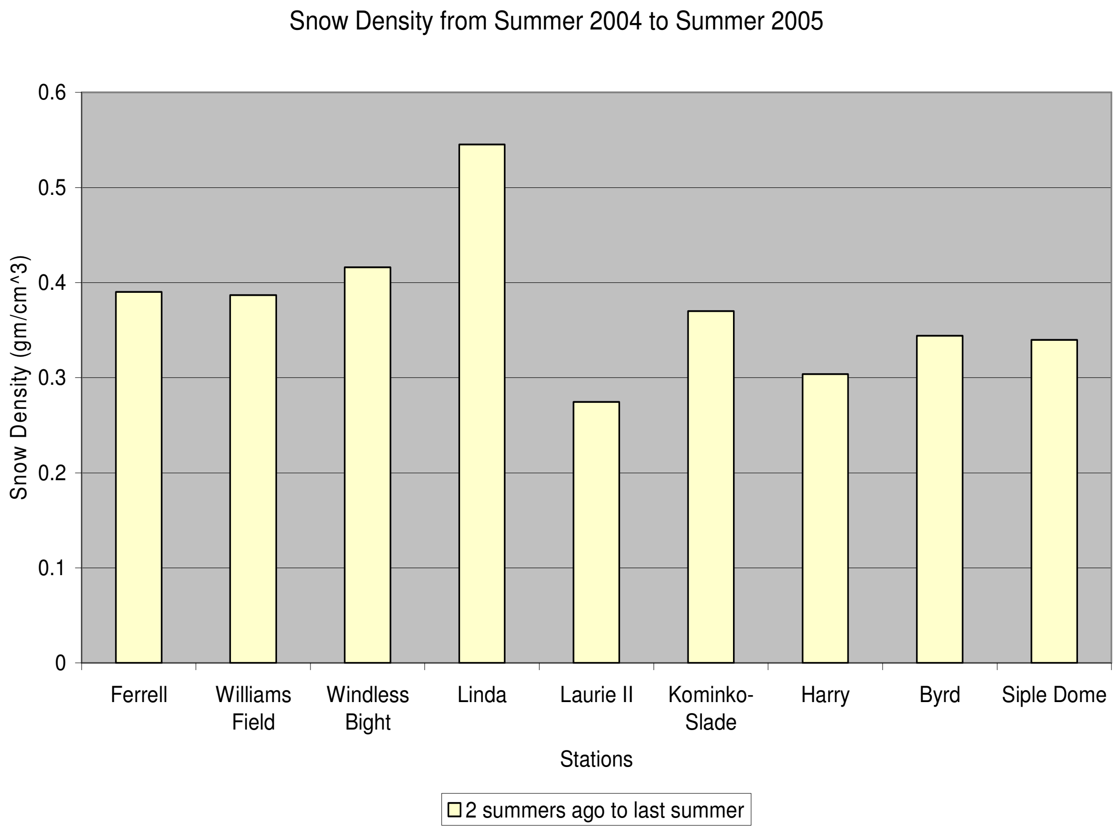


Figure 29. Densities of snow in the layer from summer 2004 to summer 2005. Stations are located on the Ross Ice Shelf and in West Antarctica.

Potentially the most interesting result from the ADG data is the realization of how little is understood about the processes resulting in the observed depth changes. To understand the nature of the measurement problem, blowing snow, precipitation, and combined events are merged into one category, called "known", and unexpected and undetermined events are depicted as "vague" results. As seen in Figure 32, every station has

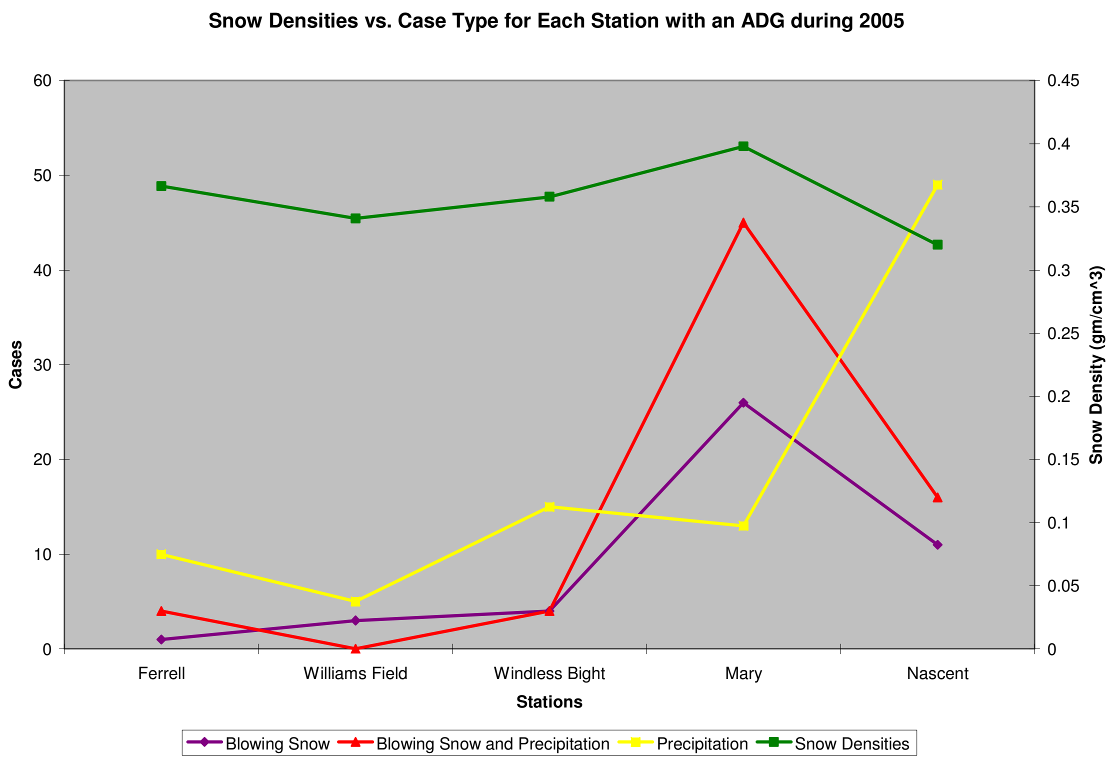


Figure 30. Snow densities for 2005 as collected from snow pit measurements versus event case type. The green line shows snow densities for each site, while the purple line shows the number of blowing snow events, the red shows the number of combined blowing snow and precipitation events, and the yellow shows the number of precipitation events.

more cases where the causes of snow depth change are vague than are known. Interestingly, the least understood site is Windless Bight, where there is also the highest accumulation over the three year period (Figure 33). Nascent is one of the most understood sites, yet has the lowest accumulation. However, Ferrell site, also having one of the highest accumulation rates, is the most understood of all sites. By this token, since precipitation has the most events of all the known cases at this site, it can be inferred that precipitation is the leading cause of accumulation at Ferrell site.

It is clear that for the majority of the cases overall, the cause of depth change is classified as "vague". 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 D in Equation 1. Then methodologies must be developed to determine the terms on the right hand side if an estimation of precipitation is to be made.

Therefore, to estimate precipitation from the ADG observations, B and S must be estimated first. But these quantities depend on a complex process of transport, diffusion, and microphysical processes of complexity comparable to the precipitation formation process itself. Fortunately, the processes occurring on the right hand side of Equation 1 have the potential to be simulated explicitly from 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 on the right hand side of Equation 1 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.

______________________________X__________Surface Layer

Hard packed snow

__________________.305 m____________________Summer 2006

Real soft granular snow X

__________________.324 m____________________

Hard packed snow

__________________.438 m____________________ Summer 2005

Soft granular snow X

__________________.489 m____________________

Hard packed snow

__________________.603 m____________________Summer 2004

Next granular layer

Notes:

.305 m is a hard packed snow

Real soft granular layer is .019 m thick

Next hard packed layer is .114 m thick

Next soft granular layer is .051 m thick

Then .102 m of hard packed snow

Layer is .603 m thick

Figure 31. Visual stratigraphy layer at Ferrell site taken in January, 2006. Depicts accumulation layers within a snow pit. The X marks shows places where density measurements were taken.

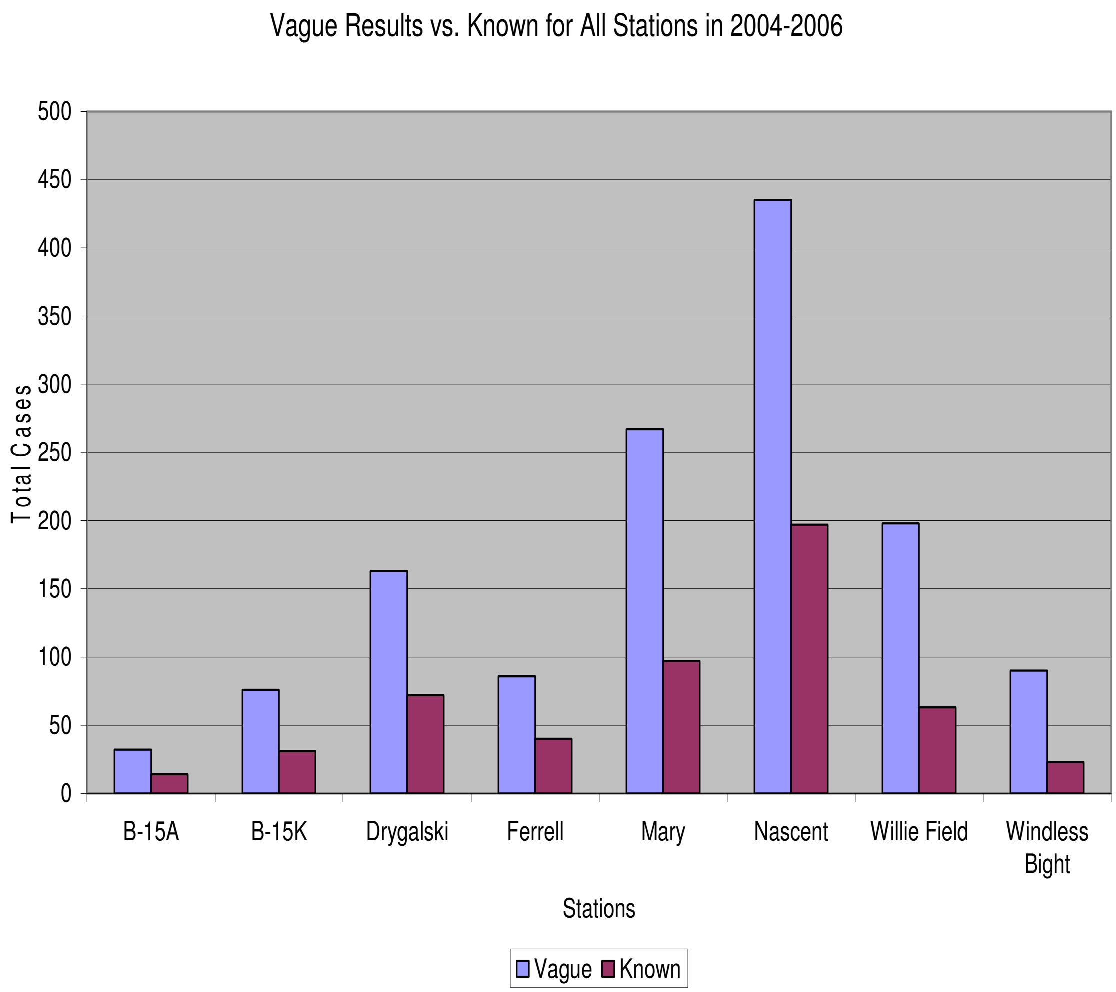


Figure 32. Shows events categorized as unknown data (undetermined and unexpected cases) vs. known cases (precipitation, blowing snow, and combined). Data for 2004-2006. Plots are normalized for the amount of time the station was in operation for accurate comparison.

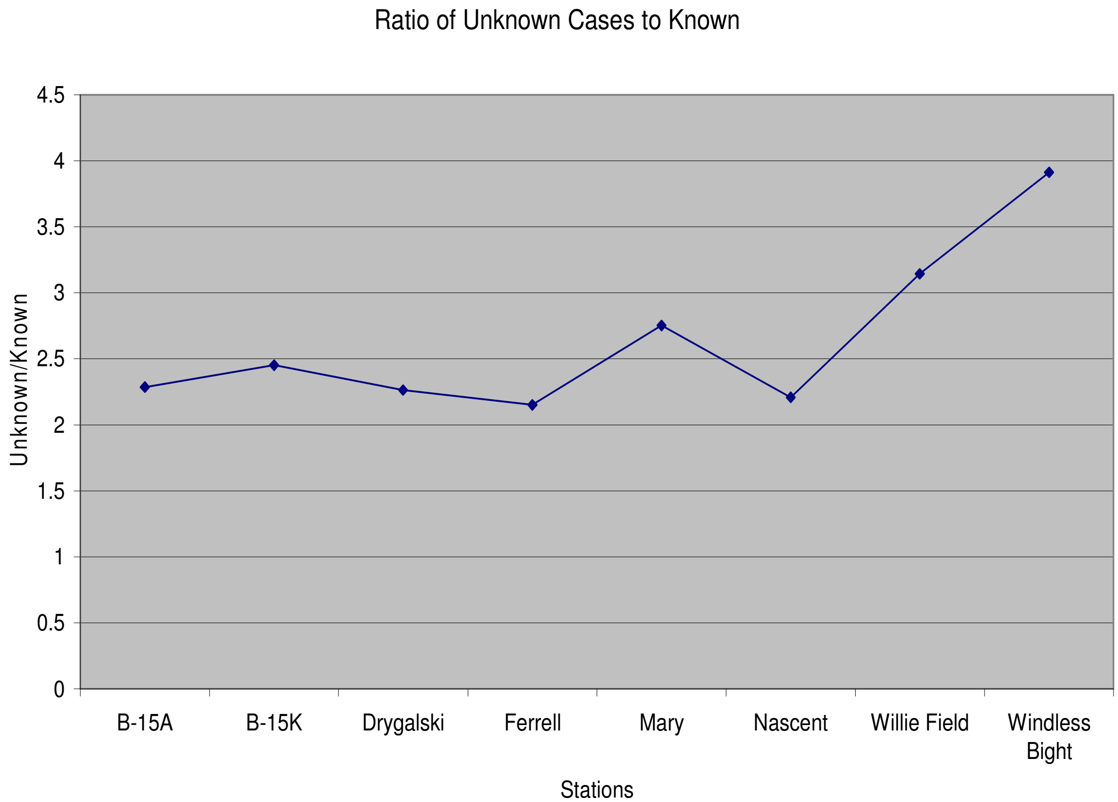


Figure 33. Depicts ratio of unknown cases to known. The higher numbers indicate that particular station is less understood than others.

6. Conclusions and Future Work

This work documents the efforts in completing the first step toward a total mapping of precipitation in Antarctica. ADGs were placed in eight strategic locations on board AWS across the Ross Ice Shelf, measuring accumulation and ablation at each site. This data was compared to snow density and visual stratigraphy measurements as well to create a basic climatology of accumulation measurements across Antarctica. Preliminary conclusions are drawn from this collection of data and plans for future work are discussed in this section.

6.1 Conclusions

The ADG data from this project has provided the Antarctic community with previously unavailable data across Antarctica. In previous field campaigns, some snow depth change data was available at particular sites, but the data was variable both in time and space. Real-time ADG data was rarely, if ever, available. For the first time, measurements of accumulation and ablation over particular areas of the continent have been provided in real-time, and over more locations across the Antarctic than had ever been available previously.

The ADGs confirm many previously assumed characteristics of snow surface change on the Ross Ice Shelf. For example, it has been shown that each site has a positive net accumulation over time rather than a net loss of snow. Net accumulations are highest at Windless Bight, Ferrell, and Drygalski sites. Windless Bight and Ferrell site in particular have been known through informal observations to have high accumulation rates per year. High accumulations at Windless Bight appear to be due to precipitation events, while causes for high accumulations are unclear at Ferrell, although preliminary results indicate that perhaps precipitation is the cause.

Every site with an ADG showed more precipitation events than blowing snow or combined events, with the exception of Mary site. Mary site shows more combined events caused by the fact that flows around Mary site are more complicated due to the proximity of this site to the Transantarctic Mountains. Ferrell has a higher number of precipitation events than any other site. Windless Bight had the lowest number of blowing snow events, while Mary site had the highest. Both of these results match observed weather at each site.

These results confirm the first hypothesis that D is significantly impacted by B as well as P. Localized affects of topography and weather regimes have important influences on the amount of depth change that occurs through the B term. In some locations, it appears that the B term, due to a negative increase in Q from Equation 2, will dominate the P term. Across the continent, however, each site had a net accumulation and a higher number of precipitation cases than any other known case (with the exception of Mary). Nevertheless, B was often important and so P tended to be ambiguous from D unless B could be estimated. These estimates were made using other information such as temperature, humidity, wind speed and even stratigraphy studies. This proved the second hypothesis that a knowledge of D was insufficient information to alone determine P for all cases.

Comparisons of accumulation rates from sites influenced by topography versus sites influenced by ocean regions showed that topographically enhanced sites have increased accumulation. Comparisons of snow density data from sites in West Antarctica to sites on the Ross Ice Shelf showed that sites on the ice shelf had higher densities. This matches observed known higher wind speeds from flow across the ice shelf.

Indications from previous modeling studies, such as by Monaghan, 2005 and Bromwich, 2004, show that topography has an important role in precipitation and accumulation rates. Observations from this project corroborate this theory strongly, as dynamical theories described in each of these papers were proven with the surface measurements of D from this project.

These results support, if not prove, the theory that P can be recovered from D by combining the observations with other information. A detailed investigation of each depth gauge record is not a suitable technique to create a continent scale precipitation map. Moreover the scarcity of the data will not allow such a mapping. However, there is hope that through cloud resolving data assimilation constrained by as many depth gauge observations as possible, a continental scale precipitation mapping, consistent with the depth gauge observations, consistent with orographic forcing, consistent with maritime moisture sources, and consistent with explicitly simulated blowing snow, can be achieved.

6.2 Future Work

Much work is needed to achieve the goal of total mapping of precipitation across Antarctica. For the more immediate future, improving the observation network of ADGs across the continent is imperative. Plans in the upcoming field seasons include the placement of additional ADGs onboard other AWS across the Ross Ice Shelf. In particular, having ADGs at other sites influenced by katabatic winds, including Eric, Elaine, and Marilyn is desired (Figure 15). Sites experiencing an expected maritime influence, such as Laurie II or Vito, are anticipated to have an ADG in the near future. The placement of ADGs at sites in closer proximity to McMurdo, including Minna Bluff and Linda is also planned. Having an additional ADG at Pegasus site, a runway for McMurdo, would also be greatly beneficial for logistical purposes. Expansion into other regions, such as West Antarctica and the peninsula area, is also planned. In addition to having supplementary ADGs, having all gauges transmitting in real-time is crucial.

As shown earlier, every site has many snow depth change events in which the causes cannot be determined. Further examination into the causes of this will need to be completed. Further analysis also needs to be completed on the data available at the present, including work on examining the influence of oceans or topography on sites, the influence of orographic precipitation on accumulation, and the influences of cyclones and katabatic flows on precipitation. Additional work on the affect of the wave cited by Adams, 2005 on Mary site and/or others in that region would also lead to a further understanding of accumulation issues in that area. A more in-depth study on the localized affects of B and P on D from Equation 1 is also required.

In the future, the implementation of a blowing snow model into a weather prediction model will be completed to more accurately predict the horizontal displacement of snow by wind. The coupled model would simulate both the amount of precipitating snow and the amount of snow transport. The final step will be to constrain the coupled model with observations of the AWS sites, satellite and whatever observations are available. In doing this, actual real-time analyses of precipitation, consistent with the depth gauge measurements, will be possible.

7. References

Adams, A.S., 2005: The relationship between topography and the Ross Ice Shelf Air Stream. Ph.D. dissertation, University of Wisconsin, 125 pp. [Available from Memorial Library, 728 State St., Madison, WI, 53706].

Aguado, E., and Burt, J.E., 2001: *Understanding Weather and Climate.* 2d ed. Prentice-Hall, Inc., 505 pp.

Andreas, E.L., 1998: A New Sea Spray Generation Function for Wind Speeds up to 32 m s^{-1}. *Journal of Physical Oceanography*, **(28)**, 2175–2184.

Arrigo, K. R., G. L. van Dijken, D. G. Ainley, M. A. Fahnestock, and T. Markus, 2002: Ecological impact of a large Antarctic iceberg. *Geophys. Res. Lett.*, **29(7)**, 1104, doi:10.1029/2001GL014160.

Braaten, D.A., 2000: Direct measurements of episodic snow accumulation on the Antarctic polar plateau. *Journal of Geophysical Research*, **(105)**, 10,119-10,128.

______, 1997: A detailed assessment of snow accumulation in katabatic wind areas on the Ross Ice Shelf, Antarctica. *Journal of Geophysical Research*, **(102)**, 30,047-30,058.

Briegleb, B.P. and D.H. Bromwich, 1998: Polar Climate Simulation of the NCAR CCM3. *Journal of Climate*, **(11)**, 1270-1286.

Bromwich, D.H., Z. Guo, L. Bai, and Q.S. Chen, 2004: Modeled Antarctic Precipitation, Part I: Spatial and Temporal Variability. *Journal of Climate*, **(17)**, 427-447.

______, A.J. Monaghan, J.G. Powers, J.J. Cassano, H.L. Wei, Y.H. Kuo, and A. Pellegrini, 2003: Antarctic Mesoscale Prediction System (AMPS): A Case Study from the 2000-01 Field Season. *Monthly Weather Review,* **(131),** 412-434.

______, Cullather, R.I., and M.L. Van Woert, 1998: Antarctic precipitation and its contribution to the global sea-level budget. *Annals of Glaciology*, **(27)**, 220-226.

______, D.H., J.G. Carrasco, and C.R. Stearns, 1992: Satellite Observations of Katabatic-Wind Propagation for Great Distances Across the Ross Ice Shelf. *Monthly Weather Review,* **(120)**, 1940-1949.

______, 1989: Satellite Analysis of Antarctic Katabatic Wind Behavior. *Bull. Amer. Met. Soc.*, **(70)**, 738-749.

______, 1988: Snowfall in High Southern Latitudes. *Reviews of Geophysics*, **(26)**, 149-168.

Budd, W., Dingle, W. R. J. and Radok, U., 1966: The Byrd Snow Drift Project, outline and basic results. *Antarctic Res. Series,* **(9)**.

Campbell Scientific (Canada) Corporation, 2003: SR50 Sonic Ranging Sensor Operator's Manual. Campbell Scientific (Canada) Corporation, Edmonton, Alberta.

Carrasco, J.F., D.H. Bromwich, and A.J. Monaghan, 2003: Distribution and Characteristics of Mesoscale Cyclones in the Antarctic: Ross Sea Eastward to the Weddell Sea. *Mon. Wea. Rev.,* **(131)**, 289-301.

Cullather, R.I., D.H. Bromwich, and M.L. Van Woert, 1998: Spatial and Temporal Variability of Antarctic Precipitation from Atmospheric Methods. *Journal of Climate*, **(11)**, 334-367.

Déry, S.J. and L.B. Tremblay, 2004: Modeling the Effects of Wind Redistribution on the Snow Mass Budget of Polar Sea Ice, *Journal of Physical Oceanography*, **(34)**, 258-271.

______ and M.K. Yau, 2001a: Simulation of an Arctic Ground Blizzard Using a Coupled Blowing Snow-Atmosphere Model. *Journal of Hydrometeorology*, **(2)**, 579-598.

______ and M.K. Yau, 2001b: Simulation of blowing snow in the Canadian Arctic using a double-moment model. *Boundary Layer Meteorology,* **(99)**, 297-316.

______ and M.K. Yau, 1999: A bulk blowing snow model, *Boundary-Layer Meteorol.*, **(93(2))**, 237-251.

Essery, R., L. Li, and J. Pomeroy, 1999: A distributed model of blowing snow over complex terrain. *Hydrological Processes*, (**13),** 2423-2438.

Fairall, C.W., J.D. Kepert, and G.J. Holland, 1994: The effect of sea spray on surface energy transports over the ocean. *Global Atmos. Ocean Sys.,* **(2)**, 121-142.

Gallée, H., 1998: Simulation of blowing snow over the Antarctic ice sheet. *Ann. Glaciol.*, (**26)**, 203-206.

______ and P.G. Duynkerke, 1997: Air-snow interactions and the surface energy and mass balance over the melting zone of west Greenland during the Greenland Ice Margin Experiment. *J. Geophys. Res.*, **(102)**(D12), 13,813-13,824.

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

Hashino, T. and G. J. Tripoli, 2006: The Spectral Habit Ice Prediction System, (accepted with revision for *Journal of Atm. Sci.*).

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

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteorol. Monogr.*, **(27).**

King, J.C. and J. Turner, 1997: *Antarctic Meteorology and Climatology.* Cambridge University Press, 409 pp.

Liston, G.E. and Sturm, M., 1989: A snow-transport model for complex terrain. *Journal of Glaciology*, **(44)**, 498-516.

Mahesh, A., R. Eager, J. R. Campbell, and J. D. Spinhirne, Observations of blowing snow at the South Pole, *J. Geophys. Res.*, **108(D22)**, 4707, doi:10.1029/2002JD003327, 2003.

Massom, R.A., M.J. Pook, J.C. Comiso, N. Adams, J. Turner, T. Lachlan-Cope, and T.T. Gibson, 2004: Precipitation over the Interior East Antarctic Ice Sheet Related to Midlatitude Blocking-High Activity. *Journal of Climate*, **(17)**, 1914-1928.

Mann, G.W., 1998: Surface heat and water vapour budgets over Antarctica. Ph.D. thesis, University of Leeds, 279 pp.

Monaghan, A.J., D.H. Bromwich, J.G. Powers, and K.W. Manning, 2005: The Climate of the McMurdo, Antarctica Region as Represented by One Year of Forecasts from the Antarctic Mesoscale Prediction System. *Journal of Climate*, **(18)**, 1174-1189.

Monahan, E.C., 1986: The ocean as a source for atmospheric particles. *The Role of Air-Sea Exchange in Geochemical Cycling*, P. Buat-Menard, Ed., D. Reidel, 129-163.

Schiffer, R.A. and Rossow, W.B. (1983): The International Satellite Cloud Climatology Project (ISCCP). *Bull. Amer. Met. Soc.,* **(64)**, 779-84.

Schwerdtfeger, W., 1984: *Weather and Climate of the Antarctic*. Developments in Atmospheric Science, Vol. 15, Elsevier Science Publishers B. V., 262 pp.

______, 1970: The climate of the Antarctic. *Climates of the Polar Regions,* Elsevier, New York, 253-355.

Seefeldt, M.W., G.J. Tripoli, and C.R. Stearns, 2002: A High-Resolution Numerical Simulation of the Wind Flow in the Ross Island Region, Antarctica. *Monthly Weather Review,* **(131)**, 435-458.

Shulski, M.D. and M. W. Seeley, 2004: Application of Snowfall and Wind Statistics to Snow Transport Modeling for Snowdrift Control in Minnesota. *Journal of Applied Meteorology*, **(43)**, 1711–1721.

Smith, M. H., P. M. Park, and I. E. Consterdine, 1993: Marine aerosol concentrations and estimated fluxes over the sea. *Quart. J. Roy. Meteor. Soc.,* **(119)**, 809–824.

Stearns, C.R., L. Keller, G.A. Weidner, and M. Sievers, 1993: *Monthly mean climatic data for Antarctic automatic weather stations*. Antarctic Research Series, Vol. 61, American Geophysical Union, 1-22.

Tabler, R.D., 1994: Design guidelines for control of blowing and drifting snow. Strategic Highway Research Program, National Research Council Tech. Rep. SHRP-H-381, 364 pp.

______, 1988: Estimating dates of the snow accumulation season. Preprints, *Western Snow Conf.,* Kalispell, MT, 35-42.

Todd, M.C., Kidd, C., Kniveton, D., and Bellerby, T.J., 2001: A Combined Satellite Infrared and Passive Microwave Technique for Estimation of Small-Scale Rainfall, *Jour. of Atm. and Ocn. Tech.*, **(18)**, 742-755.

Tripoli, G.J., 1992: A Nonhydrostatic Mesoscale Model Designed to Simulate Scale Interaction. *Monthly Weather Review,* **(120),** 1342-1359.

Vaughn, D.G., Bamber, J.L., Giovinetto, M., Russell, J., and Cooper, A.P.R., 1999: Reassessment of Net Surface Mass Balance in Antarctica *Journal of Climate*, **(12)**, 933-946.

Walmsley, J.L., P.A. Taylor, T. Keith, 1986: A simple model of neutrally stratified boundary-layer flow over complex terrain with surface roughness modulations (MS3DJH/3R), *Boundary-Layer Meteorology*, **(36)**, 157-186.

______, J.R. Salmon, and P.A. Taylor, 1982: On the application of a model of boundary-layer flow over low hills to real terrain. *Boundary-Layer Meteorology*, **(23)**, 17-46.

Wendler, G., André, J.C., Péttre, P., Gosink, J., and Parish, T., 1993: Katabatic winds in Adelie coast. *Antarctic Research Series, Volume 61: Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations,* D.H. Bromwich and C.R. Stearns, eds, American Geophysical Union, Washington, 23-46.

Xiao, J., 2001: A model of the transport and sublimation of blowing snow in the atmospheric boundary layer. PhD thesis, York University, 227 pp.

______, R. Bintanja, S.J. Déry, G.W. Mann, and P.A. Taylor, 2000: An intercomparision among four models of blowing snow. *Boundary-Layer Meteorology,* **(97)**, 109-135.