An Analysis of Near-Surface Winds, Air Temperature, and Cyclone Activity in Terra Nova Bay, Antarctica, from 1993 to 2009

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ABSTRACT

In September 2009, the first unmanned aerial vehicles were flown over Terra Nova Bay, Antarctica, to collect information regarding air–sea interactions. Prior to the field season, wind and temperature data from a local automatic weather station (AWS) were collected from 1993 to 2007 and compared with an August–October 2006–08 satellite cyclone analysis to place the September 2009 observations into a broader context. AWS wind data revealed a strong tendency toward downslope flow in the region regardless of season, as the majority (55%) of winds were from the west to northwesterly directions. Most winds observed at the site were less than 20 m s$^{-1}$, but 83% of the stronger winds were associated with downslope flow. Of 15 strong wind events (greater than 20 m s$^{-1}$ for more than 10 h) evaluated during the cyclone analysis period, 100% occurred in the presence of a cyclone in the adjacent Ross Sea. Winter experienced the greatest number of strong wind events (68%), and summer had the least (4%). Most temperatures were between $-15^\circ$C and $-25^\circ$C, with temperatures influenced by wind fluctuations. The cyclone analysis revealed that 64% of systems were comma shaped, and most cyclones (84%) within the Ross Sea were mesocyclones. A comparison of AWS data for Septembers 1993–2007 and September 2009 showed more strong wind events during 2009, while the cyclone analysis revealed a shift in cyclonic activity eastward. Reanalysis data comparing September 1993–2007 and September 2009 show an eastward shift in a deeper upper-level trough, indicating that September 2009 was an anomalous year.

1. Introduction

Since the early 1900s, when Robert Falcon Scott’s Northern Party spent an unfortunate winter on Inexpressible Island, the Terra Nova Bay region of Antarctica has been recognized as an area of harsh winds and brutally cold temperatures. These meteorological extremes make this a region where scientific research is both difficult to conduct and of great importance. The severe winds, caused by offshore downslope flow through nearby mountain valleys, transport sea ice eastward from the coast and create a relatively ice-free area within Terra Nova Bay. These ice-free windows into the ocean, termed polynyas, can exist throughout the winter season, making the region important for the alteration of oceanic currents, the production of phytoplankton, the congregation of oxygen-breathing sea mammals, and the movement of ships carrying supplies for various Antarctic scientific stations (Buffoni et al. 2002; McMahon et al. 2002; Arrigo and van Dijken 2003, 2004).

Despite the small size of Terra Nova Bay, the interaction between local atmospheric and oceanic forcing can have significant effects on the local and large-scale circulation of the Southern Hemisphere. The atmospheric effects—largely from downslope drainage from the interior of the continent—can alter existing weather patterns or enhance energy fluxes between the ocean and atmosphere (Bromwich 1989; Bove and Paolo 2009). The oceanic effects—largely caused by the open ocean water—can change currents in the southern oceans (Buffoni et al. 2002). A well-documented coastal polynya that is highly sustainable during the winter season is located at the base of the Nansen Ice Sheet in Terra Nova Bay and is largely maintained by strong downslope flow from air rushing through the valleys of the Reeves, Priestley, and to some extent David Glaciers (Bromwich and Kurtz 1984; Petrelli et al. 2008; Kern 2009) (Fig. 1).

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Oceanic sensible heat fluxes are also thought to contribute to maintaining the ice-free polynya (van Woert 1999). During the winter season, when the downslope flow is the strongest, intense winds blowing across the open water can cause large fluxes of energy out of the ocean and into the atmosphere. The injection of warmer ocean air from the polynya into the atmosphere can cause a convective surface layer to form, initiating the development of mesoscale dynamic systems, such as land breezes or cyclones (Gallée 1996; Carrasco et al. 2003; Bove and Paolo 2009). Cold atmospheric temperatures and strong winds can further the development of this convective layer.

Additionally, the polynya is an important area for the production of sea ice, as the denser, saltier water left behind when the ice forms and moves eastward sinks to the bottom of the ocean and adds to the formation of Antarctic Bottom Water (Hauser et al. 2002; Kern 2009). Despite the relatively small area of the polynya (during the winter the size varies between 3000 and 7000 km²), the impacts on the climate system are significant, as the formation of Antarctic Bottom Water influences the Southern Ocean thermohaline circulation (Hauser et al. 2002).

There is a subtle but important difference between katabatic and downslope flow, although the two are
often mistaken. Any flow down sloping terrain can be described as downslope flow. Winds blowing down the terrain can be caused by a number of factors, including a background pressure gradient force or gravity acting on negatively buoyant air adjacent to the slope. Katabatic flow is downslope flow of radiatively cooled, negatively buoyant air (Parish and Cassano 2003). Radiational cooling from the surface, particularly during the winter, will generate a strong surface inversion, which will in turn produce a pressure gradient force directed down the fall line. It is the presence of radiatively cooled, negatively buoyant air that distinguishes katabatic flow from the more general downslope flow. As such, katabatic flow is always downslope flow, but downslope flow is not always katabatic. In this paper, we will attempt to discriminate between the two types of flow, although it is important to note that from wind measurements alone it is not possible to determine whether a flow is katabatic or simply downslope (Parish and Cassano 2001). In these cases, the more general term of “downslope flow” will be used. A detailed analysis of whether the flow is downslope or katabatic requires detailed knowledge of the thermodynamic evolution of the near-surface air over the Antarctic continent and is not possible from the limited observational data available over the continent and as such is beyond the scope of this work. Since the development of the coastal polynya is due largely to the presence of strong offshore (and downslope) winds, the distinction between katabatic and the more general downslope flow is inconsequential for this study.

Despite the impacts of the Terra Nova Bay region on the local and regional climate system, few in situ observations are available to examine the significance of these atmospheric effects. Several automatic weather stations (AWS) are available near Terra Nova Bay, but these stations are widely spaced and limited to within a few meters of the surface (Stearns et al. 1993). Satellite data coverage has improved dramatically in recent years, and while the temporal and spatial scales of this data are high, the vertical resolution of the data is limited, particularly near the surface. Aircraft flights flown during field campaigns can provide excellent data throughout the atmospheric layer but can be expensive and logistically difficult. To date and to the authors’ knowledge, there have only been two field campaigns consisting of instrumented aircraft over the Terra Nova Bay region (Parish and Bromwich 1989; Davis et al. 2008). The first field campaign took place during November 1987 and consisted of two successive flights through a katabatic layer originating from Reeves Glacier, with the purpose being to study the boundary layer dynamics within a katabatic flow field. The second took place in several transects across the polar plateau, Ross Island, and Terra Nova Bay during November and December 2003, collecting measurements of temperature and pressure as part of a study aimed at understanding the processes that control trace chemicals across Antarctica (Davis et al. 2008).

In September 2009, the first unmanned aerial vehicles (UAVs), which are more easily maneuverable and require less of a logistical component than larger, manned aircraft, were flown from the Pegasus White Ice runway near Ross Island to Terra Nova Bay, with the purpose being to examine the atmospheric mechanisms responsible for the formation and modification of dense shelf water within the area polynya. The UAVs measured wind speed and direction, temperature, humidity, and pressure over Terra Nova Bay. As well, information about the surface state of the polynya, such as digital images and skin temperature measurements, were collected during the UAV flights at high vertical and temporal resolutions (Cassano et al. 2010). Prior to the September 2009 UAV field season, an examination of the local weather patterns of Terra Nova Bay from 1993 to 2008 was conducted using the only two readily available data sources in the region: AWS and satellite data. Prevailing wind speeds and directions, as well as changes with temperature, were studied from the AWS between 1993 and 2007, and synoptic and mesoscale cyclones from a manual satellite analysis for the months of August through October of 2006–08. The purpose of this examination is to explore the characteristics of the local atmospheric forcing, namely downslope flow and cyclogenesis, and use these tendencies to place the data from the September 2009 field season in a broader context. The UAV observations of the atmosphere over Terra Nova Bay can be used to determine whether expected shelf water formation from the polynya during September 2009 is stronger or weaker than the long-term average, based on our analysis.

Section 2 describes the data sources used for this analysis, including explanations regarding specific criteria for strong wind events and the use of Rita AWS. Section 3 describes the results from the 1993–2008 analysis years. Section 4 relates the 1993–2008 analysis to the meteorological pattern of September 2009. A summary is presented in section 5.

2. Data description

a. AWS observations

AWS data from the Rita site, operated by the Italian Antarctic Research Programme (PNRA), were used as the primary dataset to study atmospheric changes in Terra Nova Bay. Rita AWS is located just west of Terra Nova Bay, downstream of both Reeves and Priestley
Glaciers, at an elevation of 268 m (Fig. 1). The station measures temperature, wind speed and direction, relative humidity, and atmospheric pressure on an hourly basis. The temperature, pressure, and relative humidity data are instantaneous measurements reported at the top of the hour, while the wind measurements are the average of the data from the 10 minutes prior to the start of the hour (P. Grigioni 2009, personal communication). The Vaisala wind instruments are operational at a minimum temperature of $-50^\circ$C, while the Vaisala temperature and humidity measurements are operational to $-40^\circ$C. The tower stands 10 m tall on bare rock and is powered by two 48-W solar panels and six lead acid batteries. The data from the station is transmitted in real time via the Argos data collection system (DCS), and has been in operation since January 1993. Data from January 1993 through November 2007 have been quality controlled by PNRA and are used for this analysis. Data from September 2009 were quality controlled by the authors for comparison with the 1993–2007 dataset to place the September 2009 observations into a broader perspective. Unfortunately, because of a loss of the radiation shield the temperature sensor was not transmitting reasonable temperatures during September 2009, and the data are omitted for this period.

Analysis of the AWS data focused on wind and temperature observations. These observations were examined separately to determine the general flow pattern over Terra Nova Bay as well as the basic atmospheric properties of the region. Wind and temperature observations were then combined to determine the potential offshore interaction between the atmospheric and oceanic state. Changes in wind patterns, temperature, and wind temperature fluctuations were examined using the Rita AWS data both over the entire 1993–2007 period and the September 2009 UAV time period, as well as by season, with the seasons defined as spring (October–November), summer (December–January), autumn (February–March), and winter (April–September). The selection of these seasons was based on Seefeldt and Cassano (2008), where April was chosen as part of the winter period instead of autumn to closer match known Antarctic seasonal patterns.

Further analysis was conducted using the Rita AWS wind observations by identifying strong wind events over the study area. A strong wind event was identified as one in which the wind speeds reported were in excess of 20 m s$^{-1}$ for at least a 10-h duration. The selection of a 10-h duration was based on Seefeldt et al. (2007) in which prevailing wind regimes over the Ross Ice Shelf were examined using AWS and model data to identify corresponding wind events. The selection of a minimum wind speed threshold of 20 m s$^{-1}$ was based on several factors, including manual analysis of the dataset. Several thresholds were tested, including 15, 30, 40, and 50 m s$^{-1}$, and it was found that using 20 m s$^{-1}$ captured a representative number of wind events that were maintained for longer than 10 h. In addition to this analysis, Morales Maqueda et al. (2004) indicate the need for a wind speed threshold of at least 20 m s$^{-1}$ to exist in order to maintain ice-free polynyas around the Antarctic coast.

To account for fluctuations in wind speed due to wind gusts, winds were allowed to drop below 20 m s$^{-1}$ for no more than 10 consecutive hours during an event. Below threshold durations of 5 and 10 h were tested and compared to the criteria listed above. An example of the changes between the 10- and 5-h duration analyses during a sample period (September 2002) can be seen in Fig. 2. During this month, event 1 was eliminated during the 5-h analysis, and event 2 was shortened by 25 h. Event 1 was removed as there were more observations below the wind speed threshold than above, while event 2 was shortened due to the occurrence of a sharp peak in wind speed at the beginning of an event, followed by an immediate drop for more than 5 h. A manual analysis of these events indicated that the first event should be removed, but the second should have the duration as in the 10-h analysis. From this analysis and others throughout all months of September between 1993–2007 and 2009, it was concluded that a maximum below-threshold duration of 10 h would be used, while limitations would be imposed to eliminate those wind events where a greater period of time during the event was spent below the wind speed threshold. The criteria for the specifications of strong wind events are summarized in Table 1.

The AWS analysis was not extended through 2008 for two reasons. First, the PNRA quality-controlled dataset only included data through November 2007, and maintaining a uniform dataset throughout the analysis period was critical. Secondly, on 21 September 2008 the Rita AWS fell down, and data were unavailable until the following field season. Given that a significant portion of 2008, and in particular the month of highest interest to this study (September) was unavailable, 2008 was disregarded from the AWS analysis entirely. Additionally, there were several months during the 1993–2007 analysis period during which data were unavailable at Rita. These periods of data loss largely extended from winter through spring season, as issues with the AWS that occurred during winter were unable to be repaired until the summer field season. Periods of data loss occurred during July–October 1993, May–October 1996, and August–November 2001. No data were available for December 2007, as the data had not been quality controlled during that time. This loss of data accounted for a 25% total loss of observations in spring, a 14% loss in summer, an 8% loss in autumn, and a 21% loss in winter.
b. Selection of Rita AWS

The Rita site was chosen over other area AWS because of its representativeness of the meteorological conditions just upstream of the polynya. To confirm this, comparisons of the winds and potential temperatures at three other AWS upstream of Terra Nova Bay (Eneide, Sofia, and Zoraida) were made with the Rita AWS observations (Figs. 3 and 4). To appropriately compare the four datasets, only times when observations were available at all four stations were used in the analysis. As Sofia AWS ceased transmissions in 2002, the dataset of the four stations was between 1993 and 2002. It was expected that Eneide site would have the lowest wind speeds of all four sites, based on its low elevation (approximately 91 m) and being farthest from the terminus of the Reeves and Priestley Glaciers. Because of the location, winds at Sofia site were expected to reflect influences from both Reeves and Priestley Glaciers, and Zoraida was expected to experience the strongest wind speeds because of its elevation (884 m) and location on Priestley Glacier. Figure 3 confirms this. Prevailing winds at Eneide are almost equally dominantly from the west and north-northwest and exhibit the weakest wind...
speeds overall and the least number of strong wind events (Fig. 3). Winds at Sofia are mostly from the west but also strong from the north, indicating influences from both Reeves and Priestley Glaciers (Fig. 3). Winds at Zoraida reflect strong influences from Priestley Glacier in terms of directional flow and also show the highest number of strong wind events (Fig. 3).

It was expected that temperatures would be potentially coldest at the Zoraida site, reflecting an unstable atmosphere consistent with katabatic drainage from higher elevations. However, Fig. 4 shows temperatures to be potentially coldest at the Sofia site. With a stable atmosphere present between Zoraida and Sofia, mean katabatic forcing cannot exist between these sites on Priestley Glacier without an additional external force, such as that from a background synoptic pressure gradient. Further analysis is needed to confirm this.

This analysis shows that the Zoraida and Eneide sites are not the most ideal locations to characterize the off-continent air mass, while Sofia and Rita are. Zoraida’s location inland and on Priestley Glacier is only an accurate representation of the air flowing down the glacier from the high polar plateau. Southwesterly winds at the Eneide site (Fig. 3) show an influence from local topography that will not necessarily be representative of

Table 1. Selection criteria for strong wind events.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed threshold</td>
<td>20 m s$^{-1}$</td>
</tr>
<tr>
<td>Min duration of time at or above wind speed threshold</td>
<td>10 h</td>
</tr>
<tr>
<td>Max continuous amount of time allowed below wind speed threshold</td>
<td>10 h</td>
</tr>
<tr>
<td>Ratio of time above threshold to time below threshold</td>
<td>$\geq 1$</td>
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</tbody>
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FIG. 3. Wind roses for 1993–2002 for Eneide, Rita, Sofia, and Zoraida AWS.
the flow pattern that travels farther east over the polynya. Additionally, Eneide’s location is too far north of where the Priestley and Reeves Glaciers’ wind jet extends to depict these air masses accurately. The Sofia and Rita sites, however, are ideally placed to characterize the air mass upstream of the polynya. Sofia’s location on the Nansen Ice Sheet demonstrates flow from both Reeves and Priestley Glaciers, but the shortened observational record (which extends until 2002) is not ideal, and the lack of data in September 2009 makes this AWS ineffective to this study. The Rita site, located on the windward side of the northern foothills and farther south than Eneide, has a long data record, including wind observations during September 2009, and is the most reasonable AWS to use for this analysis.

Using all four sites for the analysis presented in this paper was not feasible, as the time period when all

stations have coincident data is severely limited. The availability of coincident data was considered critical for this study, since missing data could easily bias the high wind event analysis. For the 1993–2002 time period, only two winters could be sampled because of a loss of transmissions from at least one of the four sites. Closer examination of Fig. 5 shows that when using all four stations, upward of 80% of the observations during the winter months were missing, whereas using only Rita AWS results in only a 30% loss in observations during those months. Given the above analysis between regional AWS, and the optimization of data during the winter months, Rita is the ideal AWS to use for this study.

c. Cyclone climatology

The cyclone analysis was produced using the National Oceanic and Atmospheric Administration (NOAA)
Local Area Coverage (LAC) 1-km-resolution data provided by the Antarctic Meteorological Research Center (AMRC) at the University of Wisconsin. A time frame of August to October 2006 to 2008 was chosen as the analysis study period to acquire a reasonable sampling of cyclones around the time of year of the UAV flights in September 2009. For years 2006–08, LAC data from the NOAA-18 satellite was used; for the September 2009 comparison dataset, NOAA-19 LAC data were used. Cyclones were identified using the infrared data over a domain area centered at 74°S, 175°W (Fig. 6), which covers the entire Ross Sea including Terra Nova Bay, from one satellite image per day, typically around 0300 UTC. This dataset was expanded to include the entire Ross Sea for two main reasons: to include all systems that would have an impact on Terra Nova Bay, and to match previous climatological datasets that have included the entire Ross Sea region (Carrasco and Bromwich 1994; Gallée 1996; Carrasco et al. 2003).

**FIG. 5.** Percentage of strong wind events and percentage of missing data occurring during each month at (a) Eneide, Rita, Sofia, and Zoraida AWS between 1993 and 2002, and (b) Rita AWS between 1993 and 2007.
The cyclones found from this data were manually identified by a thorough examination of each image (Fig. 6). The analysis included any system showing cyclonic rotation over the domain, with information regarding position, time, size, and shape recorded. The sizes of the systems were identified by examining both the short and long dimensions of the system, with those smaller than 1000 km identified as mesocyclones and those larger classified as synoptic systems (Heinemann 1990; Bromwich 1991; Carrasco et al. 2003). The shapes of the system were divided into four categories: comma, merry-go-round, single-cyclonic band, and spiral form, following previous studies of cyclones in the Antarctic (Carleton and Fitch 1993; Carrasco et al. 2003). Merry-go-round systems have several small cyclones attached to a much larger system, single-cyclonic band systems are those that are in the early stages of cyclone formation, and a spiral form system has several bands that form a cyclone, as opposed to the comma-shaped systems, which are a single mass of clouds. Information on the size and shape of cyclonic systems was included in this dataset to coincide with other cyclone climatologies conducted across the Antarctic (Carleton and Fitch 1993; Turner et al. 1998; Carrasco et al. 2003).

3. Climatology of selected variables in Terra Nova Bay

a. Wind speed and atmospheric temperature tendencies

Wind rose plots from the Rita site show that the majority (55%) of winds are from the west, west-northwest, and northwest directions, indicating a dominant flow regime that is downslope (Fig. 7). Eighty-six percent of all wind speeds at Rita site are less than 20 m s⁻¹; however, of the wind speeds greater than 20 m s⁻¹, 83% are from the west to northwesterly direction, indicating that most of the extreme wind speeds are from downslope flow. Between 1993 and 2007, a total of 418 strong wind speed events (as defined in section 2) were identified, with the maximum winds found during the 1993–2007 time frame being 58 m s⁻¹. Most strong wind events occurred in July (14%), with the least occurring during January (1%) (Fig. 5b). The winter and autumn seasons showed the highest percentages of strong wind events at 68% and 17%, respectively, while spring and summer respectively had only 11% and 4% of the total wind events.

An examination of the temperatures at Rita site shows that 39% of the observations are within the range
from $-15^\circ$ to $-25^\circ$C, with a peak that exhibits a sharper decrease toward colder values and a gradual decline as temperatures get warmer (Fig. 8). Analysis of the seasonal contributions to temperatures in the bin from $-15^\circ$ to $-25^\circ$C shows that the majority (73%) of temperatures in this bin occur during winter season, while 0% occur during summer. Spring and autumn contribute 11% and 16%, respectively. The majority of observations colder than $-25^\circ$C also occur during the winter season (97%), with 0% of the observations occurring during summer and the remainder evenly split between spring and autumn. Temperatures warmer than $-15^\circ$C occur in all four seasons, with most instances occurring during summer (39%) and the least during winter (14%). Spring and autumn contribute 21% and 26%, respectively.

Histograms of temperature for various wind speed ranges are shown in Fig. 9. Relatively few observations are found at the most extreme wind speeds, as the frequency of these events is much lower. Intermediate winds, such as the 10–20, 20–30, and 30–40 m s$^{-1}$ categories exhibit a Gaussian distribution, while the 0–10 m s$^{-1}$ category exhibits a bimodal distribution of temperature, with two peaks occurring near $-20^\circ$ and 0°C. Further analysis comparing temperatures in the 0–10 m s$^{-1}$ category during each of the four seasons show that the two peaks are due to contributions from the winter and summer seasons, respectively.

### b. Synoptic-scale and mesoscale cyclone characteristics

The identification of mesoscale and synoptic-scale cyclones from a manual cyclone analysis during the August–October 2006–08 time period indicated several interesting patterns of cyclone locations across the Ross Sea (Fig. 10). In particular, two prominent features are easily visible. The first is the high density of mesocyclones (cyclones with sizes less than 1000 km) located on the lee (northern) side of Ross Island, as indicated by box 1. The many mesoscale cyclones in this area are likely cyclonic shear vortices that are produced by southerly flow around Ross Island. Previous studies suggest that some of these cyclones are spawned from cyclonic shear vortices that occur on the lee (north) side of Ross Island, which in turn arise from the persistent low-level southerly winds that flow around the island topography (e.g., Monaghan et al. 2005). Within the area outlined by box 1 are three dense regions of mesoscale cyclones. The areas to the western and eastern sides of Ross Island (the leftmost and rightmost portions of box 1) are the shear vortices produced by the southerly wind flow, which are enhanced by the topography of the island. This topography alters the flow around the barrier such that cyclonic shear vortices on the western side, and anticyclonic vortices on the eastern side, no larger than 300 km, are produced (see example in Fig. 6).

In the middle of box 1 is a predominantly cyclone-void region, with the exception of a few larger (300–500 km) mesocyclones. The few cyclones produced directly north of Mount Erebus, a nearly 4000-m volcano that sits atop Ross Island, result from the inability of flow that originates from the southern portion of the island to climb the barrier and flow over the obstacle instead of around it (Seefeldt et al. 2003). The few cyclones that do bridge this barrier assist in the production of slightly larger cyclonic shear vortices than those that are produced when the flow traverses the westerly and easterly edges of the island. This cluster of cyclonic activity on the lee side of Ross Island is in direct correlation with several
previous studies that examined cyclonic flow in the southwestern corner of the Ross Sea (Bromwich 1991; Carrasco and Bromwich 1994; Carrasco et al. 2003). It is possible for the cyclones that are produced in the lee of Ross Island to propagate northward to later impact Terra Nova Bay. A second region of interest, outlined by box 2 of Fig. 10, depicts a noticeable lack of cyclones that not only form but track through this region. This
lack of cyclonic activity will be discussed further in section 4.

To determine the influence of cyclonic activity on downslope winds, a comparison between strong wind events and cyclones in and around Terra Nova Bay was conducted for August–October 2006–07 (the only time period when both datasets coincided). This analysis showed that 100% of the 15 strong wind events occurred in the presence of a cyclone located in the Ross Sea. This is a rather important result that will need to be further addressed as part of future analysis of the potential linkages between cyclones in the Ross Sea and strong winds in Terra Nova Bay.

In addition to the location of the cyclones, other characteristics, such as size and shape, were collected as part of the satellite analysis. Figure 11 depicts the size distribution of the various cyclones during the study period. Most cyclones (63%) found in the Ross Sea are smaller than 500 km, with 84% of all cyclones being mesocyclones. Only 16% of all cyclones found were classified as synoptic-scale systems. Examination of the shape of the cyclones identified a majority (64%) of the systems, either synoptic or mesoscale, as having a comma shape, with 25% being spiral form, 6% single-cyclonic band, and 3% merry-go-round (Fig. 12). While the shape of a system will not change the system dynamics, it can be important in terms of understanding the regional circulation. For example, comma and merry-go-round systems tend to develop in regions of strong background flow, whereas spiral-form systems develop in synoptically quiet regions (Turner and Pendlebury 2000). Information regarding the shape and concurrent size of the systems can provide vital information about the individual systems and background synoptic environment that can impact the weather on a regional level, such as in Terra Nova Bay.

Knowledge of the typical atmospheric state over Terra Nova Bay is critical for understanding the UAV field measurements collected during September 2009. Changes in wind or temperature patterns can lead to changes in the opening of the polynya, which in turn can lead to changes in sea air fluxes. Variations in cyclonic activity can lead to changes in the direction and magnitude of winds and can advect warm or cold air into the region. Interactions between two air masses of different temperatures can generate mesoscale systems, which can also impact the size of the polynya. From this analysis, it can be seen that the primary air source that is advected over the polynya originates from the glacial valleys upstream of Terra Nova Bay, with a temperature typically observed at $-20^\circ$C. In future analysis, observations of this air mass from the UAV collected during September 2009 will be compared with the findings from
this study to put the UAV observations in a broader perspective. While the small number of UAV flights is not necessarily representative of the September 2009 monthly mean conditions, it is important to understand not only how the overall September 2009 conditions fit into the broader perspective, but also how the conditions sampled by the UAV relate to the broader perspective as well. Inferences can then be made as to changes in the size of the polynya and in turn sea air fluxes, which can impact changes in the shelf water of the polynya.

4. Comparison of AWS winds and cyclone activity for September 2009

An examination of wind fields and cyclone activity in Terra Nova Bay between September 1993–2007 and September 2009 shows that September 2009 experienced stronger winds and fewer cyclones, with more winds from the north-northwest, than the analysis months. As during the 1993–2007 analysis, the majority of winds originate from the west to northwesterly directions, indicating that downslope winds are the primary flow field over the polynya during September 2009. During the September of 1993 to 2007, 60% of the winds were west to northwesterly, as compared with 75% of the winds during September 2009 (Fig. 13). This shift in wind direction, particularly to the north-northwest during September 2009, indicates a displacement of surface cyclones in the Ross Sea and Ross Ice Shelf regions, accompanied by variations in an upper-level large-scale feature, as described below.

During September 2009, 39% of winds were greater than 20 m s$^{-1}$, as compared with 14% of wind observations during 1993–2007. As during the analysis years, 83% of those winds greater than 20 m s$^{-1}$ were from the west to northwesterly directions, indicating that the strongest winds correspond with downslope flow. Five strong wind speed events were recorded in September 2009, while the 1993–2007 Septembers experienced an average of 3.7 strong wind speed events per month (Fig. 14). As during the analysis years, 100% of the strong wind events that occurred during September 2009 arose in the presence of a Ross Sea cyclone.

Most of the cyclone activity shifted toward the eastern Ross Sea during September 2009, while much of the activity during the previous Septembers (2006–08) was located in the western to central Ross Sea (Fig. 15). A cyclone-void region in the approximately the area 71°–75°S, 165°–175°W, as outlined in box 2 of Fig. 10 and box 1 of Fig. 15, shows that during September 2009 this area...
had 150% more cyclones (13 versus 5) than during September 2006–08, with four of the five cyclones observed within the box occurring in 2008. During 2008, nearly double the number of cyclones was observed throughout August–October, which was due to a strong upper-level trough at 500 mb (hPa) located in the same area as the trough in 2009 (not shown).

A comparison of the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis 500-mb geopotential height composite means for September 1993–2007 to September 2009 shows an upper-level trough that was situated over the center of the Ross Ice Shelf in previous Septembers had deepened and shifted farther east over western Marie Byrd Land during September 2009 (Fig. 16). These upper-level troughs, which will tilt toward colder air, are indicative of surface cyclones to the north and northeast. Hence, typical Septembers show more cyclones in the center to just east of center portions of the Ross Sea; while during September 2009 the majority of surface cyclones would have been farther east of the Ross Sea and north of Marie Byrd Land. This shift explains the lower number of cyclones found in Terra Nova Bay during September 2009.

A comparison of Figs. 16a and 16b indicates that an enhanced west-to-east pressure gradient force, which will strengthen downslope surface winds in the vicinity of Terra Nova Bay, is present in 2009 relative to the
multiyear mean. This enhanced pressure gradient is the result of both a deeper trough in the eastern Ross Sea as well as a stronger ridge over the East Antarctic plateau. An analysis of Fig. 14 shows that the years of 1994, 2000, 2003, 2005, and 2009 had an above average number of strong wind events, while 1999, 2002, and 2007 were below average. 1995 and 1997 had an average number of strong wind events during the year. A closer examination of the NCEP–NCAR reanalysis 500-mb geopotential height fields for these years (not shown) indicates that during the average and above average years (with the exception of 1997), a ridge could be found on the high polar plateau. During the years when the number of strong wind events was below average, no ridge was found on the polar plateau; rather, a trough at 500 mb was found just west of the Ross Ice Shelf on the high polar plateau. Turner et al. (2009) suggest that a strong ridge pattern on the high polar plateau accompanied by a sea level low pressure anomaly promotes an ideal situation for generating strong wind events off the East Antarctic coast. The ridge during September 2009 was more intense than for the other strong wind event years, as was the trough over western Marie Byrd Land, implying strong downslope flow along the glacial valleys of the Transantarctic Mountains, including in Terra Nova Bay. The shifts in the 500-mb geopotential height pattern described above would also be expected to influence surface low pressure centers.
The eastward shift in cyclone locations during September 2009 is consistent with an eastward shift in the 500-mb trough during 2009 (Fig. 15). One potential explanation for the shift in the 500-mb geopotential height pattern is related to the El Niño–Southern Oscillation (ENSO) pattern of 2009, which experienced a transition from a cold ENSO (La Niña) to warm ENSO (El Niño) during the latter half of the year (Arndt et al. 2010). Correlations between ENSO events and Antarctic climate patterns are highly variable, but studies have shown that ENSO events can lead to changes in the Rossby wave pattern of the Southern Hemisphere (Turner 2004). Previous studies (Kidson 1999; Turner 2004; Fogt and Bromwich 2006) have shown that during warm ENSO events there typically exists a high pressure anomaly in the Amundsen Sea region, while in cold ENSO events a low pressure anomaly is present. These anomalies are particularly present during the September–November (SON) months (Fogt and Bromwich 2006). An examination of the difference between 500-mb heights in 2009 and the analysis years (1993–2007) shows the existence of a high pressure anomaly in this area (Fig. 17a). The intensity and location of the anomaly in SON 2009 is similar to years in which an El Niño pattern was present, and is particularly comparable to the 2002 warm ENSO event (not shown), which corroborates findings from the 2009 State of the Climate Report (Arndt et al. 2010).

While the mean SON high pressure anomaly for 2009 coincides with previous studies that indicate a similar upper-level pattern to other El Niño years, the September 2009 month does not represent the El Niño signal. Instead, a low pressure anomaly is present in the Amundsen Sea during this month, indicating that the Amundsen Sea region during September 2009 was still experiencing the effects of La Niña (Fig. 17b). Later in 2009, as Fig. 17a shows, a wave train of positive and negative height anomalies consistent with the El Niño pattern can be seen in the South Pacific and South Atlantic (Fogt and Barreira 2010).

The southern annular mode (SAM) indices in the latter half of 2009 were highly variable. In general, a negative (positive) SAM index is correlated with higher (lower) pressures over the Antarctic continent (Turner 2004; Fogt and Bromwich 2006). The SAM index of September 2009 was $-0.78$ (Fogt and Barreira 2010), indicating higher pressures over the interior. Indeed, an examination of Fig. 17 shows these higher pressures.

The eastward shift in the upper-level flow pattern and surface cyclone activity, a stronger than average ridge on the polar plateau and stronger than average low in the Ross Sea, and stronger than average winds at the Rita site indicate that September 2009 was anomalous. An understanding of the September 2009 meteorological pattern, and its relationship to previous patterns, is imperative for understanding the data collected from the UAV flights in September 2009. As discussed in several studies, including Bromwich and Kurtz (1984) and Bromwich et al. (1993), strong wind events aid in opening Antarctic polynyas, both in Terra Nova Bay and elsewhere across the continental coast. In a year such as September 2009, when winds were stronger than previously observed, the ice-free polynya will occur more frequently and exist for longer periods of time. A combination of the strong winds, colder temperatures from the westerly winds originating from the high polar plateau, and open ocean water will increase ocean to atmosphere heat fluxes during this time. An understanding of the strength of the wind flow during this month, as well as its origin (i.e., downslope) and how it compares to previous years will provide a basis to determine how the anomalous year sampled by the UAV will impact the Terra Nova Bay climate system in September 2009.
5. Summary

The climate of the Terra Nova Bay region of Antarctica was studied from 1993 to 2009 using AWS and satellite data to establish an understanding of the local flow regimes and atmospheric conditions of this region. This work was in support of an observational field campaign conducted during September 2009 that included the use of UAVs to collect information regarding the atmospheric structure of Terra Nova Bay. The analysis of weather patterns during the years prior to 2009 was used to place the AWS and satellite observations during September 2009 into a broader context.

Wind and temperature data from Rita AWS, located to the west of Terra Nova Bay in the northern foothills region of the Transantarctic Mountains, were analyzed during 1993–2007 and 2009 to determine dominant weather conditions. As several studies have shown that downslope flow is strongly driven by a pressure gradient force induced by sea level cyclonic activity, a manual satellite analysis was produced from August to October 2006–08 to study the density of cyclones throughout Terra Nova Bay and the nearby Ross Sea. The analysis of weather patterns during the years prior to 2009 was used to place the AWS and satellite observations during September 2009 into a broader context.

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Results indicate that typical winds in Terra Nova Bay originate from glaciers just west of Terra Nova Bay. The majority of the winds are less than 20 m s$^{-1}$, but of the winds greater than 20 m s$^{-1}$, 83% are from directions consistent with downslope flow. An analysis of strong wind events found 418 events between 1993 and 2007, with 100% of these events during 2006–07 associated with cyclonic activity in the Ross Sea. Winter experienced the greatest number of strong wind events (68%), with 14% of the total events occurring during July. The summer season exhibited the least number of strong wind events, with only 1% of events occurring during January.

Temperature histograms at the Rita site from 1993–2007 show that 39% of temperatures fall in the 10°C band between −15°C and −25°C, with 45% of temperatures between −15°C and 10°C, and only 16% of temperatures below −25°C. A satellite analysis over the Ross Sea found a high density of mesocyclones occurring on the lee side of Ross Island, including the southwestern corner of the Ross Sea as well as Terra Nova Bay. The majority of systems classified during this study period were found to have a size extent of less than 1000 km, with the remaining 16% identified as synoptic systems. Most of these cyclonic systems had a comma shape.

A comparison of the AWS and satellite data from the 1993–2007 Septembers and September 2009 showed an increased number of strong winds and an eastward shift of cyclonic activity during September 2009. NCEP–NCAR reanalysis 500-mb geopotential heights show an eastward shift in an upper-level trough in September 2009, as compared with Septembers 1993–2007, over the eastern Ross Sea. This eastward displacement was due
to changes in the Southern Hemisphere Rossby wave pattern, which was consistent with previous documented impacts of ENSO on high southern latitude circulation (Turner 2004; Fogt and Bromwich 2006). The intensification of the 500-mb trough and a strong ridge center over the high polar plateau enhanced the downslope-directed pressure gradient force and thus downslope flow in the region. The strong flow pattern, change in cyclone activity, and shift in synoptic flow patterns indicate that September 2009 was an anomalous year. Data collected and analyzed in future work from the UAV flights during this month will provide exciting new insights into uncharacteristic flow patterns over the region.

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