WINTER ATMOSPHERIC FORCING OF THE ROSS SEA POLYNYA

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Polynyas, or areas of combined open water and thin ice surrounded by sea and/or land ice, are thought to play important roles in heat transfer from ocean to atmosphere, ice production, the formation of dense shelf water, spring disintegration of sea ice, and the sustenance of primary and secondary productivity in polar regions. This study examines the interannual variation of the Ross Sea Polynya and winter atmospheric forcing from 1988-1991. The results show that significant interannual variability is observed in winter. The largest open water fraction occurs in 1988 in conjunction with the warmest winter temperatures and the strongest winds, with the other three winters being similar in open water fraction and atmospheric forcing. The polynya event survey shows the maximum number of events takes place in 1988 and the minimum in 1990. However, consideration of the polynya duration combined with the anomalous open water fraction during polynya events identifies the 1988 and 1990 winter polynyas as having the same large cumulative impact on the oceanic surface energy balance, and the 1989 and 1991 polynyas as having a 20% smaller impact. The result for the 1988 winter is contaminated by two long polynya events which are not clearly distinguished from the average conditions by open water fraction anomalies from the 25-day running mean. Comparison between polynya open water fractions and wind and temperature variations at automatic weather station 07 explains about 25% of the polynya fluctuation variance, similar to previous findings for the Terra Nova Bay polynya. A case study elaborates the role played by atmospheric forcing. It is found that a synoptic cyclone near Roosevelt Island induces a sea level pressure distribution over the Ross Ice Shelf with isobars oriented almost parallel to the Transantarctic Mountains. This setup, which is also seen in other years, results in an intensification and northward propagation of the katabatic winds across the ice shelf with an associated low-level warming. An immediate impact of this katabatic surge event is development of the polynya. The study reveals the high spatial variability of the atmospheric forcing fields, and indicates that fluctuations of this large polynya can only be approximately related to wind and temperature observations from one site. The interannual variability of the katabatic surge events is determined. On average for the winters of 1988-1991, about 60% of the polynya events are linked to katabatic surge events.

1. INTRODUCTION

Antarctic marine environments are characterized by strong, dynamic links between environmental conditions and biological populations. Polynyas, or areas of combined open water and thin ice surrounded by sea

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and/or land ice, are thought to play an important role in ocean-atmosphere heat transfer, ice production, the formation of dense shelf water, spring disintegration of sea ice, and the sustenance of primary and secondary productivity in polar regions [Jacobs et al., 1985; Zwally et al., 1985; Cavaliere and Martin, 1985; Budd, 1991; Massom, 1988; Smith et al., 1990]. Therefore, a better
understanding of these polynyas will help further understanding of Antarctic marine environments.

The existence of wintertime open water along the Ross Ice Shelf has been known since Scott's early explorations in Antarctica [e.g., Cherry-Garrard, 1989]. However, it was not until the development of sophisticated visible, infrared, and microwave satellite sensors that the spatial extent and temporal variations of the low concentration sea ice zone along the Ross Ice Shelf were widely appreciated [Knapp, 1972; Zwally and Gloersen, 1977; Zwally et al., 1983; Streten, 1973]. During the past fifteen years, many studies associated with the Ross Sea (Figure 1) Polynya have been conducted involving both observations and numerical simulations. In spite of the well documented existence of wintertime open water along the Ross Ice Shelf, some uncertainty exists regarding the mechanisms responsible for its maintenance. Using data from the Electrically Scanning Microwave Radiometer (ESMR), Zwally et al. [1985] observe that a polynya frequently forms along the Ross Ice Shelf and argue using weather charts that the open water is maintained by synoptic wind forcing. In contrast, Jacobs and Comiso [1989] argue that heat input from the ocean is at least partially responsible for maintaining open water along the shelf. Using Nimbus 7 scanning multichannel microwave radiometer (SMMR) observations, they note that the northern edge of the Ross Sea Polynya advances at a rate of about 40 km/day when average wind speeds at the Franklin Island automatic weather station (AWS) are less than 3 m s\(^{-1}\) and air temperatures are less than -6°C. However, this 275-meter high site (AWS 13 in Figure 1b) is often influenced by katabatic airflows from Terra Nova Bay to the northwest and by mesoscale cyclones that frequently form near Franklin Island [Bromwich, 1991; Carrasco and Bromwich, 1996]; thus the representativeness of its observations for sea surface conditions farther to the east is uncertain. Lacking any new oceanic field data, we limit this study to an examination of atmospheric forcing on the amplitude of polynya expansion. Previous studies reveal that meteorological processes strongly influence development of the Ross Sea Polynya [Zwally et al., 1985; Kurtz and Bromwich, 1985; Jacobs and Comiso, 1989; Bromwich et al., 1993, 1994]. Data from AWS deployed over the Ross Ice Shelf (Figure 1) reveal that the dominant surface airflow over the western Ross Ice Shelf is northward, passes to the east of Ross Island [Savage and Stearns, 1985] and appears to be the primary atmospheric forcing for development of the Ross Sea Polynya [Bromwich et al., 1993].

Previous studies indicate that this northward airflow is derived from three main sources: 1) katabatic drainage down the Byrd, Skelton, and Mulock glaciers [Bromwich, 1989, 1992]; 2) katabatic surges that are strong katabatic winds blowing across the Ross Ice Shelf under the support of the large-scale pressure gradient and that originate from the Siple Coast part of West Antarctica [Bromwich et al., 1993]; and 3) barrier winds that flow northward along the Transantarctic Mountains and are deflected eastward by the topographic barriers of Minna Bluff and Ross Island [Bromwich, 1988; O' Connor et al., 1994]. Wintertime katabatic surges from Siple Coast propagate horizontally for about 1000 km across the Ross Ice Shelf to its northwestern edge and strongly affect Ross Sea Polynya formation. During winter 1988, katabatic surges occur approximately every 2 weeks, last 2 to 3 days, and each event coincides with rapid enlargement of the Ross Sea Polynya. Using a hydrostatic, three-dimensional primitive equation model [Parish and Waight, 1987] and a wind-driven coastal polynya model [Pease, 1987], Bromwich et al. [1994] successfully simulate the Ross Sea Polynya during a typical katabatic surge event. During the late winter and early summer, however, Bromwich [1992] shows that katabatic drainage, primarily from the Byrd Glacier region, can result in a rapid enlargement of the Ross Sea Polynya.

In this study we take advantage of daily sea ice concentration estimates from the Special Sensor Microwave Imager (SSM/I) to examine interannual variations in the frequency and duration of polynya events in the vicinity of the western Ross Ice Shelf using time series of open water fraction and concurrent wind and temperature data. A case study is presented to provide a close look at the polynya development using data from AWS, National Oceanic and Atmospheric Administration (NOAA) satellite images, and large-scale atmospheric analyses. Although the northward flowing winds involve three components, the focus here is on the katabatic surge events because they are the main energetic events during winter [Bromwich et al., 1993]. While that study suggests that a close relationship exists between the katabatic surge events and the development of the Ross Sea Polynya, gaps in the satellite imagery and cloud obscuration prevented continuous monitoring of polynya evolution. Therefore, the generality of this relationship needs to be tested, and daily SSM/I data are exploited to achieve this. We leave evaluation of the impact of the other two airflow sources for future studies.

This paper is organized as follows: Section 2 describes the data and methods, Section 3 outlines the results from evaluating four years of SSM/I and AWS data, Section 4 gives a case study, and Section 5 presents the interannual variation of the katabatic surge events. The final section consists of conclusions and discussion.
Fig. 1. (a) Southern hemisphere map, and (b) regional map of the Ross Sea, Ross Ice Shelf, and surrounding areas. B, Sh, A, and Sc, respectively, denote Beardmore, Shackleton, Amundsen, and Scott glaciers. Farther north, By, Sk, and Mu locate Byrd, Skelton, and Mulock glaciers. Dots with attached numbers indicate automatic weather station sites.
Clearly absent from this study is an assessment of the relative importance of oceanic heating on polynya extent during these strongly wind forced regimes.

2. DATA AND METHODOLOGY

2.1. SSM/I Data and Methods

The SSM/I is a 7-channel microwave radiometer that senses the Earth's emitted radiation at 19, 37, and 85 GHz vertical and horizontal polarization and at 22 GHz vertical polarization [Hollinger et al., 1990]. The first of these sensors, launched on 19 June 1987 onboard the Block 5D-2 Defense Meteorological Satellite Program (DMSP) satellite F-8, remained operational through December 1991. The satellite flew in a sun synchronous, near-polar orbit at a height of 860 km, providing 4 to 5 passes daily at high polar latitudes.

Antarctic, daily-averaged, 25-km resolution gridded sea ice concentration data products were obtained from the National Snow and Ice Data Center [Weaver et al., 1987]. This ice product is derived by applying the "NASA TEAM" algorithm [Cavalieri and Gloersen, 1984; Gloersen and Cavalieri, 1986] to the 19 and 37 GHz vertical polarization data and 19 GHz horizontal polarization data from the SSM/I. Data from individual swaths are then projected onto a polar stereographic grid and averaged to form the distributed data.

2.2. AWS and Satellite Data

Thermal infrared satellite images used in the case study were obtained from the Arctic and Antarctic Research Center at Scripps Institution of Oceanography. These satellites images were originally collected at McMurdo Station in Antarctica by U.S. Navy personnel and shipped to the Arctic and Antarctic Research Center for archival. Thermal infrared passes (channel 5) from NOAA 9 and NOAA 10 satellites were processed on a Sun workstation using the TeraScan Package Software developed by SeaSpace. To study the polynya in detail, images with the maximum resolution (1.1 km) at nadir are used. As seen below, these Advanced Very High Resolution Radiometer (AVHRR) images have a much higher spatial resolution than SSM/I, but they suffer from temporal discontinuities and cloud obscuration, which inhibits more temporally detailed study of the polynya development.

AWS observations available for 1988-1991 [Keller et al., 1989, 1990, 1991, 1993] are used in conjunction with SSM/I data for both the survey and the case study. The geographic locations of these AWS in 1988 are depicted in Figure 1. An AWS unit measures air temperature, wind speed and wind direction at 3 m, and air pressure at 1.5 m above the snow surface. The ARGOS Data Collection System collects the data which are processed and distributed by the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin-Madison. Because no atmospheric data are available in the polynya area, AWS 07, the closest station (Figure 1), is used to monitor the offshore atmospheric conditions in the polynya area.

Numerical analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used to examine the synoptic environment during the case study. The ECMWF analyses used consist of 500-hPa and surface analyses. A validation of operational numerical analyses in Antarctic latitudes reveals that ECMWF analyses are generally superior and offer a reasonable depiction of the broadscale atmospheric circulation [Cullather et al. 1997]. The analyses used in the validation include those from the ECMWF as well as the U.S. National Centers for Environmental Prediction (NCEP) from 1985-1994. The validation also makes use of available AWS of the U.S. Antarctic Program, ship observations, and rawinsonde data.

3. MULTI-YEAR SSM/I SURVEY OF THE ROSS SEA POLYNYA

3.1. Multiple Year SSM/I Survey

Plate 1 shows daily sea ice concentration maps in the Ross Sea for the 15th of each month in 1988. Clearly evident in the imagery is the seaward expansion and subsequent contraction of a zone of low concentration sea ice near the Ross Ice Shelf during some months. To further quantify temporal changes in the local ice concentration, a region representing the apparent maximum extent of polynya expansion (defined here as a contiguous region of low SSM/I-derived ice concentration extending north-northeast from the Ross Ice Shelf) is extracted from the individual daily ice concentration images. Areal ice concentration, C, is computed by summing the sea ice areas within the region and dividing by the total study area (33808 km²). Using an areal average damps smaller polynya events, but given the inherent inaccuracies of the present sea ice algorithms (~15% [Cavalieri and Gloersen, 1984; Zibordi et al., 1995; Steffen and Mastnak, 1988; Steffen and Schweiger, 1990]), this level of smoothing seems warranted. Open water in percent is computed as (1-C)*100. The time sequence of daily-averaged open water fraction for the period January 1988 through December 1991 is shown in
Plate 1. Daily sea ice concentration maps in the Ross Sea for the 15th of each month in 1988. A region representing the apparent maximum extent of polynya expansion (defined here as a contiguous region of low SSM/I-derived ice concentration extending north-northeast from the Ross Ice Shelf) is outlined on each map by thick lines. Parallels and meridians are given every 2.5° and 10°, respectively. See color bar in Plate 2 to relate colors to sea ice concentration.
Figure 2. The data availability for this period is 94% in 1988, 98% in 1989, 96% in 1990 and 96% in 1991. The thin line portrays the daily-averaged fractional open water, while the bold black line is a 25-day running mean filtered version of the daily values.

Summer open water conditions are very similar and extend roughly from early December to mid-February. This corresponds to the annually recurring open water area in the western Ross Sea [e.g., Zwally et al., 1983]. The 10% summer ice concentration (90% open water fraction) likely represents persistent contamination by the permanent Ross Ice Shelf of the SSM/I pixels in the southern part of the study area (compare Plate 1). The summer is preceded and followed by one month periods of large changes in open water amount.

Significant interannual variability is present in the character of the open water fraction during winter months. In late July 1988, the open water fraction reaches a distinct minimum. In other years, one distinct minimum is not observed, but low frequency oscillations around the mean (about 1.5 month period) occur. Typically, the open water fraction does not decrease very much after mid April and starts to increase in September-October. Defining winter as extending from April to August, the average conditions can be examined more closely. AWS 07 provides the closest weather observations to the polynya (see Figure 1), and is used to monitor atmospheric conditions affecting it. Table 1 shows that the open water amount is highest in 1988 with 1989-1991 being similar. The 15-20% average open water amounts (25-30% minus 10% ice shelf contamination) are surprising in view of the cold southerly winds blowing off the ice shelf unless there is a large oceanic heat source. The only winter oceanographic cruise near this area [Jeffries and Adolphs, 1997] in May 1995 found evidence from the sea ice characteristics of relatively low oceanic heat flux. Further, right near the ice shelf at 180° longitude, 30% nilas (5-10 cm thick ice) and 70% first year sea ice were observed in meteorological conditions similar to the typical situation reported in Table 1 (M. Jeffries, personal communication, 1998). This observation, although from east of the study area, suggests that the passive microwave emissions for open water actually represent both open water and thin ice [compare Comiso et al., 1992], features which characterize polynyas. We assume that the SSM/I open water variability reflects actual polynya fluctuations. The AWS observations discussed below demonstrate that the greater open water amount in 1988 is accompanied by higher wind speeds and warmer temperatures than the other 3 years that, again, are similar. This situation indicates that the behavior of the polynya and the atmospheric forcing [following Pease, 1987] are closely related. Superimposed on the low frequency variations in open water fraction during winter are numerous high frequency positive (more open water) fluctuations that we call polynya events.

Polynya events are isolated by subtracting the 25-day running mean from the daily open water amounts (Figure 2) and choosing all positive departures except for the two transient, small events in June 1990 and April 1991. Bromwich et al. [1993] show that katabatic surge events (the atmospheric events of primary concern) have an average duration of 5 days but can last up to 13 days. Thus a 25-day filter is selected to separate the interaction between katabatic surge events and positive open water fluctuations from any lower frequency changes in ice cover. Table 2 lists the characteristics of the polynya events during the winters of 1988 to 1991. It is seen that the number of polynya events decreases from 1988 to 1990 and then increases. At the same time the average polynya duration reaches a maximum in 1990. The average departure of open water fraction during the polynya events from the 25-day running mean is given as well, and shows that the maximum also appears in 1990. An approximate index of polynya activity is obtained by multiplying the total polynya days by the average open water fraction anomaly, and reflects the composite event impact of surface energy losses to the atmosphere from the surface of the polynya. The winter polynya event impact on the ocean is largest in 1988 and 1990, and is 22% smaller in 1989.

3.2. Multiple Year Survey of Wind Speeds and Temperatures at AWS 07

To investigate the role that atmospheric forcing plays, winds and temperatures at AWS 07 are used. The average wind directional constancy (ratio between the vector-average wind speed and the mean wind speed) during the winters from 1988 to 1991 is approximately 0.82. Note that the wind data do not exist after June 1991. Such a high directional constancy implies that the wind directional variations can be ignored and, as a result, the wind direction is considered to be only from the southwest.

Figure 3 shows daily average wind speeds and temperatures for AWS 07 plotted against wintertime polynya events from 1988 to 1991 (derived by subtracting the 25-day running mean from the daily SSM/I open water estimates). From Figure 3, it is seen that most polynya events accompany strong winds and warm temperatures (explained at the end of Section 4). Some polynya events lag slightly behind the increased winds and temperatures probably because of the delayed polynya response to the atmospheric forcing. The wind speeds associated with polynya events mostly exceed 10 m s⁻¹, a sufficient
Fig. 2. Time sequence of daily-averaged open water fraction (thin line) for the period January 1988 through December 1991; thick line is the 25 day running mean. Open water fraction was computed as (1-C)*100 where C is daily sea ice concentration. Solid dots mark the beginning of each month.

<table>
<thead>
<tr>
<th>Winter Year</th>
<th>Average SSM/I Open Water Fraction (%)</th>
<th>Standard Deviation of Water Fraction (%)</th>
<th>AWS 07 Average Wind Speed (m s(^{-1}))</th>
<th>AWS 07 Average Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>31.2</td>
<td>8.5</td>
<td>7.4</td>
<td>-28.8</td>
</tr>
<tr>
<td>1989</td>
<td>25.0</td>
<td>9.5</td>
<td>6.1</td>
<td>-31.1</td>
</tr>
<tr>
<td>1990</td>
<td>26.1</td>
<td>8.2</td>
<td>6.3</td>
<td>-33.4</td>
</tr>
<tr>
<td>1991</td>
<td>26.5</td>
<td>7.8</td>
<td>6.8(^{a})</td>
<td>-30.8(^{a})</td>
</tr>
</tbody>
</table>

\(^{a}\) Wind and temperature values for 1991 are approximate because there are no data for July and August. 1988 - 1990 average values for these two months are used to fill in the missing data.

condition to maintain a polynya according to Pease [1987]. However, there is one occasion near Julian Day 150 (end of May) in 1990 when strong winds and warmer temperatures are not accompanied by a polynya event. In contrast, winds of less than 10 m s\(^{-1}\), but with variable temperatures, accompany polynya events 5 times in the winters of 1988 and 1989. It is clear that there is a close, but not one-to-one relationship between the polynya fluctuations and the atmospheric variables at AWS 07.

To establish more quantitative associations between SSM/I polynya sizes and concurrent AWS 07 winds and temperatures, a regression analysis is performed. Both positive and negative departures from the 25-day SSM/I running mean of open water fraction are considered here to capture the full temporal variability of sea ice amounts in the data box, not just the (major) polynya events considered above. Van Woert [1998] demonstrates from a detailed evaluation of the Pease [1987] polynya model that polynya size is inversely proportional to air temperature and has a secondary dependence on wind speed. Table 3 presents the regression results. Generally, open water fraction anomaly correlates more closely (and consistently) with inverse air temperature (the same correlation coefficients are obtained if temperature is used) than wind speed (see Figure 4). The winter of 1991 is an apparent exception, perhaps resulting from the smaller number of AWS observations. Regression of polynya size on both inverse temperature and wind speed does not increase the correlation over that of inverse temperature by itself; this is due to the cross correlation between wind and temperature. This finding contrasts with that obtained by Van Woert [1998] for the Terra Nova Bay polynya in winter where consideration of the wind speed modulation of the net longwave radiation significantly adds to the open water variance explained by inverse air temperature alone. The explanation for the contrast resides in the differing interrelationships between the winds and temperatures in the two areas. The present analysis does not measure the full association between the polynya size and the atmospheric forcing because of the variable time lag between the forcing and the polynya response (see Figure 3a) and because of spatial inhomogeneities in the atmospheric fields.

Through the multi-year SSM/I and AWS surveys, it is seen that there is a strong atmospheric role in the fluctuations of the polynya. With 75% of polynya size variability unexplained by temperature observations from one site, more complicated processes must be involved. Van Woert [1998] shows that fluctuations in downward longwave radiation due to cloud cover variations can have a significant impact on polynya size variability. There is also the unknown impact of oceanic heating. To examine the spatial variability of the atmospheric fields more closely the following case study is presented.

4. A CASE STUDY

Through a case study, Jacobs and Comiso [1989] make the first attempt to explain the passive microwave depiction of the Ross Sea Polynya using several AWS along the coastal Ross Ice Shelf. Although this case provides some information on the approaching low pressure system, a complete description of this low system is not presented. By contrast, Bromwich et al. [1993] focus on the mean atmospheric conditions for the katabatic surge events and do not describe the detailed evolution of the atmospheric conditions. The following case study provides a detailed picture of the atmospheric forcing and the polynya evolution using daily open water estimates from SSM/I, available NOAA satellite images, and ECMWF analyses.

From Figure 2, it is seen that near the end of March 1988 (Julian Day 90) the open water fraction increases from approximately 33% to around 65% in just a few days. This increase is the largest in 1988 (Figure 3) if the seasonal melting in spring is omitted. It is shown below
that SSM/I images are particularly useful for this event due
to cloud obscuration that makes it impossible to estimate
the polynya development from NOAA AVHRR images.

Daily sea ice concentration (SIC) maps based upon
SSM/I data during the period of 26 March to 5 April 1988
are plotted in Plate 2. It is seen that the SIC in the data
box is almost identical on 26 and 27 March. On 28 March,
a green pixel appears in the data box, signaling a decrease
of SIC. More of these pixels appear on the next day (29
March). Little change is found on 30 March. A dramatic
change occurs on 31 March. On this day, the number of
green pixels expands in the north-south direction and they
occupy almost the entire data box. On 1 April, the color of
some pixels turns from green to dark blue, indicating a
further reduction of SIC. Also noticeable is that the blue-
green area shifts away from the data box and moves to the
northeast. Meanwhile, the size of this area expands.
Approximately half of the area is outside the data box. On
2 April, the low ice concentration pixels (greens and blues)
decrease in number. On 3 April, the dark blue pixels are
almost gone and the low ice concentration area continues
to shrink. The area moves to the northwest. By 5 April
almost all of the green pixels are gone.

In order to understand the role of the atmosphere in
this event, the daily average wind speed, air temperature,
and station pressure at AWS 07 along with daily SIC
during this event are plotted in Figure 5. On 26 and 27
March, the wind speeds at AWS 07 are around 5 m s\(^{-1}\),
which is much lower than the polynya wind speed
threshold proposed by Pease [1987]. As a result, there is
little change in the daily maximum, minimum, and average
SIC. The pixels in the data box during these two days are
almost identical (Plate 2). SIC decreases on 28 March as
the wind speed and air temperature increase. A green pixel
appears in the data box on 28 March in conjunction with
the decrease of SIC. Notice that this pixel, indicating the
lowest SIC in the box, appears near the southern boundary
of the data box rather than right at the boundary as might
be expected. This is probably associated with the 25-km
resolution of the SSM/I data that results in the southern-
most polynya pixels being contaminated by the Ross Ice

<table>
<thead>
<tr>
<th>Winter Year</th>
<th>Total Polynya Events</th>
<th>Total Polynya Days</th>
<th>Average Days Per Polynya Event</th>
<th>Average Open Water Fraction Anomaly (%)</th>
<th>Polynya Index (Total Days X Anomaly %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>11</td>
<td>82</td>
<td>7.5</td>
<td>5.3</td>
<td>435</td>
</tr>
<tr>
<td>1989</td>
<td>10</td>
<td>63</td>
<td>6.3</td>
<td>5.4</td>
<td>338</td>
</tr>
<tr>
<td>1990</td>
<td>7</td>
<td>70</td>
<td>10.0</td>
<td>6.2</td>
<td>434</td>
</tr>
<tr>
<td>1991</td>
<td>9</td>
<td>73</td>
<td>8.1</td>
<td>5.0</td>
<td>365</td>
</tr>
</tbody>
</table>

Shelf, as discussed previously. The wind speed and air
temperature continue to increase from 28 to 29 March,
resulting in a continuous decrease of SIC and more green
pixels. On 30 March, the wind speed and air temperature
decrease slightly, and this signal is also found in the
minimum SIC as a slight increase.

The wind speed is strongest and the air temperature
the warmest on 31 March, and the average and the
maximum SIC reach a minimum. These wind speed
(approximately 12 m s\(^{-1}\)) and air temperature (about -16\(^\circ\) C) maxima substantially exceed the March means of 5.6 m
s\(^{-1}\) and -32\(^\circ\) C, respectively. At the same time, the green
pixels occupy almost the entire data box, resulting in the
minimum average SIC. Notice that there is a convergence
between the average and minimum SIC. This is because
SIC in most pixels is reduced. The station pressure drops
following a slight rise on 27 March and reaches a
minimum on 31 March, suggesting an incoming low
pressure system (the details of which are presented next).

From Figure 5, it is found that the minimum of average
SIC coincides with the maximum wind speed and air
temperature and minimum station pressure. Such a match
suggests a strong atmospheric role in this polynya event.

This relationship is elaborated next in conjunction with
ECMWF analyses.

After 31 March, the average SIC starts to increase as
the wind speed and air temperature decrease. However,
the minimum SIC still continues to decrease. Examining
the maximum and minimum SIC in Figure 5, it is found
that the minimum SIC does not follow the trends of the
average and maximum SIC. In fact, the minimum SIC
occurs on 2 and 3 April, whereas the minimum of average
SIC occurs on 31 March. Although no obvious in Plate 2,
5% pixels are found in the data box only on 2 and 3 April,
consistent with minimum SIC occurring on these two days.

Because the low SIC area moves out the data box, the
average SIC during these two days actually increases. This
partially explains the timing mismatch found in Figure 5.
This difference also raises a question as to whether or not
the wind speed and air temperature at AWS 07 sufficiently
represent the entire data box. Based on the evidence here,
Fig. 3a. Time sequence of polynya events (dashed lines, see text for details) versus daily average wind speeds at AWS 07 (solid lines) for the four winters from 1988 through 1991. The 10 m s$^{-1}$ line is plotted for reference. Solid dots mark the beginning of each month.
Fig. 3b. Time sequence of polynya events (dashed lines, see text for details) versus daily average air temperatures at AWS 07 (solid lines) for the four winters from 1988 through 1991. Solid dots mark the beginning of each month.

<table>
<thead>
<tr>
<th>Winter Year</th>
<th>Open Water Anomaly (%) vs. Wind Speed (m s⁻¹)</th>
<th>Open Water Anomaly (%) vs. Inverse Temperature (K⁻¹)</th>
<th>Temperature vs. Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>0.38</td>
<td>-0.52</td>
<td>0.69</td>
</tr>
<tr>
<td>1989</td>
<td>0.30</td>
<td>-0.44</td>
<td>0.51</td>
</tr>
<tr>
<td>1990</td>
<td>0.44</td>
<td>-0.48</td>
<td>0.62</td>
</tr>
<tr>
<td>1991</td>
<td>0.52</td>
<td>-0.55</td>
<td>0.56</td>
</tr>
</tbody>
</table>

it appears that the wind speed and air temperature at AWS 07 are capable of doing so because the average SIC increases as the wind speed and air temperature decrease. However, the SSM/I data show that the low SIC area actually partially moves out of the data box and a higher SIC area is established near the ice shelf in response to the decrease of wind speed and air temperature. This situation suggests an atmospheric forcing difference in the data box: stronger winds and warmer temperatures in the north than in the south of the box. Also, starting on 1 April and certainly by 2 April the polynya moves away from the Ross Ice Shelf and dissipates thereafter; this situation probably can be monitored because the SSM/I is also detecting thin ice, as discussed previously. More explanations of the atmospheric variability are given below in conjunction with ECMWF analyses.

The ECMWF sea-level-pressure analysis at 0000 UTC 30 March (Figure 6) shows an intense eastward moving low to the north of the Ross Sea near 60° S. This is connected to a weak low at 500 hPa (Figure 7). A ridge over the Amundsen Sea appears to block the eastward moving low (Figure 6). This blocking pattern continues during the next 24 hours and is more evident at 500 hPa (Figure 7). A 500-hPa ridge near 90° E extends into the interior of Wilkes Land.

The NOAA AVHRR satellite images at 0711 UTC and 1032 UTC 30 March (Figures 8a and 8b) respectively show that the low is to the north of Roosevelt Island. Lots of clouds cover Ross Island and areas eastward, making it impossible to observe polynya development in that area.

At 0000 UTC 31 March, the ridge over the Amundsen Sea continues to develop toward the south (Figures 6 and 7). As a result, the low changes course and moves toward Roosevelt Island. The entire Ross Ice Shelf is within the circulation. The central pressure of the low decreases by 6 hPa (Figure 6b), and the low is centered to the north of Roosevelt Island. The NOAA AVHRR image at 0345 UTC 31 March (Figure 8c) provides a more precise position of the low. A large band of clouds can be seen over the Ross Ice Shelf. The polynya is completely covered by the clouds. At 0900 UTC 31 March, the maximum wind speed is recorded at AWS 07. The sea-level-pressure analysis based on AWS records (Figure 9) shows that the low circulation and the resulting strong winds span the entire Ross Ice Shelf; note the ageostrophic flow at AWS 13 probably associated with the intense katabatic winds at Terra Nova Bay (AWS 05). At 1200 UTC 31 March (Figures 6 and 7), the low moves closer to Roosevelt Island and starts to weaken (the central pressure increases). Figure 10 shows the ECMWF wind analysis at 10 m above the surface. The circulation of this low over the Ross Sea and the Ross Ice Shelf is very evident. It is also seen that the airflows from West Antarctica and East Antarctica converge in the Siple Coast area. This convergent flow blows across the Ross Ice Shelf as a katabatic surge. Figure 8d shows the weakening low at 1511 UTC 31 March with the clouds spiraling into the low center. Figure 8d also shows that the katabatic winds from the glaciers along the Transantarctic Mountains (dark signatures on the image) add to the mountain-parallel air stream. Unfortunately, the polynya area is still covered by thick clouds that make it impossible to observe. During the next 24 hours (Figures 6 and 7), the low continues to weaken and starts to merge with an incoming cyclone that is discussed next.

Wind speeds and station pressures from several AWS during this event are plotted in Figure 11. These AWS consist of two near the ice shelf edge (AWS 00 and 07), two near the Transantarctic Mountains (AWS 11 and 15), two farther away from the mountains (AWS 08 and 24) and one over the Ross Sea (AWS 13). From Figure 11 it is seen that no matter where these AWS are located, the station pressure evolutions are nearly identical. For example, the minimum pressure at all these AWS occurs on 31 March. This suggests that these stations are under the same synoptic low influence and that the entire ice shelf is affected by this event. From the wind speed plots (Figure 11), it is seen that wind speeds at all AWS respond to the low pressure system. The maximum wind speeds at the AWS primarily occur near 31 March when the pressures reach a minimum.

It is noted earlier in this case study that the polynya still develops even after the wind speed at AWS 07 decreases. The wind records at AWS 13 (situated right on
Fig. 4. Open water anomalies (departures from 25-day running mean) versus inverse of daily average air temperature at AWS 07 for the four winters 1988-1991. Solid lines are regression lines of best fit. The inverse temperature scale spans -10°C (on the left) to -56°C (on the right).
Plate 2. Daily sea ice concentration maps in the Ross Sea from 26 March through 5 April 1988. The region where the daily sea ice concentration was extracted is outlined by the thick lines.
Fig. 5. Time sequence of daily average sea ice concentration, wind speed (solid) and air temperature (dashed), and station pressure, respectively, at AWS 07 from 26 March through 5 April 1988. Filled triangles (diamonds) in the top plot denote minimum (maximum) sea ice concentrations.
Fig. 6. ECMWF sea-level-pressure analyses from 0000 UTC 30 March through 0000 UTC 1 April 1988. Contour interval is 5 hPa.

the west side of the data box) provide additional information on this question. It is noticeable that the wind speed at AWS 13 actually starts to increase from 1 April and reaches a maximum of 14 m s\(^{-1}\) on 3 April as the wind speed decreases at AWS 07 (Figure 11). From the ECMWF 10-m wind analyses in Figure 10, it is seen that the same cyclone still dominates the southwest Ross Sea on 1 April, but the wind switches from the south to southwest. This probably explains the northeasterward movement of the polynya (Plate 2). From Figure 5, the wind speed at AWS 07 on 1 April is still quite strong (near 10 m s\(^{-1}\)) though it is decreasing. From 0000 UTC 2 to
Fig. 7. Similar to Figure 6, but for 500 hPa. Contour interval is 60 geopotential meters (gpm).

0000 UTC 3 April, the cyclone merges with another cyclone coming from the Southern Ocean to the north of Victoria Land (Figure 10). Based on Figure 10 and the wind records at AWS 07 and 13, it appears that the strong wind area of this cyclone is very limited because it has little influence on the wind speed at AWS 07. As this cyclone approaches the Ross Ice Shelf, the wind speed at AWS 13 increases and reaches the maximum for the study period at 0300 UTC 3 April (Figure 11). Based on these findings, the continued development of the polynya observed from the SSM/I data is the result of the intensified synoptic wind at AWS 13.

To summarize, this case study demonstrates that surface winds and air temperatures over the western Ross
Ice Shelf move in parallel during polyny event, which is consistent with the strong influence of the synoptic pressure gradient. Implicit to this discussion is the presence of katabatic winds from the Siple Coast part of West Antarctica and from East Antarctica via the glacier valleys that cut through the Transantarctic Mountains. The pressure gradient associated with the synoptic low supports the propagation of these boundary-layer airflows across the flat Ross Ice Shelf, and the warm maritime air (in the free atmosphere) and cloud fields associated with the low modify their characteristics. The case study shows that the atmospheric evolution can be highly complex and spatially variable and that not all aspects of polyny evolution can be understood from atmospheric observations at one site.

Fig. 8. NOAA AVHRR thermal infrared satellite images showing the synoptic cyclone at the end of March 1988. See text for details.
According to Bromwich et al. [1993], katabatic surge events involve propagation of katabatic airflow from West and East Antarctica across the Ross Ice Shelf with the assistance of the synoptic scale pressure field. Numerical simulations using a three-dimensional primitive equation model also confirm this assertion [Bromwich et al., 1994].

AWS 07 in the northwestern part of the ice shelf is affected by katabatic surge events. Further connections between winds at AWS 07 and katabatic surge events are demonstrated below.

Previous studies [Bromwich, 1989; Carrasco and Bromwich, 1993] of katabatic winds using satellite imagery and AWS data show that when a katabatic satellite signature is observed over an AWS, the air temperatures recorded by this AWS are warmer than those measured outside the signature. In addition, the temperatures recorded by an AWS during a katabatic event are warmer than before and after the event (a more detailed dynamic description can be found in Bromwich et al. [1993]). The same result is found for the 1988 study [Bromwich et al., 1992, 1993, 1994] in which a significant increase of the temperature is recorded by AWS 08 (see Figure 1b) on signature days (defined as days when a katabatic surge is observed on satellite imagery [Bromwich et al., 1992]).

Thus, air temperatures recorded at AWS 08 are chosen in the 1988 study as the best variable to gauge the likely existence of katabatic airflow across the Ross Ice Shelf [Bromwich et al., 1993]. In the previous study, a katabatic surge event (KSE) is defined to occur when the daily average surface-air temperatures recorded near the southern margin of the Ross Ice Shelf (by AWS 08) are continuously warmer than the respective monthly average for at least 2 days.

One weakness of the above definition is that it is based solely on temperature anomalies and does not incorporate a description of the wind. Another weakness is that the magnitude of the positive temperature anomaly necessary to be classified as a katabatic surge event is not specified. A small positive daily surface-air temperature anomaly may not be caused solely by turbulent vertical mixing associated with katabatic airflow [Bromwich, 1989]. Other factors, such as clouds, can cause the warming. In numerical simulations conducted by Bromwich et al. [1994], average wind speed and temperature differences (from the five-month mean) over the Ross Ice Shelf for signature days during the 1988 austral winter are plotted. Significant increases in both temperature and wind speed near the southern margin of the Ross Ice Shelf at AWS 08 and 11 during the signature days are found to exist. The follow-up numerical simulations confirm this result. To reflect the situation that the warming is caused by turbulent vertical mixing.
Fig. 10. 10-m vector winds from the ECMWF analyses (length is proportional to wind speed). Crowded vectors have been removed. Maximum (minimum) vectors for 1200 UTC 31 March, 0000 UTC 1 April, 0000 UTC 2 April, and 0000 UTC 3 April 1988 are: 19.5 m s\(^{-1}\) (2.5 m s\(^{-1}\)), 22.1 m s\(^{-1}\) (2.8 m s\(^{-1}\)), 22.9 m s\(^{-1}\) (2.9 m s\(^{-1}\)) and 22.9 m s\(^{-1}\) (2.9 m s\(^{-1}\)), respectively.

Associated with katabatic winds, it is necessary to add wind speed to a modified definition. Finally, for katabatic airflow propagation across the Ross Ice Shelf, it is found that the wind speed is at least 6 m s\(^{-1}\) at AWS 08 [Bromwich et al., 1993].

Based on the signature days provided by Table 1 in Bromwich et al. [1993], wind speed information is extracted, leading to a modified definition for katabatic surge events: A katabatic surge event is defined to occur when the daily average surface-air temperatures recorded near the southern margin of the Ross Ice Shelf (by AWS 08) are continuously warmer than the respective monthly average, daily average wind speeds exceed 6 m s\(^{-1}\), and daily average wind directions fall in the range between the east (90°) and the southwest (225°) for at least two days.

To demonstrate that katabatic surge events indeed involve the entire Ross Ice Shelf, Bromwich et al. [1994] show differences for 1988 of wind speed, wind direction,
Fig. 11. Three-hour station pressures and wind speeds based on AWS records from 26 March through 5 April, 1988.

pressure and temperature for signature days from the winter mean at most sites shown in Figure 1b. The results from that analysis (Figure 12 in Bromwich et al. [1994]) show that: 1) wind speeds increase markedly during katabatic surge events; 2) pressures decrease by several hPa with the maximum fall being found in the eastern part of the ice shelf, reflecting the influence of the synoptic low centered over the Amundsen/Ross Sea; and 3) temperatures increase at most stations. In conclusion, katabatic surge events associated with a synoptic low over the Amundsen/Ross Sea indeed influence the entire Ross Ice Shelf.

To further demonstrate the link between strong winds and warm temperatures at AWS 07 and katabatic surge events monitored by AWS 08, Figure 12 compares the daily average wind speeds and the daily average air
temperatures at the two sites. It can be seen that each katabatic surge event is accompanied by winds generally stronger than 10 m s\(^{-1}\) and warm temperatures (greater than -25°C) at AWS 07. This relationship is not surprising because AWS 07 is situated in the path of these katabatic surge events. However, Figure 12a also shows that strong winds at AWS 07 do not necessarily imply strong winds at AWS 08, and vice versa. For example, there is a strong wind event at AWS 07 around 16 May (Julian Day 137). The maximum wind speed in this event is about 14 m s\(^{-1}\). By contrast, the maximum wind speed at AWS 08 in the same period is less than 6 m s\(^{-1}\). It can be seen from Figure 3 that this event is linked to polynya development. A similar situation occurs near 18 June (Julian Day 170). As
mentioned above, the airflow passing through AWS 07 is from three sources. It is likely that during these events the wind at AWS 07 was influenced by the other two sources.

5.2. Interannual Variation of Katabatic Surge Events and the Associated Large Scale Circulation

The new definition of katabatic surge events given above is applied to the winters from 1988 to 1991. Table 4 lists the number of katabatic surge events occurring in each month and annual total days. Comparing these katabatic surge events with the polynya events, it is found that all katabatic surge events are associated with polynya events. The percentages of the polynya events that are associated with katabatic surge events are 73% in 1988, 50% in 1989, 57% in 1990 and 67% in 1991 (number of katabatic surge events are divided by the number of polynya events). It is seen that roughly 60% (four year average) of the Ross Sea Polynya events are associated with the katabatic surge events. Further investigations of the other one-third of polynya events are needed to fully understand the atmospheric forcing of this polynya.

From Table 4, it is seen that katabatic surge events are favored at the beginning and end of winter. This probably reflects the semi-annual variation of the circumpolar low-pressure trough which is deepest and closest to Antarctica in the fall and spring [Carleton, 1992], characteristics shared by the Amundsen Sea low which is one of three centers in the circumpolar trough. It is also noticeable that both the total katabatic surge days and the number of the events are highest for 1988, with the other three winters being similar. It can be seen from Tables 1 and 2 that the 1988 winter also has the largest number of polynya events and the warmest average air temperature and highest average wind speed at AWS 07, with the other three winters being similar. These results confirm the close linkage between the atmospheric forcing and the polynya response.

The only apparent inconsistency involves the average open water fraction which is largest in 1988 (Table 1).
This can be understood from the close association with the katabatic surge events. Table 4 reveals that the number of katabatic surge days is greatest in 1988. The 1988 composite is dominated by two long surge events (exceeding 10 days in duration) near the end of April and the middle of August, which together span about 20% of the winter period. It is likely that these events are partly reflected in the 25-day running means of open water estimates. As a result, Table 1 shows the average water fraction is largest in 1988 with the three other winters being similar. In addition, Table 2 likely underestimates the polynya event impact for the 1988 winter.

To compare with the 1988 circulation results of Bromwich et al. [1993], large-scale digital data from the

**TABLE 4. Number of katabatic surge events occurring in each winter month and the annual total surge days from 1988 to 1991.**

<table>
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<td>3.8</td>
<td>2.5</td>
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Fig. 13a. Average southern hemispheric sea-level-pressure analysis for the winters from 1988 through 1991. The contour interval is 5 hPa.

Australian Bureau of Meteorology are used. Figures 13 and 14 are the mean sea-level-pressure and 500-hPa fields for the winter and the katabatic surge events from 1988 to 1991. It is seen that the average intensity (based on the innermost sea level isobar) of the quasi-stationary synoptic cyclone for katabatic surge events is much stronger than the respective winter mean. The differences range from 5 hPa in 1988 and 1989 to 10 hPa in 1990 and 1991 (Figure 13). The differences in and near the Ross Sea are statistically significant for all winters (Figure 13c). However, not all the average intensities (based on the innermost isohypse) of the quasi-stationary synoptic low at
500 hPa during the katabatic surge events are as strong as those at sea level. For example, the intensities of the low are equal to those of the winter means in 1989 and 1991 (Figure 14). The sea-level-pressure analyses during the first three winters (Figure 13) show an eastward shift of the center of the quasi-stationary low. In the last winter, the low center shifts back to the northeast Ross Sea area. These shifts are also reflected by a decrease in the number of katabatic surge events for 1988 - 1990 followed by an increase in 1991. At 500 hPa, these shifts are not nearly as
Fig 13c. The t-test of the difference between 13b and 13a. Dark shaded areas indicate negative differences that are significant at the 95% confidence level, and light shaded areas indicate the significant positive differences.

pronounced (Figure 14). A ridge over Wilkes Land at 500 hPa is found in the winter of 1988, weakens during the next winter, totally disappears in 1990, and reappears in the 1991 winter (Figure 14a). It is noticeable that this ridge is present for the katabatic surge events in all winters (Figure 14b). More discussion of this ridge is given in the next section.

6. CONCLUSIONS AND DISCUSSION

This paper examines the interannual variations of the Ross Sea Polynya and atmospheric forcing. The results show that significant interannual variability is observed in winter. The largest open fraction occurs in 1988 in conjunction with the warmest winter temperatures and the
strongest winds, with the other three winters being similar in open water fraction and atmospheric forcing. The polynya event survey shows the maximum number of events takes place in 1988 and the minimum in 1990. However, consideration of the polynya duration combined with the anomalous open water fraction during polynya events identifies the 1988 and 1990 winter polynyas as having the greatest cumulative impact on the oceanic surface energy balance, and the 1989 polynyas the least. The result for the 1988 winter is contaminated by two long polynya events which are not clearly distinguished from the average conditions by open water fraction anomalies from the 25-day running mean. Comparison between open water fraction anomalies and wind and temperature
Fig. 14b. Same as Figure 13b, except for 500 hPa. The contour interval is 60 gpm.

variations at AWS 07 explains about 25% polynya fluctuation variance, similar to previous findings for the Terra Nova Bay polynya [Van Woert, 1998]. Consideration of all atmospheric effects would substantially increase the percentage of explained variance.

A case study elaborates the role that atmospheric forcing plays. It is found that a synoptic cyclone near Roosevelt Island induces a sea level pressure distribution over the Ross Ice Shelf with isobars oriented almost parallel to the Transantarctic Mountains. This setup results in an intensification and northwestward propagation of the katabatic winds across the ice shelf with an associated low level warming. An immediate impact of this katabatic surge event is development of the polynya. However, the
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Fig. 14c. Same as Figure 13c, except for 500 hPa.

atmospheric conditions in the data box are highly inhomogeneous. Thus, the SSM/I data can only be approximately described by observations from a single point (AWS 07).

The interannual variability of the katabatic surge events has been established. The results show that, on average, about 60% of the polynya events are linked to katabatic surge events. The katabatic surge events are most frequent for the winter of 1988. In addition, the synoptic situation characterizing 1988 surge events, in which a synoptic low is situated to the north of Roosevelt Island and a midtropospheric ridge lies over Wilkes Land, is found in all winters.

It is seen that development of the ridge over the Wilkes Land is linked to katabatic surge events. The role of this ridge is described by Bromwich et al. [1993] in their Figure 12 as follows: 1) development of a midtropospheric ridge over Wilkes Land, resulting in 2) enhancement of the split jet (or polar front jet) and reinforcement of the blocking over the Australia-New Zealand region. Then, 3) a greater number and/or more intense synoptic scale cyclones are steered toward the
Amundsen Sea/Marie Byrd Land area, 4) where they become nearly stationary inducing a sea level pressure field over the Ross Ice Shelf with isobars oriented almost parallel to the Transantarctic Mountains. This results in 5) an intensification and northwesterly propagation of the katabatic winds across the ice shelf.

A recent study [Chen et al., 1996] provides important information on the behavior of this polar front jet. The study shows that the jet strength is closely linked to El Niño-Southern Oscillation (ENSO) events. In their Figure 1, it is shown that the jet strengthens in 1988, corresponding to an early cold phase. By contrast, the jet is substantially weaker in 1991, corresponding to a maximum warm phase. Examining the katabatic surge events in 1988 and 1991, it is found that there are more events in 1988 than in 1991, similar to the polynya events. As described above, a stronger polar front jet steers a greater number of and/or more intense synoptic scale cyclones toward the Amundsen Sea/Marie Byrd Land area.

Because of the close relationship between the katabatic surge events and polynya events, more polynya events occur in 1988. The association is only approximate, however, because the number of surge and polynya events reaches a pronounced minimum in 1990 whereas the polar front jet is weakest in 1991.

The other 40% of polynya events are most likely linked to the northward airflow associated with the other two components: katabatic drainage from Byrd, Skelton and Mulock glaciers, and barrier winds. No direct evaluation is presented here of the impact of these two airflows on the polynya and is a subject for future investigations. This study also does not address the contribution of oceanic heating to winter polynya formation [Jacobs and Comiso, 1989], and awaits simultaneous observations from the atmosphere and ocean.

The persistent presence of a large area of open water/thin ice in the study domain implies that AWS 07 wind and temperature observations may not adequately quantify the atmospheric forcing of the polynya and/or that oceanic heating plays a major role in reducing the ice cover in this area.

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