Identification of Surface Wind Patterns over the Ross Ice Shelf, Antarctica, Using Self-Organizing Maps

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ABSTRACT

The interaction of synoptic and mesoscale circulations with the steep topography surrounding the Ross Ice Shelf, Antarctica, greatly influences the wind patterns in the region of the Ross Ice Shelf. The topography provides forcing for features such as katabatic winds, barrier winds, and barrier wind corner jets. The combination of topographic forcing and synoptic and mesoscale forcing from cyclones that traverse the Ross Ice Shelf sector create a region of strong but varying winds. This paper identifies the dominant surface wind patterns over the Ross Ice Shelf using output from the Weather Research and Forecasting Model run within the Antarctic Mesoscale Prediction System and the method of self-organizing maps (SOM). The dataset has 15-km grid spacing and is the first study to identify the dominant surface wind patterns using data at this resolution. The analysis shows that the Ross Ice Shelf airstream, a dominant stream of air flowing northward from the interior of the continent over the western and/or central Ross Ice Shelf to the Ross Sea, is present over the Ross Ice Shelf approximately 34% of the time, the Ross Ice Shelf airstream varies in both its strength and position over the Ross Ice Shelf, and barrier wind corner jets are present in the region to the northwest of the Prince Olav Mountains approximately 14% of the time and approximately 41% of the time when the Ross Ice Shelf airstream is present.

1. Introduction

The interaction of synoptic and mesoscale circulations with the steep topography that surrounds the Ross Ice Shelf (RIS), Antarctica, greatly influences the wind patterns in this region (Fig. 1). The topography provides forcing for features such as the Ross Ice Shelf airstream (RAS), katabatic winds, barrier winds, and barrier wind corner jets (BWCJs). The combination of these features with the synoptic and mesoscale forcing from cyclones that traverse the RIS sector creates a region of strong, but varying winds.

The winds in the region of the RIS are an important component of the Southern Hemisphere tropospheric circulation. These winds are a major transport mechanism of cold, continental air from the Antarctic continent to more northerly latitudes (Bromwich et al. 1992, 1993; Parish and Bromwich 1998; Parish et al. 2006; Seefeldt and Cassano 2012, hereafter SC12). This was illustrated by a case study of a 20-mb (1 mb = 1 hPa) drop in pressure over the Antarctic continent over a 4-day period in the winter of 1988 (Parish and Bromwich 1998). The case study concluded that the drop in pressure was a result of katabatic winds (negatively buoyant winds) draining atmospheric mass off of the continent. During this event, approximately one-third of the mass drained from the continent passed through the Siple Coast confluence zone (see Fig. 1 for location) and onto the RIS (Parish and Bromwich 1998). This case study illustrates that the RIS is a major drainage basin for cold, continental air from the interior of the continent. The southerly winds over the RIS then transport the cold, continental air to more northerly latitudes, indicating the importance of the RIS winds in transporting air drained from the interior of the continent to lower latitudes.

Southerly winds, which characterize the RAS, are the dominant wind regime over the RIS. The RAS is a dominant stream of air flowing north from the Siple Coast confluence zone, over the western to central RIS, to the Ross Sea (Parish et al. 2006; SC12). As shown by satellite imagery, the RAS can propagate northward up...
FIG. 1. Map of the (a) Antarctic continent and (b) Ross Ice Shelf region. The shaded grid points indicate the model grid points used to train the SOM. The black dots in (b) indicate the AWS used in the statistical analysis of the AMPS output. Contour lines show elevation with contour interval of 400 m.
to 1000 km away from the Siple Coast confluence zone (Bromwich et al. 1992, 1993). These satellite observations indicate the extent of the cold, continental air transport in this region.

The RAS is driven by a combination of katabatic winds, barrier winds, and forcing from the semipermanent synoptic cyclone located off the coast of Marie Byrd Land (Parish et al. 2006; SC12). Parish et al. (2006) and SC12 used the polar-modified 30-km fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) output from the Antarctic Mesoscale Prediction System (AMPS) to study the forcing of the RAS. These studies conclude that although a combination of katabatic winds, barrier winds, and synoptic forcing drive the RAS, the semipermanent synoptic cyclone off the coast of Marie Byrd Land provides the dominant forcing for the RAS.

Katabatic winds occur when negatively buoyant air flows downward over sloping terrain (Parish 1988). In general, these winds drain the cold, continental air from the interior of the Antarctic continent, through confluence zones, to the edges of the continent (Parish and Bromwich 1987). This causes an indirect meridional circulation to form with sinking motion over the interior of the continent and convergence aloft (Parish and Bromwich 1991; Parish 1992; Parish et al. 1994; Parish and Bromwich 1998). In the region of the RIS, katabatic winds flow through the glacial valleys of the Transantarctic Mountains and the Siple Coast confluence zone onto the RIS, providing forcing for the RAS.

Barrier winds, which flow parallel to the barrier, commonly occur along the Transantarctic Mountains in the region of the RIS. Barrier winds form when stably stratified flow is directed toward a topographic barrier. Depending on the stability and strength of the flow and the height of the barrier, this flow can be blocked. If the flow is blocked, mass convergence occurs and the pressure at the base of the barrier increases. The increase in pressure creates a pressure gradient force (PGF) directed away from the barrier. The wind induced by the PGF reaches approximate geostrophic balance, resulting in a barrier parallel flow at the base of the barrier (O’Connor et al. 1994; Parish et al. 2006; Seefeldt et al. 2007; Steinhoff et al. 2009). Barrier winds along the Transantarctic Mountains provide forcing for the RAS.

Nigro et al. (2012) showed that a BWCJ is a mesoscale wind feature that occurs over the RIS. BWCJs are commonly located to the northwest of the Prince Olav Mountains (Fig. 1) and are within the path of the RAS. BWCJs form when a barrier wind reaches the end of a barrier or protrusion in the topography. At this point, the flow transitions from a region of terrain-induced high pressure to the background pressure field of the region, and the PGF aligns with the direction of the flow, increasing the magnitude of the winds in this region. This results in an area of maximum wind speed downstream of the barrier (Nigro et al. 2012). BWCJs have similar forcing to Northern Hemisphere left-sided corner winds (Dickey 1961; Kozo and Robe 1986; Olafsson 2000; Olafsson and Agustsson 2007; Lefevre et al. 2010) and easterly tip jets (Moore and Renfrew 2005; Renfrew et al. 2009; Outten et al. 2009, 2010).

This paper identifies the dominant wind patterns that occur over the RIS using the polar-modified 15-km Weather Research and Forecasting Model (WRF) output from AMPS. SC12 identified the dominant wind patterns over the RIS using the polar-modified 30-km MM5 model output from AMPS. The results presented here, which use the 15-km grid spacing model output, provide the first RIS wind analysis at this higher resolution. The wind analysis presented below provides information on the types of wind patterns present over the RIS, the frequency of these patterns, and the seasonality of these patterns.

Subsequently, an analysis of RAS patterns, the most dominant pattern in the low-level wind field over the RIS, is presented. The RAS analysis provides a better understanding of the variability in the strength and position of the RAS, as well as, information on the frequency and seasonality of the various RAS patterns. Future work by the authors will analyze the atmospheric dynamics that drive the variability in the strength and position of the RAS.

2. Data

a. Model

Output from the archived 15-km WRF from AMPS is used to create the low-level wind climatology over the RIS. The polar-modified version of WRF is currently run within AMPS and has been optimized for use in the polar regions (Hines and Bromwich 2008; Bromwich et al. 2009; Hines et al. 2011). The major changes made to WRF include implementation of a scheme to treat fractional sea ice, improved treatment of heat transfer through ice and snow surfaces, a revised surface energy balance calculation, and a selection of model physics options that are appropriate for polar applications.

AMPS is run with a set of six two-way nested domains. The grid spacing of the six domains is 45, 15, 5 (three domains), and 1.67 km and the vertical grid includes 44 eta levels, with the lowest model at approximately 12 m above ground level (AGL) and 12 levels within the lowest 1 km of the atmosphere. AMPS is run twice daily by NCAR. The first-guess initialization and boundary
FIG. 2. Node-averaged (a) 10-m winds and (b) sea level pressure anomalies over the Ross Ice Shelf. The maximum and minimum node-averaged wind speeds and SLP anomalies are listed above the top-left corner of each node. The colored outlines indicate nodes identified as being dominated by RAS (red), northward transport over the eastern RIS (orange), katabatic winds (blue), mesocyclones over the RIS (purple), and weak winds (green).
FIG. 2. (Continued)
conditions are taken from the National Centers for Environmental Prediction 0.5° Global Forecast System model output. Observations are assimilated into AMPS using WRF’s three-dimensional variational data assimilation. The twice-daily AMPS output is archived by and available from NCAR. For the RIS wind climatology, output from the AMPS 15-km continental domain was analyzed. This domain is run for a duration of 120 h, and the output is archived every 3 h. The 12–21-h forecasts are used to create the wind climatology presented here. The 0–9-h forecasts are not used as the model is still adjusting from the coarse-resolution initial conditions during this time. The use of the 12–21-h forecasts is consistent with Bromwich et al. (2005) and Seefeldt and Cassano (2008). [For more information on AMPS see Powers et al. (2012) and the AMPS website at http://www.mmm.ucar.edu/rt/amps/]

b. Observations

Observations of wind speed and wind direction from University of Wisconsin automatic weather stations (AWS) located over the RIS are compared to the AMPS output. This type of comparison provides information on how well the AMPS output represents the low-level wind field over the RIS. Each AWS records the temperature, pressure, wind speed, and wind direction every 10 min. The data are then transmitted in real-time via satellite using the Argos system. The Antarctic Meteorological Research Center (AMRC) at the University of Wisconsin–Madison retrieves the AWS observations and uses a semiautomatic process to quality control the dataset. The observations are then processed into a 3-hourly time series by extracting the nearest observation to the 3-hourly time within a plus or minus 40-min time limit (Keller et al. 2010; Lazzara et al. 2012). The resulting 3-hourly time series of AWS observations is at the same temporal resolution as the 15-km AMPS output and therefore can be used as a direct comparison between the two datasets.

The AMPS 10-m winds, which are included as an AMPS output variable, are adjusted to the height of each AWS using the logarithmic wind profile equation (Holton 2004). This calculation uses a roughness length of 0.0001 m, which is the same roughness length used in AMPS for permanent ice surfaces, and neglects the stability correction term since the adjustment from 10 m to the AWS observation height is over a short distance.

3. Methods

The method of self-organizing maps (SOM) is used to identify the dominant 10-m wind patterns over the RIS. The SOM training method uses a neural network algorithm and an unsupervised, iterative learning process to identify a user-specified number of patterns within a dataset. See Kohonen (2001) for a thorough explanation of the SOM training method and algorithm. For this paper, the SOM was trained using a 2-yr dataset (October 2008 through September 2010) of the u and v components of the 15-km AMPS-WRF 10-m winds over the RIS. The extent of the dataset was limited to the model grid points over the RIS (see the shaded grid points in Fig. 1). In contrast to the SOM analysis conducted by SC12, this domain was chosen such that it excludes the strong winds that surround the RIS (i.e., katabatic winds in the Transantarctic Mountains and synoptic-scale cyclonic winds in the Ross Sea). By excluding the surrounding winds, the SOM results provide a more detailed analysis of the mesoscale wind features present over the RIS.

The SOM training method, differing from traditional cluster analysis, does not require predetermined assumptions about the distribution of the data. Instead, the SOM method uses the user-specified number of patterns to create a rectangular array of SOM nodes, also referred to as a SOM map. The rectangular array of nodes is altered during the iterative training process to represent the full continuum of the training dataset. At the end of the training, the individual nodes represent the dominant patterns within the dataset (Kohonen 2001).

Reusch et al. (2005) provide a thorough explanation on determining the number of patterns that should be used in a SOM analysis. For the wind climatology presented here, a variety of different SOM array sizes (number of patterns) (4 × 3, 5 × 4, 6 × 4, 6 × 5, 7 × 5) were evaluated. The results were analyzed to determine how many patterns were necessary to capture each of the dominant wind patterns over the RIS. The results indicated a 6 × 4 array size, or 24 patterns, was sufficient for identifying the dominant wind patterns over the RIS. In the smaller SOM array sizes, some of the wind patterns that are present in the 6 × 4 grid were missing. In the larger array sizes some of the patterns in the 6 × 4 grid were duplicated, or the differences between the adjacent patterns were difficult to identify. A similar process was used to determine the grid size for the RAS SOM climatology and a 5 × 4 grid was determined sufficient to capture each of the RAS patterns over the RIS.

Figure 2a shows the 10-m wind patterns identified by the SOM. Each pattern is referred to as a node and is referenced by its column number (zero is the leftmost column) and row number (zero is the top row). For example, the pattern in the upper-left corner is referred to as node [0, 0] and the pattern in the bottom-right corner
is referred to as node [5, 3] (each node on the SOM (Fig. 2a) is labeled in its upper right-hand corner). The patterns are organized such that similar patterns are located adjacent to each other and nonsimilar patterns are located farther away from each other.

Once the dominant 10-m wind patterns of the dataset have been identified by the SOM, each of the 10-m wind forecasts used to train the SOM is matched to the node it most closely resembles. This process is called “mapping.” The process uses a least squared differencing method to quantitatively determine the node that an individual forecast is most similar to. Specifically, the squared differences between the 10-m $u$- and $v$-wind components in the forecast and the 10-m winds in a given SOM node are calculated. The node that results in the smallest squared difference is the pattern to which the 10-m wind forecast maps.

Once each forecast is mapped to a node, averages of any other variable can be calculated for the times that correspond to a given node. The average of the 10-m wind forecasts that map to each node is referred to as the node-averaged 10-m wind (Fig. 2a). The node-averaged 10-m winds are very similar to the original SOM-identified wind patterns (not shown), as should be expected. Node-averaged SLP anomalies (calculated as the difference between the gridpoint SLP and the domain-averaged SLP for the time period being considered) are shown in Fig. 2b and provide an indication of the near-surface pressure field responsible for driving the winds in each SOM node.

In addition to the node-averaged 10-m winds and SLP, the node-averaged PGF is presented. The PGF is not included as an AMPS output variable and is therefore a calculated value. The PGF is calculated for each model grid point using a two-point centered finite-differencing calculation. The calculation uses the pressures (adjusted to a common elevation using the hypsometric equation) at the four adjacent model grid points to evaluate the partial derivatives. Because of errors that occur when calculating horizontal derivatives in the vicinity of steep topography, grid points with an elevation greater than 500 m are not used in the calculation.

4. Results

a. 10-m wind patterns

Previous studies (Parish et al. 2006; SC12) have used the AMPS-MM5 30-km output to study the low-level winds over the RIS, while this study uses the AMPS-WRF 15-km output to study the low-level winds over the RIS. Figure 3a shows the average lowest model level winds for the AMPS-MM5 30-km output (approximately 13 m AGL over the RIS) from January 2001 through December 2005 (the time period used in the SC12 study) and Fig. 3b shows the average lowest model level winds for the AMPS-MM5 30-km output (approximately 13 m AGL over the RIS) from January 2001 through December 2005 (the time period used in the SC12 study) and Fig. 3b shows the average lowest model level winds for the AMPS-MM5 30-km output (approximately 12 m AGL over the RIS) from October 2008 through September 2010 (the time period for this study). The average winds from these datasets both show southerly winds, or northerly transport, over the RIS. However, the average winds from these datasets differ in magnitude and the location of the corridor of strongest winds flowing from the Siple Coast confluence zone, northward to the Ross Sea. The winds in the AMPS-MM5 30-km dataset are, in general, stronger than the winds in the AMPS-WRF 15-km dataset; and the corridor of strongest winds in the AMPS-MM5 30-km dataset are located adjacent to the Transantarctic...
Mountains while the corridor of strongest winds in the AMPS-WRF 15-km dataset is located through the center of the RIS. Analysis of the average Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) 10-m winds for these two time periods (not shown) does not show a climatic shift in the winds. Therefore, the wind differences between the two datasets are likely related to the differences in the model, physics options, grid sizes, data assimilation packages, and observations used in the two versions of AMPS.

Because of the differences in the average low-level winds in the two datasets (Figs. 3a,b), a statistical comparison of the AMPS-MM5 30-km (January 2001 through December 2005) and AMPS-WRF 15-km (October 2008 through September 2010) datasets to AWS-observed winds was conducted. Each dataset was compared to wind speed and wind direction observations from 12 RIS AWS (shown in Fig. 1). The statistical analysis was conducted for the $u$ and $v$ components of the wind, the wind speed, and the wind direction. The bias, root-mean-square error (RMSE), and correlation were calculated for each category, except for wind direction where only the bias was calculated. Table 1 shows the results of the statistical analysis. For the $u$ and $v$ components of the wind and the wind speed, the RMSE was lower and the correlation was higher for the AMPS-WRF 15-km dataset. Additionally, the wind direction bias decreased from $-35^\circ$ in the AMPS-MM5 30-km dataset to $-6^\circ$ in the AMPS-WRF 15-km dataset.

The wind speed and direction for each of the 12 RIS AWS used in the statistical comparison are depicted in Fig. 4. Figure 4a shows the wind roses created from the available AWS observations from January 2001 through December 2005. The wind roses created from the corresponding AMPS-MM5 30-km wind forecasts are shown in Fig. 4b. A comparison of Fig. 4a and Fig. 4b reveals the fact that, in general, the AMPS-MM5 30-km winds are more southerly than the observed winds over the RIS. Conversely, a comparison of the wind roses created from the available AWS observations from October 2008 through September 2010 (Fig. 4c) and the wind roses created from the corresponding AMPS-WRF 15-km wind forecasts (Fig. 4d) reveals that the AMPS-WRF 15-km output better represents the observed low-level wind field over the RIS. Given the more realistic representations of the RIS winds in the AMPS-WRF 15-km dataset, the results presented here are likely an improvement over prior RAS studies conducted with the AMPS-MM5 30-km data.

The SOM node-averaged 10-m winds, in Fig. 2a, show the typical low-level wind patterns that occur over the RIS region. The figure shows that the wind patterns vary across the SOM. Moving from left to right across the SOM, the winds change from strong, terrain parallel flow on the left side of the SOM to weak winds on the right side of the SOM. In the center of the SOM, the top two rows show winds through the center of the RIS and the bottom two rows show cyclonic flow. Moving from top to bottom along the SOM, the magnitude of the winds weaken and the patterns transition from predominantly southerly flow to flow with more of a zonal component. In some columns, the southerly flow transitions into either cyclonic (columns 1–3) or anticyclonic flow (column 5).

The frequency of each wind pattern in Fig. 2a is shown in Fig. 5a. The frequency plot indicates the percentage of time each wind pattern occurs during the 2-yr time span. The shading in this plot is scaled by the frequency, with darker shading indicating a greater frequency of occurrence. The frequency of the patterns ranges from 3.03% to 6.55%. The SOM analysis identified a total of 24 patterns, which would result in a pattern frequency of 4.17% if each pattern occurred equally. Therefore, the

<table>
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<th>Variable</th>
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<th>AMPS-MM5 30 km</th>
<th>AMPS-WRF 15 km</th>
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<td>$u$ wind</td>
<td>Bias (m s$^{-1}$)</td>
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<td>RMSE (m s$^{-1}$)</td>
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<td></td>
<td>Correlation</td>
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<td>0.58</td>
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<tr>
<td>$v$ wind</td>
<td>Bias (m s$^{-1}$)</td>
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<tr>
<td></td>
<td>RMSE (m s$^{-1}$)</td>
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<tr>
<td>Wind direction</td>
<td>Bias $-35^\circ$</td>
<td>$-6^\circ$</td>
<td></td>
</tr>
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</table>
dataset is fairly evenly distributed over the identified patterns.

The seasonality of each wind pattern in Fig. 2a is shown in Fig. 5b. The seasonality plot indicates the percentage of time each pattern occurs during the summer [December–January (DJ)], fall [February–March–April (FMA)], winter [May–June–July–August (MJJA)], and spring [September–October–November (SON)]. These seasonal definitions better align with the temperature changes over Antarctica than the calendar three-month seasons and have been used in previous research (Seefeldt and Cassano 2008; SC12). The seasonality of the patterns varies across the SOM. The patterns in two leftmost columns (columns 0 and 1) are
FIG. 5. (a) Node frequency and (b) seasonal frequency for each wind pattern in Fig. 2a. The seasonality plot indicates the percentage of time each pattern occurs during the summer (DJ), fall (FMA), winter (MJJA), and spring (SON).
generally nonsummer patterns (with the exception of node [1, 3]), the patterns in the two middle columns (columns 2 and 3) tend to occur most often during the winter months (MJJA), and the patterns in two rightmost columns (columns 3 and 4) tend to be slightly more evenly distributed throughout the year (with the exception of nodes [4, 0], [5, 2], and [5, 3]). To analyze the SOM results in more detail, the wind patterns are subjectively grouped into the following categories: “RAS” (outlined in red in Fig. 2), “northward transport over the eastern RIS” (outlined in orange in Fig. 2), “katabatic winds” (outlined in blue in Fig. 2), “mesocyclones over the RIS” (outlined in purple in Fig. 2), and “weak winds” (outlined in green in Fig. 2).

The dominant wind feature present within each pattern drives the identification of these categories. Other wind features may also be present within a pattern, such as katabatic winds within RAS patterns, although the pattern is categorized with respect to its dominant wind feature. Each of these categories will be described below, as well as, the frequency (Fig. 5a) and seasonality (Fig. 5b) of each category.

The RAS patterns (outlined in red in Fig. 2) show the RAS, or northward transport of air over the western to central RIS, as defined by SC12. These patterns have strong winds over the RIS that transport air from the southern tip of the RIS toward the north, over the western to central RIS, to the Ross Sea. Within these patterns, the location of the strongest winds over the RIS varies. Nodes [2, 0] and [3, 0] show the fastest winds located through the center of the RIS (Fig. 2a). These patterns have a synoptic cyclone located off the coast of Marie Byrd Land and a strong pressure gradient over the RIS with SLP contours that are oriented meridionally (Fig. 2b). Node [0, 0] shows the strongest winds dominating the RIS. This pattern has a synoptic cyclone located over the eastern Ross Sea and a strong pressure gradient over the RIS. Nodes [0, 2] and [0, 3] show the strongest winds over the RIS located adjacent to the Transantarctic Mountains. These patterns have a weak synoptic cyclone in the Ross Sea, with a trough of low pressure extending from the primary low and penetrating the RIS. The remaining nodes—[0, 1], [1, 0], [1, 1] and [1, 2]—have a combination of the features discussed in this paragraph. The RAS patterns have a combined frequency of 34% (Fig. 5a). The patterns are predominantly nonsummer patterns (Fig. 5b), with 5% of the RAS patterns occurring during the summer, 25% during the fall, 40% during the winter, and 30% during the spring.

The northward transport over the eastern RIS patterns (outlined in orange in Fig. 2) have strong winds over the northern and eastern portions of the RIS (Fig. 2a). The node-averaged SLP anomalies for these patterns have a synoptic cyclone located off the coast of Marie Byrd Land (Fig. 2b). The combined frequency of the northward transport over the eastern RIS patterns is 9% (Fig. 5a). These patterns tend to occur less frequently in the summer months and are fairly evenly distributed throughout the rest of the year (Fig. 5b).

The katabatic wind patterns (outlined in blue in Fig. 2) show katabatic drainage onto the RIS. These patterns have weaker winds over the RIS, with areas of stronger winds at the base of Byrd Glacier (Fig. 1) and the Siple Coast confluence zone (Fig. 2a). The katabatic wind patterns can be broken into “strong katabatic” patterns (nodes [2, 1] and [3, 1]) and “weak katabatic” patterns (nodes [4, 1] and [4, 2]). For these patterns the synoptic cyclone off the coast of Marie Byrd Land is shifted to the east, toward the Amundsen Sea (Fig. 1), resulting in a weaker pressure gradient over the RIS. The SLP contours over the RIS are generally oriented meridionally (Fig. 2b). Strong katabatic winds occur 8% of the time and are nonsummer patterns with a slight maximum in the frequency during the winter months. Weak katabatic winds occur 8% of the time and occur in all seasons (Fig. 5).

The mesocyclones over the RIS patterns (outlined in purple in Fig. 2) have a mesocyclone over the RIS, which can be seen in the node-averaged SLP anomalies (Fig. 2b). Additionally, cyclonic flow over the RIS is shown in the node-averaged 10-m winds for these patterns (Fig. 2a). Mesocyclone patterns occur over the RIS approximately 20% of the time (Fig. 5a). Mesocyclone patterns occur throughout the year, with a slight maximum in the frequency during winter for nodes [2, 2], [3, 2], and [3, 3] (Fig. 5b).

The weak winds patterns (outlined in green in Fig. 2) show light, variable winds over the RIS (Fig. 2a). The SLP anomalies for these patterns show high pressure and a weak pressure gradient over the RIS. Additionally, there is little to no influence from a synoptic cyclone in the Ross Sea (Fig. 2b). Weak winds occur approximately 21% of the time over the RIS (Fig. 5a). These patterns are predominantly summer patterns (Fig. 5b).

b. RAS patterns

An additional SOM can be trained using a subset of the original dataset, providing a more detailed analysis of the patterns chosen for the subset. To better understand the RAS patterns in Fig. 2a, a new SOM was trained using only the weather patterns identified as RAS patterns (outlined in red in Fig. 2). The results for the subset SOM are shown in Fig. 6, with the node-averaged 10-m winds in Fig. 6a and the node-averaged SLP anomalies in Fig. 6b.
The figure of node-averaged 10-m winds (Fig. 6a) shows variability in the strength and position of the RAS. The RAS patterns range from strong winds that dominate the majority of the RIS (column 0) to the strong winds that are located adjacent to the Transantarctic Mountains (column 4), with the patterns in the center of the SOM showing a progression between the patterns on the left and right sides of the SOM. Therefore, moving from left to right across the SOM, the corridor of strong winds narrows and moves westward, becoming more terrain parallel. Moving from top to bottom across the SOM, the 10-m winds weaken (with the exception of columns 0 and 1) and the strongest winds generally shift westward (with the exception of node [2, 3]).

Figure 7 shows the frequency and seasonality of each of the RAS patterns. The frequency plot (Fig. 7a) indicates the percentage of time each RAS pattern occurs over the 2-yr period (the summation of these frequencies is 34%, or the total frequency of the RAS patterns identified in Fig. 2a). The darker shades indicate patterns that are more frequent and lighter shades indicate patterns that are less frequent. Again, the dataset is fairly evenly distributed over the SOM. The seasonality plot (Fig. 7b) shows that the RAS patterns can occur during any season [consistent with the conclusions from Parish et al. (2006)], but generally occur least frequently during the summer months (December and January). The bias of the RAS patterns to non-summer months is consistent with the seasonality plot presented in Fig. 5b.

The RAS patterns shown in Fig. 6a will not be further broken down into subjective groups, since all of the
patterns are RAS patterns. Instead, how the patterns transition when moving left to right across the SOM will be analyzed in further detail. Starting on the left side of the SOM (column 0), the patterns show strong winds that dominate the majority of the RIS (Fig. 6a). The synoptic cyclone positioned from Marie Byrd Land to the central Ross Sea is strong and appears to be approximately axis symmetric (with the exception of node [0, 3]). The synoptic cyclone creates a strong pressure gradient over the RIS with the highest pressures located adjacent to the Transantarctic Mountains (Fig. 6b).

The patterns in the center of the SOM (columns 1 through 3) show a transitional progression between the patterns on the left side of the SOM and the patterns on the right side of the SOM. Moving across the rows, from left to right, the corridor of strong winds becomes narrower and moves closer to the Transantarctic Mountains (Fig. 6a). Moving from left to right across the SOM, the synoptic cyclone in each pattern becomes weaker and generally shifts eastward (Fig. 6b). Additionally, moving down the columns, the strong winds tend to move toward the Transantarctic Mountains (Fig. 6a), which is consistent with the pressure gradient associated with the synoptic cyclone shifting westward.

The patterns in column 4 of the SOM show strong winds that are adjacent to the Transantarctic Mountains (Fig. 6a). In general, these patterns have a weaker synoptic cyclone off the coast of Marie Byrd Land and a weaker pressure gradient over the RIS than the patterns on the left side of the SOM (Fig. 6b). These
FIG. 7. (a) Node frequency and (b) seasonal frequency for each RAS wind pattern in Fig. 6a. The seasonality plot indicates the percentage of time each pattern occurs during the summer (DJ), fall (FMA), winter (MJJA), and spring (SON).
patterns also show a low pressure trough extending from the synoptic cyclone over the eastern RIS, near the Siple Coast.

The RAS SOM analysis shows that the RAS varies in its strength and position. The wide variety of RAS patterns, as identified by this study, suggests that the combination of forcing mechanisms (i.e., katabatic, barrier winds, and synoptic forcing) that drive the RAS vary between the identified patterns. Future work by the authors will investigate the forcing mechanisms that drive each of the SOM identified RAS patterns and will analyze how the combination of these mechanisms varies across the patterns.

**BWCJ Identification**

During RAS events, BWCJs can form to the northwest of the Prince Olav Mountains (Nigro et al. 2012). Therefore, the RAS SOM analysis presented here can be used to estimate the frequency of BWCJ events. Nigro et al. (2012) showed that BWCJs form off the coast of the Prince Olav Mountains when a southern RIS barrier wind reaches the end of the barrier, or the area of maximum protrusion by the Prince Olav Mountains. At this point, the flow transitions from an area of terrain-induced high pressure to the background pressure field of the region and the PGF aligns with the direction of the flow. The alignment of the PGF with the direction of flow increases the magnitude of the wind speed, creating the BWCJ. In Nigro et al. (2012) this was depicted using the PGF plot in their Fig. 13c (reproduced here as Fig. 8). The PGF plot shows a strong PGF in the southern tip of the RIS (the region of the southern RIS barrier wind) and a weaker PGF to the northwest of the Prince Olav Mountains (the region of the BWCJ).

Figure 9 shows the PGF calculated from the SLP for each node. The nodes in columns 3 and 4 of Fig. 9 show a strong PGF in the southern tip of the RIS and a weaker PGF to the northwest of the Prince Olav Mountains (the location of these mountains is marked with a triangle in Figs. 6 and 8), which is similar to the BWCJ pattern identified by Nigro et al. (2012). Additionally, the 10-m wind plots (Fig. 6a) for the nodes in columns 3 and 4 show an area of strong winds located in the region of weaker PGF, or directly to the northwest of the Prince Olav Mountains. Therefore, the patterns in columns 3 and 4 of the subset SOM (Fig. 6a) are consistent with the characteristics of a BWCJ in the region to the northwest of the Prince Olav Mountains (Nigro et al. 2012). If it is assumed that a BWCJ is present in the patterns in columns 3 and 4 of the RAS SOM analysis, it can be estimated that BWCJs occur approximately 14% of the time (Fig. 7a) and approximately 41% of the time when the RAS is present. The BWCJ patterns are mostly nonsummer patterns (Fig. 7b), although BWCJs can occur during the summer months.

**5. Discussion**

Because of the differences in the AMPS-WRF 15-km and AMPS-MM5 30-km datasets, the results of the SOM analysis presented here are compared to the results of the SOM analysis presented by SC12. SC12 conducted two separate SOM analyses using 5 years of AMPS-MM5 30-km output. The first analysis trained the SOM using the winds from the lowest model level, which has an average height of approximately 11–13 m AGL. The results of this analysis are shown in Fig. 3 of SC12. The second analysis trained the SOM using the winds on the fifth lowest model level, which has an average height of approximately 150–160 m AGL. The results of the second analysis are shown in Fig. 9 of SC12.

The SC12 analysis of the winds on the lowest model level (approximately 11–13 m AGL) is comparable to the analysis conducted on the 10-m winds for this paper. The wind patterns identified by SC12 show almost exclusively southerly flow (see Fig. 3 in SC12) over the RIS. In the SC12 analysis, the strongest winds over the RIS are located adjacent to the Transantarctic Mountains in each of the identified patterns. The patterns show weak winds over the center of the RIS and the eastern RIS (see Fig. 3 in SC12). The SC12 analysis estimated the frequency of RAS patterns to be approximately 53.2%.

The SOM analysis of the AMPS-WRF 15-km 10-m winds provides more detail about the low-level winds.
over the RIS (Fig. 2a). The SOM-identified patterns, shown in Fig. 2a, show more variation in the wind direction than the exclusively southerly winds identified by SC12. The SOM-identified wind patterns shown in Fig. 2a range from patterns with southerly flow to patterns with cyclonic flow (nodes [2, 2] and [1, 3] to [3, 3]), anticyclonic flow (node [5, 3]), and westerly flow (nodes [3, 2] to [4, 2] and [3, 3] to [4, 3]). Additionally, the AMPS-WRF 15-km 10-m wind analysis shows more variation in the location of the strongest winds over the RIS. In Fig. 2a, the strongest winds over the RIS are located in the following regions: adjacent to the Transantarctic Mountains (nodes [0, 2] to [0, 3] and [1, 2] to [1, 3]), over the western RIS (nodes [0, 0] to [0, 1] and [1, 0] to [1, 1]), through the center of the RIS (nodes [2, 0] to [2, 1] and [3, 0] to [3, 1]), over the eastern RIS (node [4, 0]), and over the northern RIS (nodes [5, 0] to [5, 1] and [4, 1] to [4, 2]). The frequency of the RAS patterns in this study was estimated to be approximately 34%, less than the frequency determined by SC12 (53.2%).

Analysis of the SLP anomalies for the two different studies provides a similar analysis. The AMPS-WRF 15-km SOM SLP analysis provides more detail about the pressure field over the RIS than the AMPS-MM5 30-km SOM SLP analysis. The SC12 results show SLP anomalies with high pressure adjacent to the Transantarctic Mountains. These results show little influence of mesoscale features over the RIS, while the AMPS-WRF 15-km results show patterns with mesocyclones over the RIS (nodes [1, 3] to [2, 3] and [2, 2]) and a trough extending from the synoptic cyclone off the coast of Marie Byrd Land to the RIS (nodes [0, 3] and [1, 2]).

Fig. 9. Node-averaged pressure gradient force over the Ross Ice Shelf for the subset SOM of RAS patterns. The triangle indicates the location of the Prince Olav Mountains.
The differences between the two SOM analyses can more than likely be contributed to two factors. The first being the differences between the two datasets. Figure 3 shows the differences between the AMPS-MM5 30-km data and the AMPS-WRF 15-km data. These differences are likely caused by the differences between MM5 and WRF run within AMPS, as well as the higher resolution of the AMPS-WRF 15-km dataset. The second factor is the differences in the domains used for the SOM analysis. SC12 used a SOM training domain that included the East and West Antarctic plateaus, the Transantarctic Mountains, and the Ross Sea. This domain included the strong katabatic winds over the Antarctic plateaus and the Transantarctic Mountains, as well as the strong synoptic winds over the Ross Sea. These strong winds likely dominated the SOM training and potentially masked some of the mesoscale details of the RIS wind field in the results. The AMPS-WRF 15-km analysis used a SOM training domain that covered only the RIS, thereby removing the influence of these strong winds from the SOM analysis and thus providing a more detailed description of the low-level wind field over the RIS.

6. Conclusions

This paper used the method of SOMs and the AMPS-WRF 15-km output to identify the dominant 10-m wind patterns over the RIS. The patterns identified were grouped into the following categories: “RAS,” “northward transport over the eastern RIS,” “katabatic winds,” “mesocyclones over the RIS,” and “weak winds” patterns over the RIS. The patterns within the RAS category occur approximately 34% of the time and are more frequent than the patterns in any of the other categories.

To investigate this dominant wind regime over the RIS, a subset SOM was trained to identify the dominant RAS patterns that occur over the RIS. The identified RAS patterns show that the RAS varies in strength and position over the RIS. The RAS patterns range from strong winds over the majority of the RIS, to a narrow corridor of strong winds through the center of the RIS, to the strongest winds located adjacent to the Transantarctic Mountains. The SOM-identified RAS patterns were also used to estimate the frequency of BWCJs in the region to the northwest of the Prince Olav Mountains, providing a broader climatological context to the case study results presented in Nigro et al. (2012). BWCJs were estimated to occur 14% of the time and 41% of the time when the RAS is present. It was also determined that the RAS and BWCJs can occur during any season, but are generally nonsummer features.

The results presented here were compared to the results of a SOM analysis of the low-level winds over the RIS using the AMPS-MM5 30-km dataset (SC12). In general, the wind patterns identified with the AMPS-WRF 15-km dataset (the analysis presented in this paper) showed more variation in the wind direction, wind speed, and placement of the strongest winds over the RIS. A statistical analysis of the lowest model level winds in each dataset with respect to AWS wind observations showed that the AMPS-WRF 15-km dataset better captured the low-level wind field over the RIS. Therefore, the wind patterns identified with the AMPS-WRF 15-km dataset are likely a better representation of the wind patterns over the RIS.

Future work by the authors will investigate the forcing mechanisms that drive the variations in the strength and position of the RAS, as shown in Fig. 5a. The forcing mechanisms that drive each of the SOM-identified RAS patterns will be investigated, as well as how the combination of these mechanisms vary across the patterns.

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