A High-Resolution Numerical Simulation of the Wind Flow in the Rossi Island Region, Antarctica

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ABSTRACT

A detailed description of the characteristics of the three-dimensional wind flow for the Ross Island region of Antarctica is presented. This region of Antarctica has complex topographic features, and the wind flow is dependent on the topography and the local meteorological conditions. High-resolution nonhydrostatic numerical simulations are conducted over a high-resolution domain in the Ross Island region. Two simulations are performed corresponding to the two dominant wind flow patterns in the Ross Island region. The first simulation is a light wind case with a stable lower atmosphere and the second is a high wind speed event. Froude number calculations, along with a study of the equation of motion, are included for a more complete understanding of the dynamics of the wind flow. The results of the simulations show a favorable correlation to past research results and observations, and provide a more complete understanding of the three-dimensional wind flow in the region. In addition to a more thorough understanding of the wind flow, the results indicate the usefulness and future applicability of nonhydrostatic simulations to understanding the unique meteorological conditions and features in the Antarctic.

1. Introduction

The wind flow in the Ross Island region of Antarctica has unique characteristics that are related to the meteorological environment and the local topography. During light wind and stable atmospheric conditions, the wind flow tends to follow the topography. In this case, the prevailing surface wind directions are dependent on the location of the observation in relation to the topography. During high wind speed events, the surface wind directions are consistently from the south throughout the region, and they are not as dependent on the local topography.

The topography of the Ross Island region is characterized by steeply rising, complex terrain. Figure 1 is a map detailing many of the locations and topographic features in the Ross Island region. At the center of the region is Ross Island, with two mountains, Mount Erebus and Mount Terror, placed symmetrically on the island and extending from sea level to over 3000 m. Ross Island is approximately 75 km west to east and 35 km south to north in size. Hut Point Peninsula, with typical elevations greater than 200 m, extends approximately 20 km to the southwest beyond the main portion of the island. Black Island and White Island, characterized by elevations of 1000 and 750 m, respectively, are located approximately 30 km south of Ross Island. Minna Bluff, with an elevation greater than 800 m, is located approximately 80 km south of Ross Island. The Ross Ice Shelf, a permanent ice shelf extending over 900 km with a slight rise in elevation, lies to the south of Ross Island. The Ross Sea extends to the north of Ross Island and it is typically ice free during the summer season and ice covered during the winter. The Transantarctic Mountains, located west of Ross Island at a distance of approximately 80 km, quickly rise to elevations greater than 2000 m and run the entire range of the Ross Ice Shelf and the Ross Sea.

The topographic features of this region force complex patterns of wind flow, which often vary sharply over short distances. This wind flow provides a significant obstacle to human activities in the region. The locations of McMurdo station (the largest of the U.S. Antarctic Program bases) and Scott Base (of the New Zealand Antarctic Program) on the southwestern edge of Ross Island expose a large number of Antarctic scientists and support staff to these variable winds. This is particularly important for aircraft operations in the region (the primary means of transportation for the scientists and support staff) and provides a strong motivation for improved understanding of the wind flow around Ross Island. The history of this region is also filled with the stories of Robert Scott and Ernest Shackleton, from the Antarctic exploration age, encountering the challenges of the complex wind flow pattern influenced by the local terrain.

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Interest in the wind flow in the Ross Island region dates back as far as some of the early explorers. A classic Antarctic meteorology study by Simpson (1919) uses the meteorological observations from Scott’s and Shackleton’s expeditions in the early twentieth century to formulate an understanding of the wind flow in the region. Simpson’s work includes a streamline analysis of the region during a high wind speed event. Schwerdtfeger (1984) uses University of Wisconsin Antarctic Automatic Weather Station (UWAAWS) data and manned observations in a comparison to Simpson’s work. Schwerdtfeger proposes that the primary processes for the consistently southerly winds in the Ross Island region are due to a few potential meteorological conditions. These conditions include the development of barrier winds due to the Transantarctic Mountains, a cyclone stationed over the central part of the Ross Ice Shelf or the southern part of the Ross Sea, and to a lesser degree, the result of katabatic winds flowing down the Transantarctic Mountains during the winter months.

Bromwich (1988) and O’Connor et al. (1994) go into more depth on the development of barrier winds in the region. Stable air is moved up against the high barrier of the Transantarctic Mountains. The air cannot flow over the barrier, so it piles up against the barrier establishing a pressure gradient with the highest pressure at the base. Under the influence of this pressure gradient force and the Coriolis force, the winds then flow along the barrier with a southerly direction through the Ross
Island region. Bromwich (1988) and O’Connor et al. (1994) also propose the development of barrier wind events due to a mesocyclone or synoptic-scale cyclone in the region. Bromwich (1988) describes the influences of the topography in the Ross Island region on the barrier winds. Downwind wake zones are formed at the lower levels on the northern sides of Minna Bluff and Ross Island. Polynyas, open areas of water indicating high wind speeds, have been observed to form on the eastern and western edges of Ross Island.

Savage and Stearns (1985) present results from a climatological study in the region based on the early years of the UWAAWS program. The study concludes that the wind field in the region shows a high degree of persistence and has indications of terrain-following characteristics.

Sinclair (1988) conducts a more specific climatological study based on the area around Scott Base (eastern side of Hut Point Peninsula). Sinclair’s study shows that during inversion conditions the surface winds at Scott Base usually flow from the northeast. During neutral or unstable conditions the surface winds at Scott Base may flow from directions other than northeast. Sinclair suggests that during inversion conditions the wind flow will resist vertical displacements and will tend to flow around rather than over topographic features.

O’Connor and Bromwich (1988) use a fluid dynamics approach to study the wind flow around Ross Island, with particular attention on the Windless Bight area. Windless Bight is an area of anomalously calm winds of varying direction on the southern side of Ross Island (Fig. 1). In the O’Connor and Bromwich study, the wind flow around Ross Island is modeled with a two-dimensional potential flow model. The study focuses on two southerly wind cases in the Ross Island region. One is a strong barrier wind event with a wind speed of 20 m s$^{-1}$, and the other is a climatological case with a wind speed of 5 m s$^{-1}$. The model results show a favorable correlation to the automatic weather station observations; however, it is not able to show the marked increase in wind speeds on the eastern and western edges of Ross Island as has been indicated by the presence of polynyas. The results from their two-dimensional potential flow model are not able to account for the smaller topographic features in the Ross Island region.

A dynamical study by Slotten and Stearns (1987) is based on a triangulation of observations from UWAAWS sites in the region. This study shows the presence of cold stable air piling up on the windward side of Ross Island.

A simple primitive equation model is used by O’Connor et al. (1994) to study the formation of barrier wind events in the western Ross Ice Shelf and Ross Sea area. The model uses a step topography representation, with the 1000-m-elevation contour representing the major topographic features in the region. Two different cases representing actual barrier wind events are studied by O’Connor et al. The simulation accurately represents the stagnation zones north of Ross Island and Minna Bluff, and it does a good job showing the southerly and southeasterly winds during a barrier wind event. However, results from the simulation are unable to address the wind flow within the Ross Island region, and cannot account for the smaller topographic features and the vertical wind flow.

The motivation for the current study is to use the University of Wisconsin-Nonhydrostatic Mesoscale Modeling System (UW-NMS) to simulate the three-dimensional wind flow in the Ross Island region. The UWAAWS observations for the year 1994 are scanned and conditions are found that match the results from previous research with a low wind speed with terrain-following characteristics pattern (22 April), and a high wind speed with a southerly direction pattern (3 November). Simplifications are made to the UW-NMS model to focus specifically on how the topography affects the wind flow for these cases. A high-resolution topography dataset is used to initialize the UW-NMS so that the impact of many of the smaller topographical features in the region can be successfully studied. The first case (22 April) simulates the ambient flow conditions with a strong stable boundary layer and light winds. The second case (3 November) simulates high winds with a predominantly southerly surface flow over the entire Ross Island region. From these two model simulations, an attempt is made to gain an understanding of the three-dimensional wind flow in relation to the topography, the atmospheric stability, and the wind forcing mechanisms. Additional analyses are conducted calculating the Froude number and the acceleration of the wind flow due to the topographically induced pressure perturbation. The results are compared to previous research using UWAAWS data and the conclusions from previous modeling studies.

A short description of the UW-NMS and the numerical simulations is described in section 2. Section 3 includes a description of the methodology performed in selecting the dates for the two case studies, and sections 4 and 5 detail the case study simulations, analyses, and results. A summary of the results concludes the paper in section 6.

2. UW-NMS model

The University of Wisconsin-Nonhydrostatic Modeling System is used to analyze the topographic influences on the wind flow in the Ross Island region of Antarctica. The UW-NMS model is a fully three-dimensional quasi-compressible nonhydrostatic model using a split time step. A thorough description of the model formulation, including the governing equations, is given by Tripoli (1992).

a. Operation and configuration

Two grids are used in this study and the grids in the UW-NMS model are nested using the Clark and Farley
Fig. 2. (a) Location of the inner and outer grid for the UW-NMS simulations. (b) Topography representation for the UW-NMS outer grid. Contours are from 100 to 2300 m in 200-m steps. The tick marks along the outside border correspond to model grid points, with an interval spacing of 15 km. (c) Topography representation for the UW-NMS inner grid. Contours are from 100 to 3100 m in 200 m steps. The tick marks along the outside border correspond to model grid points, with an interval spacing of 3 km.
(1984) nesting scheme. The model is configured with two-way interactive nesting between the inner and outer grids. Figure 2a shows the inner and outer grid model domains in the Ross Island region. The outer domain is configured with the center at 78°S and 166°E, 30 grid points west to east, 40 grid points south to north, and a gridpoint spacing of 15 km. The inner domain is configured with the center at 78°S and 168°E, 52 grid points west to east, 92 grid points south to north, and a gridpoint spacing of 3 km. The inner domain is set with the western boundary just to the east of the Transantarctic Mountains, and all other boundaries are sufficiently beyond the influence of the major topographical features of the Ross Island region.

The model uses a vertical coordinate system based on height and a step representation of topography. The step topography system is similar to the National Centers for Environmental Prediction’s Eta Model, which uses the so-called eta coordinate that contains similar steps to represent topography. The step topography system is chosen over the available coordinate transform system because of its ability to handle steep topography. Thirty vertical levels are specified for this study from 0 to 12,000 m. The spacing at the lowest levels is 20 m and the vertical spacing increases approximately linearly to a spacing of 1000 m in the upper levels. The vertical coordinate system remains constant for the inner and outer domains.

The UW-NMS model uses a split-time-step technique as described by Klemp and Wilhelmson (1978). The time step in the outer domain is set to 30 s. The nesting ratio for the time step is set to 5, corresponding to the ratio for the grid spacing between grids. The radiation parameterization is updated every 900 s and the surface layer fluxes are updated every 30 s.

Fluxes of heat and moisture at the surface are calculated by the Businger–Dyer equations (Businger et al. 1971). An iterative approach, using the mean wind speed and temperature, is used by the UW-NMS model to solve for the empirical relationships found in the Businger–Dyer equations. The turbulence parameterization is set to first-order closure as described by Stull (1988). The radiation parameterization incorporates both longwave and shortwave radiation, and is described in more detail by Chen and Cotton (1983). All simulations are cloud free with water vapor acting as a passive tracer. The cumulus parameterization for the UW-NMS model is not used.

The horizontal boundaries for the outer domain are restricted to the large-scale initialized gridded analysis and are updated every 12 h with a linear interpolation done at intermediate times. A Rayleigh absorbing layer with four model points is used to adjust the boundary values of the outer domain to the initialized gridded analysis. The top of the model is set as a wall with a Rayleigh absorbing layer located just below the top and extending for three model points. The Rayleigh absorbing layer is used to absorb and prevent reflection of vertically propagating gravity waves. The lower boundary uses a multilayer soil model, incorporating the porosity, heat capacity, and albedo for the specified soil type (Tripoli and Cotton 1982). In this study the soil type is set to “pure snow” for the entire model domain, including the frozen sea ice. The albedo is equal to 0.85 for the pure snow soil type.

b. Initialization

The UW-NMS model is initialized with a topography dataset provided by the United States Geological Survey (USGS). The dataset created by the USGS uses values from the Scientific Committee for Antarctic Research Antarctic Digital Database, version 1 (C. Hallum 1996, personal communication). Figures 2b and 2c show the resulting topography contours for the outer and inner grid domains.

The annual fluctuation in sea ice coverage in the Ross Island region and the importance of the surface type to the UW-NMS model necessitates a sea surface temperature–ice coverage (SST) dataset. SST data retrieved from the Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory is used in this study. The dataset consists of values computed from the National Oceanic and Atmospheric Administration’s Advanced Very High Resolution Radiometer. The weekly averaged daytime interpolated SST dataset corresponding to the week of each simulation model case is used. Extent of ice coverage is included in the SST dataset by setting a specific flag value for ice and land.

The UW-NMS model is initialized with gridded data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global tropospheric analysis. The initialization uses ECMWF gridded data received from the Data Support Section at the National Center for Atmospheric Research. At each level the geopotential height, horizontal wind components, temperature, and relative humidity are specified. The data are interpolated horizontally along the mandatory pressure levels to the location of the model grid points, and then vertically to model grid levels.

c. Additional analysis

After completion of the model simulations, additional analyses are performed to gain a more comprehensive understanding of the dynamics of the wind flow in the Ross Island region. The analyses are calculated using sounding output from the UW-NMS simulations at selected model grid points, and they are used to describe specific features of the wind flow.

The internal Froude number (Fr) is often used as a method to describe the stratification of the atmosphere in relation to the wind flow around an obstacle. Previous research with an emphasis on the internal Froude number has been conducted by Brighton (1978), Hunt and Snyder (1980), and Snyder et al. (1985). The conven-
The functional definition of the internal Froude number is \( \text{Fr} = \frac{U}{N\sqrt{h}} \), where \( N \) is the Brunt–Väisälä frequency, \( h \) is the characteristic height of the obstacle, and \( U \) is the mean wind speed over the characteristic height. The square of the internal Froude number is equal to the ratio of the kinetic energy of the approaching wind and the necessary potential energy required to lift the parcel of air over the obstacle. For a subcritical wind flow (\( \text{Fr} < 1 \)) the air lacks the energy to flow over the obstacle and must instead flow around it. For a supercritical wind flow (\( \text{Fr} > 1 \)) the air is able to flow over the obstacle resulting in a linearized flow.
TABLE 1. UWAAWS units.

<table>
<thead>
<tr>
<th>UWAAWS name</th>
<th>ID</th>
<th>Lat (°S)</th>
<th>Lon (°E)</th>
<th>Elev (m)</th>
<th>Apr 1994</th>
<th>Nov 1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrell</td>
<td>FER</td>
<td>78.020</td>
<td>170.800</td>
<td>65</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
<tr>
<td>Marble Point</td>
<td>MPT</td>
<td>77.440</td>
<td>163.750</td>
<td>120</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
<tr>
<td>Minna Bluff</td>
<td>MNB</td>
<td>78.560</td>
<td>166.690</td>
<td>980</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
<tr>
<td>Pegasus North</td>
<td>PGN</td>
<td>77.952</td>
<td>166.507</td>
<td>8</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
<tr>
<td>Pegasus South</td>
<td>PGS</td>
<td>77.989</td>
<td>166.580</td>
<td>8</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
<tr>
<td>Willie Field</td>
<td>WFD</td>
<td>77.865</td>
<td>167.019</td>
<td>24</td>
<td>T, P, WS, WD</td>
<td>T, P, WS, WD</td>
</tr>
</tbody>
</table>

T = temperature, P = pressure, WS = wind speed, WD = wind direction.

A simplified version of the Froude number equation is used in this study based on previous studies by O’Connor and Bromwich (1988), O’Connoer et al. (1994), and Burk et al. (1999):

\[
Fr = U \left( \frac{g \cdot h \cdot \Delta \theta}{\theta} \right)^{-1/2},
\]

where \( U \) is the mean wind speed and \( \theta \) the mean potential temperature through the characteristic height of the obstacle \( h \), and \( \Delta \theta \) is the change in potential temperature from the surface to the characteristic height. The Froude number is calculated at two locations in this study, upstream of Minna Bluff (\( h = 500 \text{ m} \)) and upstream of Ross Island (\( h = 2000 \text{ m} \)).

An analysis of the resultant pressure field around Ross Island is studied to analyze the forcing at the strong winds on the eastern and western edges of Ross Island. The approach is similar to the study of gap winds (a flow of air in a sea level channel, which accelerates under the influence of a pressure gradient parallel to the axis of the channel) by Overland and Walter (1981) and Smedman and Bergström (1995). The acceleration of the wind flow is under the influence of a pressure gradient parallel to the wind flow during stably stratified conditions. A scale analysis for the equation of motion for the wind flow can be written as

\[
\frac{du}{dt} - fu = -\frac{1}{\rho} \frac{\partial p}{\partial x} + F_x,
\]

where \( u \) is the wind component along the pressure gradient, \( v \) is the wind component across the pressure gradient, \( f \) is the Coriolis parameter, \( \rho \) is the density, \( p \) is the pressure, \( F_x \) is the component of friction along the pressure gradient, and \( d/dt \) is the total derivative.

The distance of the pressure gradient between the windward and leeward sides of Ross Island is less than 80 km and the wind component across the pressure gradient is minimal. Therefore the Coriolis parameter will be neglected to a first approximation. The acceleration of the wind flow will be studied at a height of 500 m, which is approximately the location of the strongest pressure gradient. This is at a level above the boundary layer so the friction component will be neglected. The equation of motion simplifies to

\[
\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x}.
\]

Integration of this equation results in the Bernoulli equation:
Fig. 5. (a) Upper-air observation for McMurdo station from 1200 UTC 22 Apr 1994. (b) Upper-air plot for the center grid point of the inner grid at hour 12 (1200 UTC 22 Apr 1994) for case 1. Skew T–logp plots using conventional format: temperature (°C), pressure (hPa), wind direction, and wind speed (half barb, 2.5 m s⁻¹; full barb, 5.0 m s⁻¹).

The acceleration of the wind flow between Windless Bight and the locations of high wind speed on the eastern and western edges of Ross Island is studied with this equation.

\[
\frac{u^2}{2} = \frac{u_0^2}{2} - \frac{\Delta p}{\rho}.
\]

3. Case selection
   a. Observations

Meteorological observations from the UWAAWS program are used at various points in this project. A climatological description of the wind flow in the region is completed using the UWAAWS data. The results are
then used to select the dates corresponding to the surface meteorological conditions desired for the model simulations. The UWAAWS observations are also used in verifying the results from the UW-NMS model.

UWAAWS units provide a good source of meteorological data in an environment where the harsh conditions provide little opportunity for other sources of meteorological data. Keller et al. (1996) gives a description of the UWAAWS program for the calendar year 1994. The station pressure, air temperature, wind direction, and wind speed values are used. UWAAWS data used in this study come from the 3-hourly summaries provided by the UWAAWS group. Mean sea level pressure is calculated using the hypsometric equation and data from the station pressure, station elevation, and a mean temperature from the UWAAWS measurements. Table 1 lists the available data from the selected UWAAWS sites for the simulated cases.

Upper-air data from McMurdo station are used in this study for initialization and verification of the UW-NMS model. Naval Support Force Antarctica was responsible for the upper-air measurements at McMurdo station.

**b. Climatology study**

The surface winds in the Ross Island region can be described as having a bimodal pattern. The two wind regimes are light wind speeds with topography following characteristics and high wind speeds with a predominantly southerly flow. Figures 3a and 3b show the bimodal wind patterns. Figure 3a shows the UWAAWS wind direction frequency for each 10° wind direction sector. Figure 3b shows the average UWAAWS wind speed for each 10° wind direction sector.

The values at Pegasus North illustrate the bimodal wind pattern. The prevailing wind direction frequency is from the northeast. The wind speed observations from this direction are light and average less than 5 m s⁻¹. The wind direction is less frequent from the south; however, the average wind speed is highest from that direction, averaging close to 10 m s⁻¹. Similar results are found in measurements from Willie Field and Pegasus South. These results cannot be plotted in the figures due to the close geographical proximity of these UWAAWS units to the Pegasus North site.
c. Summary

The wind flow in the Ross Island region is dependent on the topography in the region. Typically the wind flow is initiated as katabatic winds. Katabatic winds are a common result due to cold air drainage through the Transantarctic Mountains at Byrd, Skelton, Mullock, and Beardmore Glaciers. Katabatic winds can be indicated in UWAAWS observations, located at the base of the glaciers and extending onto the Ross Ice Shelf, by the wind direction coming from the glaciers. The katabatic winds are light and they can extend for hundreds of miles across the Ross Ice Shelf. Barrier winds, related to the high and steep topography of the Transantarctic Mountains, also play a large role in the wind flow in the Ross Island region. The barrier winds are typically indicated by strong southerly wind flow in the UWAAWS observations throughout the Ross Ice shelf.

Topographic influences also occur within the Ross Island region during stable conditions and light winds. As the light winds flow northward through the Ross Island region they encounter barriers such as Minna Bluff and Ross Island. The steepness of the barriers act as a wall to the northward moving air. The stable atmospheric conditions resist vertical movement, the air then must flow around the barriers. The result is a wind flow pattern that is related to the varying terrain in the Ross Island region. The terrain-following pattern is indicated by the prevailing winds in the Ross Island region (Fig. 3a).

Predominantly southerly winds are seen throughout the Ross Island region during neutral or unstable atmospheric conditions or high wind speed events. With these conditions, the wind flow has the necessary energy to allow vertical movement to flow over the topographic obstacles. The winds then rise over the topography and...
are not inhibited by the terrain. The southerly winds during high wind speed events are indicated by the highest average wind speed coming from the south in the Ross Island region (Fig. 3b).

4. Case 1: Light wind speed with stable lower atmosphere

a. Overview of case

The first numerical simulation by the UW-NMS model matches the conditions for light winds and a stable lower atmosphere in the Ross Island region. A study of the UWAAWS observations and upper-air observations from McMurdo station during 1994 show a period around 22 April that matches the expected characteristics. At this time of the year, the Ross Island region is transitioning to the long winter night, and the region is under 24-h darkness. The long nights lead to an increase in radiational cooling and the development of strong surface inversions and a statically stable atmosphere that is resistant to parcel displacements in the vertical.

The UWAAWS units on the Ross Ice Shelf show light surface winds throughout the region. Moderate to light katabatic winds are flowing down Byrd Glacier, indicated by the westerly wind directions at the UWAAWS units at the base of the glacier (not shown). Figure 4a shows the UWAAWS station plot for the Ross Island region at 1800 UTC 22 April 1994. Figure 4b is a time series of UWAAWS station plots for the six units in the Ross Island region in 3-h intervals from 0000 UTC 22 April to 0000 UTC 23 April. Starting at 0900 UTC 22 April and lasting until 0000 UTC 23 April, the Ross Island region UWAAWS observations indicate the expected wind flow pattern. Pegasus North AWS and Pegasus South AWS have wind directions from the northeast and wind speeds varying from calm to 8.0 m s$^{-1}$. Willie Field AWS has wind directions from the northeast and wind speeds from 3.9 to 8.4 m s$^{-1}$. Ferrell AWS has wind directions from the south to southwest and speeds between 8.9 and 12.7 m s$^{-1}$. Minna Bluff AWS has wind directions from the south and Marble Point has wind directions from the south to southeast. The wind speeds throughout the region increase with time.

Figure 5a is the upper-air sounding from McMurdo station at 1200 UTC 22 April 1994. The existence of a strong stable surface layer is clearly present in the temperature profile. A closer look at the data shows a temperature increase of 4.0$^\circ$C from 22 (surface) to 322 m. At 785 m the temperature was 8.7$^\circ$C warmer than at the surface. The upper-air observations indicate wind from the northeast in the lowest 3000 m.

b. Initialization of model

The first simulation is for 24 h, originating at 0000 UTC 22 April 1994 and ending at 0000 UTC 23 April 1994. The initialized mean sea level pressure analysis for the outer model domain indicates an increase in surface pressure from the northeast to the southwest, with a surface high pressure region over the Antarctic plateau in the southwest corner. The initialized wind pattern has wind directions from the southeast over the northeastern section of the outer model domain. The wind flow south of Minna Bluff is light and varying with wind speeds less than 4 m s$^{-1}$. A surface inversion is not observed at the initial time.

Figure 5b is a skew $T$–log$p$ plot for the center grid point of the inner domain from the UW-NMS simulation for hour 12 (1200 UTC 22 April). A strong surface inversion, matching the temperature profile of the ob-
A served sounding from McMurdo station, is observed in the sounding.

The classical Ross Island region wind pattern, with the wind flow adjusting to the topography, is observed as early as hour 6 of the simulation. Figure 6 is an analysis of mean sea level pressure and wind vectors, at a height of 20 m, for the outer domain at hour 18 of the simulation. Light katabatic winds are flowing down Byrd, Skelton, and Mullock Glaciers onto the Ross Ice Shelf from the Polar Plateau, corresponding favorably

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**Fig. 11.** Vertical cross section of potential temperature (solid thin lines) and wind speed (dashed lines) along a west-to-east line approximately 25 km south of the center of Ross Island, from the UW-NMS inner grid at hour 18 for case 1 (1800 UTC 22 Apr 1994). Isentropes are in intervals of 2 K, isotachs are in intervals of 5 m s\(^{-1}\), and the vertical scale is in m. The small tick marks on the vertical scale represent the locations of the horizontal cross sections (Figs. 7-9). The heavy solid line is an outline of Ross Island in the distance.

**Fig. 12.** Vertical cross section of streamlines (solid thick lines), potential temperature (solid thin lines), and wind speed (dashed lines) along a south-to-north line approximately at the center of Mount Terror on Ross Island, from the UW-NMS inner grid at hour 18 for case 1 (1800 UTC 22 Apr 1994). Isentropes are in intervals of 2 K, isotachs are in intervals of 5 m s\(^{-1}\), and the vertical scale is in m. The small tick marks on the vertical scale represent the locations of the horizontal cross sections (Figs. 7-9). The heavy solid line represents the surface of Ross Island.
to the UWAAWS observations. The wind flow is deflected around Minna Bluff and Ross Island in the lower levels. Light and variable winds are observed in the Windless Bight region and a downstream wake zone has formed north of Ross Island.

c. Horizontal analysis

The UW-NMS simulation results for 1800 UTC 22 April are analyzed as a representation of the wind flow in the Ross Island region for a case involving light winds and a stable lower atmosphere. Figures 7–9 are horizontal cross sections of pressure, wind speed, and wind vectors, from the inner model domain. Figure 7 is at a height of 20 m, Fig. 8 at a height of 250 m, and Fig. 9 at a height of 1000 m.

The general surface wind flow (Fig. 7) is from the south over the entire domain with a terrain-following pattern as the flow goes around obstacles. A portion of the wind flow starts as katabatic drainage through the Transantarctic Mountains. The wind flow is deflected by Minna Bluff as it goes around the barrier. The flow splits as it approaches Ross Island, and then it travels to the east and west sides of Ross Island. The stream of air moving to the west is further deflected by Hut Point Peninsula. The northeast wind directions on the southern side of Hut Point Peninsula agree with Sinclair’s (1988) study on wind flow during stable conditions. The split wind flow around Ross Island creates a large downwind wake zone on the northern side of Ross Island with calm to light wind speeds and varying wind directions. The wind speeds in the Windless Bight area are all less than 5 m s$^{-1}$. A stream of greater than 5 m s$^{-1}$ airflow is observed to be channeled around Hut Point Peninsula; this is due to the deflection by Hut Point Peninsula. Isolated locations with wind speeds greater than 15 m s$^{-1}$ are observed on the eastern and western edges of Ross Island. The modeled surface wind flow is in agreement with the UWAAWS climatological study (Fig. 3a) indicating prevailing wind directions in the Ross Island region.

The horizontal cross section at 250 m (Fig. 8) describes the wind flow just above the lowest topographic obstacles. The influence of Hut Point Peninsula and other low-lying features is no longer observed. Minna Bluff, along with White Island and Black Island, still play a role in the wind flow as a slight deflection is noticed around these features. The largest wind speeds are again observed on the eastern and western edges of Ross Island.

The horizontal cross section at 1000 m (Fig. 9) shows the influence of the local topography on the wind flow at a height above all topographic features, except Ross Island. The wind flow south of Ross Island is predominantly from a southeastern direction. The change in direction of the upstream wind flow, in comparison to the lower levels, results in the location of the split in the wind flow, in front of Ross Island, to be farther east than at lower levels. The pronounced downstream wake zone is still clearly defined with light and varying winds with wind speeds less than 5 m s$^{-1}$. Minna Bluff, White Island, and Black Island are showing some influence on the wind pattern with isolated locations of faster moving air slightly downstream from these locations.
d. Vertical analysis

An analysis of the vertical structure and circulation of the atmosphere is studied to gain a more complete understanding of the three-dimensional wind flow in the Ross Island region. Emphasis will be placed on the flow around the eastern side of Ross Island. Figure 10 shows the locations of the vertical cross sections for this analysis. Figures 11–13 are vertical cross sections of potential temperature and wind speed around Ross Island;

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Fig. 14. Time series of horizontal cross sections around Ross Island. Plot of pressure and wind vectors, at a height of 500 m, from the UW-NMS inner grid for case 1 (22 Apr 1994). Isobars are in intervals of 0.5 hPa: (a) hour 6 (0600 UTC), (b) hour 12 (1200 UTC), and (c) hour 18 (1800 UTC).
Fig. 16. Upper-air plot for the center grid point of the inner grid at hour 18 (1800 UTC 3 Nov 1994) for case 2. Skew $T-\log p$ plot is in conventional format: temperature (°C), pressure (hPa), wind direction, and wind speed (half barb, 2.5 m s$^{-1}$; full barb, 5.0 m s$^{-1}$).

Fig. 17. Plot of wind vectors at 20 m and mean sea level pressure from the UW-NMS outer grid at hour 18 for case 2 (1800 UTC 3 Nov 1994). Isobars are in intervals of 2 hPa.

Figs. 12 and 13 include streamlines. Figure 11 is along a west-to-east line approximately 25 km south of the center of Ross Island. Figure 12 is along a south-to-north line running through the peak of Mount Terror on the eastern side of Ross Island. Figure 13 is along a south-to-north line running approximately 25 km to the east of the Mount Terror summit.

The stability in the Ross Island region is more completely understood by looking at the vertical cross sections. A layer of highly stable air is indicated by the closely spaced isentropes near the surface in all vertical cross sections (Figs. 11–13). Above the highly stable surface layer is a layer with neutral stability, highlighted by the 254-K isentropic surface. This isentropic surface shows a slight increase in height in front of Ross Island indicating the buildup of colder air in front of the barrier (Fig. 12). On the eastern side of Ross Island the 254-K isentropic surface decreases in height as the flow moves beyond the barrier (Figs. 12 and 13). Above the 254-K isentropic surface an increase in stability is observed (Figs. 11–13). On the eastern side of Ross Island (Fig. 13), the isentropic surfaces, above the highly stable surface layer, decrease in height toward the north.

With an understanding of the vertical stability, a more thorough understanding of the wind flow can be accomplished. The highly stable layer near the surface resists the vertical displacement of the surface winds, resulting in the wind flowing around the topographic features. In the layer of neutral stability the wind flow is less resistant to vertical motion and shows a slight increase in height as the wind flow encounters the barrier (Fig. 12).
Since the wind must flow around Ross Island, it splits in front of Ross Island with some of the flow traveling to the east and some to the west (Fig. 7). A region with very slow wind speeds (less than 2.5 m s$^{-1}$) is observed in the surface layer at the center of the split in the wind flow (Figs. 11 and 12). This region coincides with the location of Windless Bight. As the wind flows away from Windless Bight the wind speeds increase to around 10 m s$^{-1}$. On the eastern side of Ross Island, the wind speeds increase as the flow moves to the northern side of Ross Island (Fig. 13).

e. Additional analysis

For a more complete understanding of the characteristics of the wind flow, the Froude number was calculated upstream of Minna Bluff and upstream of Ross Island. During the initial 15 h the Froude number upstream of Ross Island is less than 0.07, and at hour 18 the Froude number is 0.1. Upstream of Minna Bluff the Froude number is approximately 0.2 during the entire simulation. These values are in agreement with previous studies indicating a highly stratified flow with the air required to move around the obstacle in the horizontal plane as it lacks the necessary energy to flow over the obstacle.

Since the wind flow does not have the energy to flow up and over Ross Island, a stagnation zone forms at the base of the center of Ross Island. The location of this stagnation zone corresponds with Windless Bight. Sloten and Steams (1987) and O’Connor and Bromwich (1988) study the characteristics of this area. As the cold air is dammed up in front of Ross Island, the isentropic surfaces increase with height (Figs. 11 and 12). The increase in height of the isentropic surface, along with the piling up of air in the area, results in an increase in
calculate the expected wind speed based on this pressure gradient. The results from the calculations show a favorable correlation with the calculated wind speeds in comparison to the actual wind speeds at the eastern Ross Island location. The calculated values for 0600, 1200, and 1800 UTC, range from 15.9 to 21.3 m s\(^{-1}\), and they are all within 2 m s\(^{-1}\) of the simulated wind speeds. The results from these calculations give strong evidence that the creation of the isolated jet streaks are directly related to the induced pressure gradient.

5. Case 2: High wind speed event

a. Overview of case

The second numerical simulation by the UW-NMS model simulates a case with high wind conditions throughout the Ross Island region. UWAAWS observations indicate that during a typical high wind speed event, the wind directions are consistently from the south with wind speeds greater than 10 m s\(^{-1}\) at all locations. A review of the UWAAWS observations during 1994 reveals 3 November as having conditions similar to a typical high wind speed event. High wind speed events during the summer months play a critical role in how scientific operations are conducted in the Ross Island region. Intercontinental flights from New Zealand and local aviation operations are significantly affected by the meteorological conditions during a high wind speed event.

The UWAAWS observations record the presence of a high wind speed event over the Ross Island region with wind directions from the southern sector over the entire region. The conditions are similar to the well-defined barrier wind event cases defined by O'Connor et al. (1994). Figure 15a shows the UWAAWS station plot for the Ross Island region at 0000 UTC 3 November 1994. Figure 15b is a time series of UWAAWS station plots for the six UWAAWS units in the inner Ross Island region, in 3-h intervals from 0000 UTC 3 November to 0000 UTC 4 November. The 24.2 m s\(^{-1}\) wind speed observation at 0000 UTC 3 November from Pegasus North AWS indicates the onset of the high wind speed event. The observations at Pegasus North AWS, Pegasus South AWS, and Willie Field AWS show wind directions consistently from the south and wind speeds greater than 10 m s\(^{-1}\), with the exception of 1800 UTC. Wind observations from Minna Bluff are missing due to hardware failures.

An upper-air sounding is not available for the period 0000 UTC 3 November to 0000 UTC 4 November 1994 due to an equipment malfunction at McMurdo station.

b. Initialization of model

The second 24-h simulation originates at 0000 UTC 3 November 1994 and ends at 0000 UTC 4 November 1994. The initialized analysis of the mean sea level...
pressure shows a north–south orientation of the isobars paralleling the Transantarctic Mountains over the western half of the domain. The isobars have a southeast to northwest orientation over the eastern half of the domain. The pressure is decreasing from west to east. The wind flow is entirely from the south with wind speeds greater than 5 m s$^{-1}$ over nearly the whole domain, and greater than 10 m s$^{-1}$ over the central area of the domain.
Figure 16 is a skew $T$-$\log p$ plot for the center grid point of the inner domain from hour 18 (1800 UTC 3 November) of the UW-NMS simulation. The lowest layer is less stable than an overlying isothermal layer. Then above the isothermal layer, the atmosphere has a large layer of air with weaker stability. These conditions match the expected atmospheric profile from previous research for a strong southerly wind flow with minimal terrain-following characteristics. The wind direction at the center grid point is from the south at the surface.
FIG. 25. Time series of horizontal cross sections around Ross Island. Plot of pressure and wind vectors, at a height of 500 m, from the UW-NMS inner grid for case 2 (3 Nov 1994). Isobars are in intervals 0.5 hPa: (a) hour 6 (0600 UTC), (b) hour 12 (1200 UTC), and (c) hour 18 (1800 UTC).

and turns progressively to the southeast with increasing height.

Hour 18 of the simulation (1800 UTC 3 November) shows a well-defined strong wind case. Figure 17 is a plot of wind vectors at 20 m and an analysis of mean sea level pressure for the outer domain at hour 18. The outer Ross Island region shows southerly wind directions over the entire northwest Ross Ice shelf. Most locations are indicating wind speeds greater than 5 m s\(^{-1}\), and the south-central portion of the outer domain has wind speeds greater than 10 m s\(^{-1}\). The variations in the wind flow around Ross Island, due to the topography, are not as well defined as in the low wind case. A feature of notable interest is the development of the mesocyclone in the Ross Sea north of Ross Island. This mesocyclone is not present in the initialized conditions.

c. Horizontal analysis

The UW-NMS simulation results for 1800 UTC 3 November are analyzed as a representation of a high wind speed event in the Ross Island region. Figures 18–20 are horizontal cross sections of pressure, wind speed, and wind vectors, from the inner model domain. Figure 18 is at a height of 20 m, Fig. 19 at a height of 250 m, and Fig. 20 at a height of 1000 m.

The horizontal cross section at 20 m (Fig. 18) indicates the characteristics of the surface wind flow. A southerly wind flow is present over the entire region south of Ross Island, indicating minimal deflection in the wind flow, due to the topography, until it reaches Ross Island. A split in the wind flow south of Ross Island is similar to what was seen in the low wind case. Light wind speeds with varying wind direction are indicated in Windless Bight. The isolated jet streaks, observed on the eastern and western edges of Ross Island in the low wind case, are even further defined in the high wind case. Locations with wind speeds greater than 20 m s\(^{-1}\) are observed in both regions. The wind flow on the eastern side of Ross Island curves to the west as it flows past Ross Island. A relatively small and less-defined wake zone appears on the northwest side of Ross Island. This surface wind flow analysis corresponds favorably to the classic meteorological study by Simpson (1919). Simpson’s streamline analysis was described as analysis during blizzard conditions, similar to a high wind speed event.

The horizontal cross section at 250 m (Fig. 19) shows the complex pattern over the Ross Island region during a high wind speed event. The wind flow at 250 m ap-
pears to be similar to that at 20 m, but with higher wind speeds. The wind is consistently from the south on the southern side of Ross Island. The size of the locations of high wind speeds, on the eastern and western edges of Ross Island, is larger at 250 m than at 20 m, and the wind speeds are faster with values exceeding 25 m s$^{-1}$. The wind flow on the northeastern side of Ross Island curves to the west as if flows past Ross Island and a wake zone is indicated on the northwest side of Ross Island.

The horizontal cross section at 1000 m (Fig. 20) provides a description of the wind flow at 1000 m. Less variance in the wind flow is indicated over the entire domain than what was seen at lower levels. South of Ross Island the wind direction is relatively constant. The locations of high wind speeds on the western and eastern edges of Ross Island are less defined. The downwind wake zone to the northeast of Ross Island has expanded from what is seen at the lower levels. This is in response to the reduction in the curvature of the wind flow on the eastern side of Ross Island. Locations of high wind speeds on the leeward sides of Minna Bluff, White Island, and Black Island are observed with locations of wind speeds greater than 20 m s$^{-1}$.

d. Vertical analysis

Further understanding of the three-dimensional wind flow during a high wind speed case is understood by analyzing the vertical structure. Similar to case 1, emphasis will be placed on studying the flow around the eastern side of Ross Island. Figures 21–23 are vertical cross sections of potential temperature and wind speed around Ross Island; Figs. 22 and 23 include streamlines. Figure 21 is along a west-to-east line approximately 25 km south of the center of Ross Island. Figure 22 is along a south-to-north line running through the peak of Mount Terror on the eastern side of Ross Island. Figure 23 is along a south-to-north line running approximately 25 km to the east of the Mount Terror summit. All of the locations for the vertical cross sections are the same as were studied in case 1, and they are indicated in Fig. 10.

An initial understanding of the wind flow is gained by analyzing the atmospheric stability in the Ross Island region. The high wind case does not have the highly stable layer near the surface as was seen in case 1. Instead sparsely spaced isentropes are observed in front of Ross Island indicating weaker static stability (Fig. 21). The isentropic surfaces increase in height as they approach Ross Island from the south (Fig. 22). The sloping of the isentropic surfaces indicates cold air damming in front of the barrier. The increase in height of the isentropic surfaces is much greater in the high wind case compared to the light wind case (Fig. 12). On the eastern side of Ross Island the isentropic surfaces show a strong decrease in height as they flow by the side of the barrier, with a low height typically observed just to the north of Ross Island. The isentropic surfaces then have a slight
increase in height continuing to the north. The streamlines indicate that the wind flow increases in height at it approaches Ross Island, but does not flow over the barrier, except at heights near the height of Ross Island (Fig. 22). As the wind flows by the barrier, the streamlines indicate that the flow decreases with height (Fig. 23). On the eastern side of Ross Island (Fig. 23) there is a large area with wind speeds greater than 20 m s$^{-1}$. The strong surface winds observed on the eastern edge of Ross Island (Fig. 23) show a favorable correlation to the development of polynyas (areas of open water surrounded by ice). The formation of polynyas due to strong surface winds in the Ross Island area is in agreement with the study by Bronwich (1988), where a strong correlation of satellite observed polynyas to high surface wind speeds is shown at McMurdo.

e. Additional analysis

The calculation of the Froude number for the high wind case shows the different characteristics of the wind flow as it encounters Ross Island and Minna Bluff. Upstream of Minna Bluff the calculated Froude number is greater than 1.5 during the entire simulation. The wind flow at this location is supercritical and it has the necessary energy to flow over the barrier. This results in a wind flow that goes over Minna Bluff, as is seen in the horizontal cross sections (Figs. 18–20). An internal gravity wave forms and it propagates downstream from Minna Bluff. Figure 24 shows the features of this gravity wave: it is a vertical cross section of potential temperature, wind speed, and streamlines along a south-to-north line over Minna Bluff and Black Island. The entire vertical upstream wind flow goes over Minna Bluff resulting in a primarily two-dimensional pattern with no horizontal deflection. This is in contrast to the wind flow encountering Ross Island, which has a primarily three-dimensional pattern with both horizontal and vertical displacement.

The Froude number for Ross Island is approximately 0.5 for the entire simulation. This indicates that the flow is subcritical and it does not have the necessary energy to flow over the barrier. The cold air damming at the base of Ross Island remains present, and it is amplified in the high wind case due to the larger wind speeds and increased airflow that is forced up against the barrier. This is in agreement with the vertical cross sections (Figs. 21–23), which show a more pronounced elevation of the isentropes in front of Ross Island. Figure 25 is a time series (0600, 1200, and 1800 UTC) of horizontal cross sections around Ross Island. The plots are analyses of pressure and wind vectors valid for each model time. There is an increase in pressure at Windless Bight from 0600 through 1800 UTC. The higher pressure at Windless Bight creates a negative pressure gradient force acting to slow the approaching wind flow, resulting in a decreasing wind speed in Windless Bight. The wind speeds in Windless Bight are not as low as was seen in the low wind case because the incoming wind flow has a higher initial wind speed. As the wind flow enters the stagnation zone, Windless Bight, it is now located at a relatively high pressure, with an induced pressure gradient toward the eastern and western edges of Ross Island. The wind flow then accelerates toward the terrain-induced low pressure perturbations on the eastern and western edges of Ross Island. As the wind flows away from Windless Bight, the isentropic surfaces decrease and the wind flow decreases in height (Fig. 23). The subsidence, from the decrease in height, results in a hydrostatically lower pressure on the eastern and western edges, which amplifies the pressure gradient between Windless Bight and the western and eastern edges of Ross Island.

The acceleration of the wind flow due to the pressure gradient between Windless Bight and the western edge of Ross Island is analyzed using the integrated form of the simplified equation of motion (4). The selected model grid point on the western side of Ross Island is near the center of the high wind speed region. The calculated
values for the wind speed show a strong correlation to the actual modeled wind speed. Calculated values for the western grid point range between 18.1 and 25.0 m \( \text{s}^{-1} \) from 0600 to 18 UTC, with all of the values within 1 m \( \text{s}^{-1} \) of the model results. These results confidently show that the primary forcing for the locations of high wind speed is the topographically induced pressure gradient between the windward and leeward sides of Ross Island.

Figure 26 is a vertical cross section of streamlines, potential temperature, and wind speed from the north-west to the southeast on the southwestern side of Ross Island (Fig. 10). This cross section is useful in diagnosing the vertical structure as the wind flows from Windless Bight to the location of high wind speeds on the western side of Ross Island. The isentropes decrease in height from the southern side to the northwestern side of Ross Island. This decrease in height is the result of the airflow moving away from cold air damming in Windless Bight and the stretching of the isentropic surfaces as the wind flow increases in speed as it flows around Ross Island. The decrease in height of the isentropic surfaces accompanies a decrease in the hydrostatic pressure, resulting in a leeward-side pressure perturbation. It is this leeward-side pressure perturbation, in combination with the windward-side pressure perturbation at Windless Bight, that causes the strong pressure gradient between the two locations, inducing the large acceleration of the wind flow on the western side of Ross Island.

6. Conclusions

A detailed three-dimensional understanding of the wind flow in the Ross Island region, Antarctica, can be concluded based on the numerical simulations from the UW-NMS model and previous research. The wind flow in this region is characterized by the harsh topographical features and the extreme Antarctic meteorological environment.

An analysis of UWAAWS data in the region, and previous research, shows that a bimodal wind regime exists. The first regime involves a strongly stable lower atmosphere and light winds having terrain-following characteristics throughout the region. The second regime is a high wind speed event with predominantly southerly wind flow and high wind speeds over the entire region.

Figure 27a shows the three-dimensional wind flow pattern during conditions with light wind speeds and a strongly stable lower atmosphere. Near the surface the strongly stable conditions resist vertical motion, and whenever the wind flow encounters a barrier, it must flow around the barrier. Above the stable surface layer the conditions are less stable, allowing for some vertical displacement of the wind flow. However the light wind speeds allow for only minimal vertical motion and the wind flow is still primarily around the barriers. The wind flow above the stable surface layer is able to flow over Minna Bluff with little deflection; once north of Minna Bluff the wind flow has little vertical motion. Some of the wind flow during the light wind case originates as katabatic flow down the glaciers in the Transantarctic Mountains.

Figure 27b shows the three-dimensional wind flow pattern during a high wind speed event in the Ross Island region. The strongly stable surface layer, as seen in the low wind case, does not exist and the wind flow is able to have a large amount of vertical motion. The wind is able to flow over Minna Bluff at all levels and creates a region with propagating gravity waves downstream of Minna Bluff. The wind flow is able to flow over minor barriers such as White Island, Black Island, and Hut Point Peninsula. However, the wind flow still does not have the necessary energy to flow over Ross Island, resulting in air piling up in front of Ross Island. The piling up of air increases the heights of the isentropic surfaces in the Windless Bight region, resulting in an increase in the hydrostatic pressure in that region. As the wind flow approaches the Ross Island barrier, it has a large rise in height, and then splits and flows around Ross Island. The isentropic surfaces rapidly decrease in height as the wind flows past the Ross Island barrier, resulting in locations of hydrostatically low pressure.

Calculations of the Froude number indicate that the flow is subcritical \((F_r < 1)\) throughout the region in the light wind case. The airflow lacks the kinetic energy to flow up and over the obstacles and so it remains in the horizontal plane flowing around the obstacle. In the high wind case the flow is supercritical \((F_r > 1)\) at some locations, including upstream of Minna Bluff. At these locations the air has the necessary energy to flow over the mountain, resulting in a linearized two-dimensional flow, typically producing strong gravity waves. Upstream of Ross Island the flow remains subcritical as it does not have the energy to flow over the island but must instead flow around it.

Locations of high wind speeds on the eastern and western edges of Ross Island are observed in both the light wind case and the high wind case. The acceleration of the wind flow from Windless Bight to the sides of Ross Island is the result of a strong topographically induced pressure gradient between the windward and the leeward sides of Ross Island. The pressure gradient is created by an increase in pressure in the Windless Bight region as a stagnation zone forms due to the damming up of cold air at the base of Ross Island. On the western and eastern edges of Ross Island, regions of low hydrostatic pressure are formed as the flow is decreasing in height due to the decreasing height of the potential surface levels from Windless Bight toward these regions.

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