4.2 REAL-TIME MESOSCALE NWP IN SUPPORT OF ANTARCTIC SCIENCE AND OPERATIONS

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1. INTRODUCTION

Logistical and scientific operations in Antarctica are critically dependent on numerical weather guidance. To the operation of real-time mesoscale numerical weather prediction (NWP) models, the challenges Antarctica presents include poor first-guess and boundary condition sources, the shortage of conventional meteorological observations over the continent and Southern Ocean, and the polar atmosphere itself, to which models generally have not been tuned.

In September 2000, the Antarctic Mesoscale Prediction System (AMPS) (Powers et al. 2001; Powers et al. 2003) began providing numerical forecasts for Antarctica (see Fig. 1) and, in particular, the McMurdo Station area (Figs. 2(a), (d)). Funded by the National Science Foundation, AMPS has been an experimental real-time mesoscale modeling system using the Polar MM5 (Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research Mesocale Model [Grell et al. 1995]) (described below). The system has been producing forecasts in support of the United States Antarctic Program (USAP) and a broad range of international activities. The history of AMPS itself dates from May 2000 and the assembly of the Antarctic Weather Forecasting Workshop (AWFW) at the Byrd Polar Research Center (BPRC) of The Ohio State University. It was formally recognized at the AWFW that output from NWP models was critical to forecasters at McMurdo Station (see Fig. 2(c)), who provide the forecasts controlling USAP flights to/from McMurdo and over the continent. At the time, two versions of the MM5 addressing the Antarctic semi-operationally were being run at BPRC (60-km, with the Polar MM5) and the Air Force Weather Agency (AFWA) (45-km). Although global models were also available, their guidance was felt to be of limited utility. The reasons included: (i) horizontal resolutions inadequate to resolve mesoscale features crucially affecting short-term (6–24 hr) forecasting and flight operations, (ii) inadequate representation of physical properties unique to the Antarctic troposphere and boundary layer, and (iii) poor representation of Antarctic topography and surface features (Bromwich and Cassano 2000).

Foremost among the AWFW's recommendations to the National Science Foundation (NSF) for improving NWP capabilities for the USAP were an Antarctic mesoscale modeling initiative and the implementation of a higher-resolution Antarctic forecast domain (i.e., grid sizes ≤15 km) (Bromwich and Cassano 2000). Other key recommendations to NSF from the AWFW addressed: (i) the need for a robust capability offering a flexible product suite tailored to the evolving requirements of the forecasters, (ii) implementing a research program for improving model physical parameterizations for use in the Antarctic, and (iii) performing verification.

From these needs identified at the AWFW, the AMPS Project was conceived. The principals have been the Mesoscale and Microscale Meteorology (MMM) Division of the National Center for Atmospheric Research (NCAR) and the Polar Meteorology Group, a member of BPRC. NSF has provided the support. Since September 2000, AMPS has been furnishing twice-daily numerical guidance for Antarctica and the McMurdo Station area. Foremost, it has served flight forecasters guiding aircraft missions between Christchurch, New Zealand and McMurdo Station and between McMurdo and the South Pole.

Since AMPS's inception the McMurdo forecasters have provided feedback, and the system has been regularly upgraded. Beyond its expected use for forecast guidance, however, special applications have figured prominently. These have included a scientific field campaign, medical and marine rescues, and support for a host of international facilities. This paper summarizes AMPS's mesoscale NWP in support of such international Antarctic science and operations.

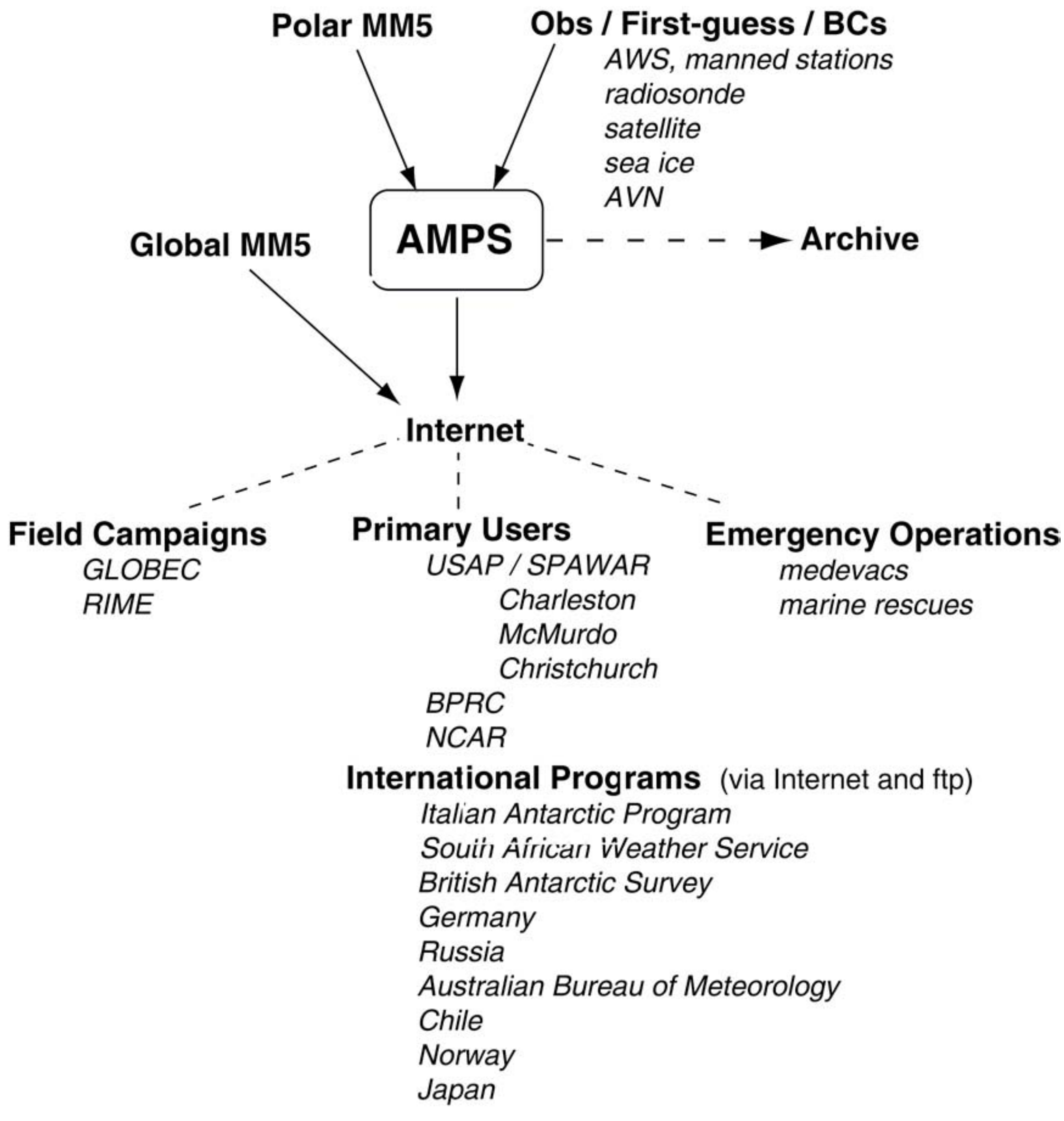

Fig. 1: Schematic of AMPS: input, output, and users and programs (e.g., meteorological services, field programs, installations, etc.) served. Obs= observations; BCs= boundary conditions. For other abbreviations, see text.

2. THE NWP SYSTEM

2.1 *Configuration*

The model used in AMPS is the MM5 (Grell et al. 1995). The current setup has five grids, with horizontal spacings of 90 km, 30 km, 10 km (2 grids), and 3.3 km. The 90-km domain (Fig. 2(a)) includes New Zealand, as Christchurch is the origin of flights to McMurdo. Covering Antarctica, the 30-km domain (Fig. 2(b)) reflects the users' desire that the entire continent be contained in a mesoscale grid with better resolution, topographic data, and landuse information than available in other models when the system was created. The first 10-km grid (Fig. 2(b)) was designed to cover the McMurdo Station area with, when the project began, the highest resolution practicable given the computer resources.

For focussing on conditions over the South Pole (for the several hundred flights flown there annually), another 10-km grid was added (Fig. 2(b)) to cover that area. In addition, to bring the flows and resulting structures around Ross Island into still better focus, a 3.3-km grid was nested within the 10-km McMurdo/Ross Is. domain (Fig. 2(c)).

All nesting is two-way interactive. The vertical resolution reflects 29 σ-levels between the ground and the model top at 100 mb. Model initializations are at 0000 and 1200 UTC. Forecast lengths are 72 hours for the 90-km and 30-km grids, and 36 hours for the 10-km and 3.3-km grids.

The AMPS MM5's initial and boundary conditions are derived from NCEP's (National Centers for Environmental Prediction) global spectral (AVN) model. The AVN first-guess field is objectively reanalyzed with the available observations using a multiquadric technique (Nuss and Titley 1994). The data within the domains include reports from manned surface stations, surface automatic weather stations (AWSs), upper-air stations, and satellite cloud-track winds. The system ingests sea ice data daily from the National Snow and Ice Data Center for initializing its fractional sea ice depiction.

Associated with AMPS is a global implementation of the MM5 (the "Global MM5" [GMM5]; Dudhia and Bresch 2002) which produces 5-day forecasts twice a day. Its role in AMPS is to provide a longer-range look at conditions over the continent.

AMPS employs the "Polar MM5" (Bromwich et al 2001; Cassano et al. 2001). This is a version of the model which has been developed by BPRC and contains modifications to a number of key physical schemes to improve their performance in the polar regions and to capture features unique to extensive ice sheets, such as steep coastal margins and lack of conventional soil and vegetation types. The Polar MM5 (PMM5) modifications include the following:

(i) accounting for a separate sea ice category with specified thermal properties;
(ii) representing fractional sea ice coverage in grid cells;
(iii) using the latent heat of sublimation for calculations of latent heat fluxes over ice surfaces, and assuming ice saturation when calculating surface saturation mixing ratios over ice; and
(iv) modification of the CCM2 (Community Climate Model 2) radiation scheme to include the radiative properties of clouds as determined from the model's microphysical species (as opposed to relative humidity).

Details on the PMM5 may be found in Bromwich et al. (2001) and Cassano et al. (2001).

Users may access the range of AMPS products via the Internet at http://www.mmm.ucar.edu/rt/mm5/amps. To support verification work, as well as scientist and graduate student research, there is an archive of the AMPS forecasts. The AMPS archive is open to the public, and the web page provides information on it.

Figure 1 shows AMPS in relation to inputs and users (explained below). The main user interface is the Internet, although the archive may be accessed by those working on verification, case studies, or climatologies.

Tight coordination is maintained with the primary user, the Space and Naval Warfare Systems Center (SPAWAR), headquartered in Charleston, South Carolina. SPAWAR is responsible for forecasting for the USAP, which is done primarily from its weather office at McMurdo Station, Antarctica. SPAWAR provides feedback on desired products, enhancement priorities, and model performance in significant weather events.

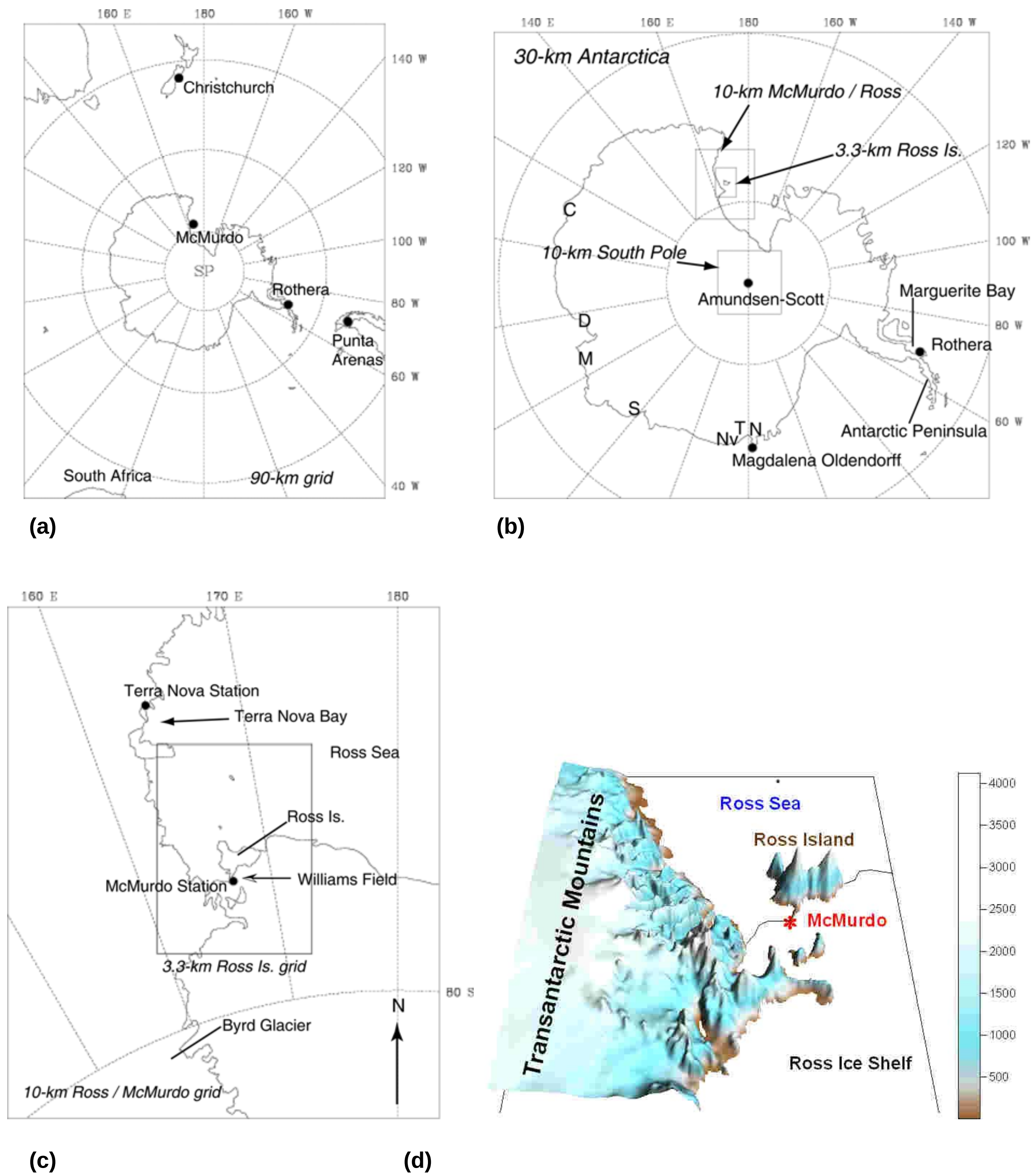

Fig. 2: AMPS domains and Antarctic locations. (a) 90-km grid. (b) 30-km grid (outer frame) and 10-km McMurdo/Ross grid and 10-km South Pole grid. Locations of stations mentioned in text indicated. N= Neumayer, Nv= Novolazarevskaya, T=Troll, S= Syowa, C=Casey, D= Davis, M= Mawson. (c) 10-km McMurdo/Ross grid and 3.3-km Ross Island grid. (d) 3-D view of topography (m) of the Ross Island region. The Transantarctic Mtns. exceed 2000 m, while the two main peaks of Ross Is. each exceed 3200 m. East–West dimension of Ross Is. is approximately 75 km.

2.2 *System performance*

System performance is monitored and evaluated in two main ways. The first is through the daily scrutiny of forecasts by SPAWAR. SPAWAR apprises the development team of forecast hits and misses, as well as areas for improvement. Second, systematic verifications are undertaken. These have been both event-based (Bromwich et al. 2003; Monaghan et al. 2003) as well as seasonal. The users' experience thus far has been that AMPS's fine resolution does capture the flight-critical, near-surface variations in temperature, humidity, and wind (Cayette 2002). During the 2001–2002 field season at McMurdo, for example, AMPS provided significant contributions to operational forecasts on 44 of the observed 53 occurrences of "poor weather", meaning conditions such as fog, snow, blowing snow, and low cloud layers that hamper or threaten flight operations (Cayette 2002). This represents a capability and a level of assistance not previously available.

Case verification is also undertaken. One of the scenarios of concern in the Ross Island region is mesoscale cyclogenesis. This is troublesome because it can produce conditions hazardous to McMurdo flight operations and threaten "turn-backs": the retreat of McMurdo-bound aircraft to Christchurch due to the bad weather at the station. In a particular case of mesoscale cyclogenesis affecting McMurdo and its flights, Bromwich et al. (2003) found that the AMPS configuration featuring the 10-km Ross Island grid [1] reproduced well the evolution of upper-level conditions and showed skill in resolving the small-scale surface features endemic to the region, such as katabatic winds and mesolows/highs induced by topography. They also found, however, that the AMPS first-guess field (from the AVN) could impart a particularly lasting impression on the forecast. The lack of conventional observations over Antarctica was seen to be influential (Bromwich et al. 2003). Exploring 3-dimensional variational data assimilation (3DVAR) as a means to ingest indirect observations, such as GPS radio occultations, is a key element of AMPS's next phase.

[1] The case was from January 2001, before the implementation of the 3.3-km domain.

3. SPECIAL APPLICATIONS

3.1 *Forecasting for the U.S. Antarctic Program*

One of the original goals for AMPS was to provide real-time mesoscale products for Antarctica, tailored to the needs of field forecasters at McMurdo Station. These meteorologists are from SPAWAR, which provides forecasting services for the USAP and the flight operations to/from McMurdo and across the continent (e.g., McMurdo–South Pole) that the USAP oversees. Prior to AMPS, SPAWAR relied upon the global models available to it such NCEP's AVN, NCEP's Medium-Range Forecast Model, and the U.S. Navy's global NOGAPS. It also received forecast products from a 45-km MM5 AFWA grid over Antarctica and, starting in January 2000, a 60-km version of the PMM5 run at BPRC. SPAWAR found the implementation of AMPS, however, to allow the McMurdo Meteorology Office to forecast events for longer periods with greater accuracy.

One focal point for which the need for detail is constant is Williams Field, the USAP airstrip McMurdo uses most. Figure 3 presents examples of products tailored for the activity there: time series of surface temperature, wind, and pressure (Fig. 3(a)) and moisture and wind parameters (Fig. 3(b)). One of the special products is the cross-field wind component at Williams, shown as the solid, dark curve in Fig. 3(b). This is important output for landings and take-offs, where crosswinds above a 15 kt threshold will preclude either for aircraft with skis.

AMPS supports both the main season (summer) work of SPAWAR, as well as the first fly-ins in the late winter. The latter missions are part of "WINFLY", or winter fly-in, in which the initial flights to McMurdo Station following the fall/winter isolation period are dispatched. "Main body" flights usually commence around the beginning of October and bring the bulk of the approximately 1000 scientists and support staff to the station.

The stakes are high in forecasting for the flights from New Zealand, and not only

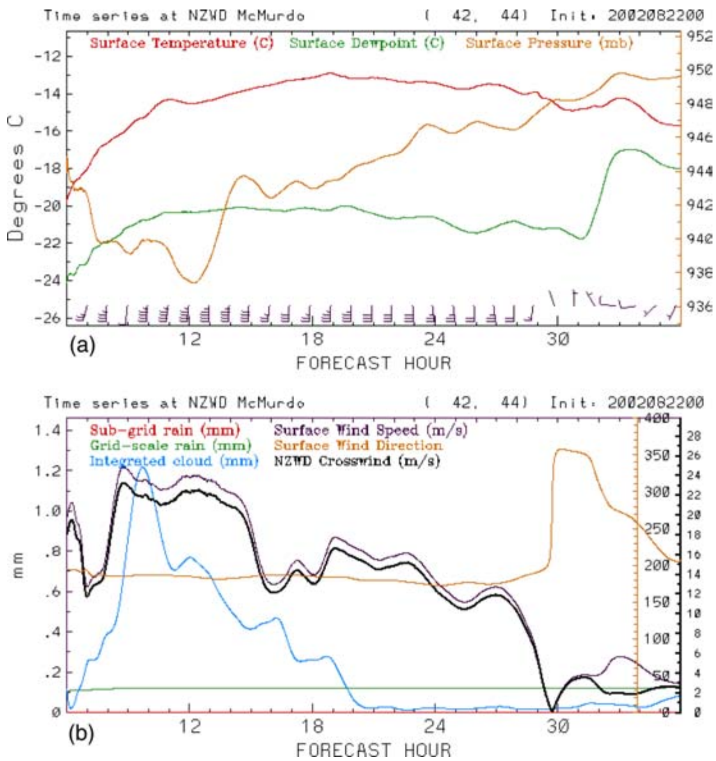

Fig. 3: Surface time series at Williams Field from 3.3-k grid for forecast initialized 22 August 2002. 3.3-km grid at this time ran for hours 6–36. (a) Temperature (red, °C, scale to left), dewpoint (green, °C, scale to left), pressure (orange, hPa, scale to right), and wind (barbs). (b) Wind speed (purple, light, m/s, scale to right), crosswind component at Williams Field (black, heavy, m/s, scale to right), surface wind direction (orange, deg., scale to right), and integrated cloud water & ice (blue, mm, scale to left). Accumulated sub-grid scale precipitation (red, mm, scale to left) and grid-scale precipitation (green, mm, scale to left) also shown. Note that in this region, references to "rain" in the figure are actually to precipitation that falls as snow.

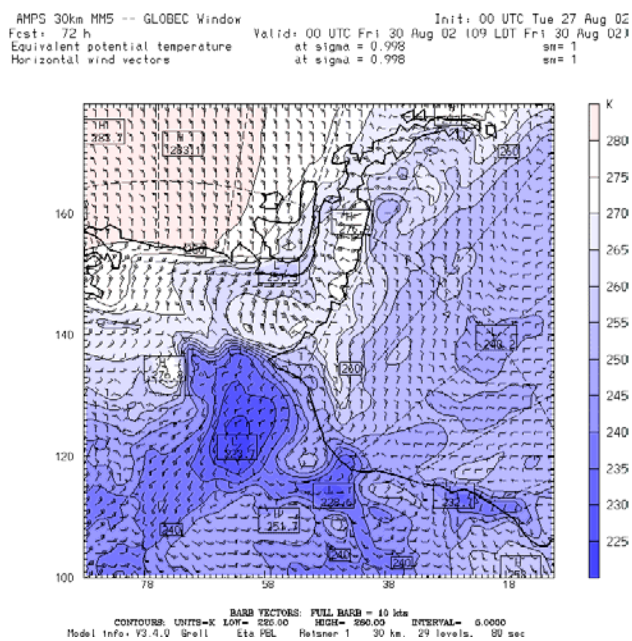

Fig. 4: Example of GLOBEC plot window. Surface wind (barbs, full barb= 10 kt) and θ_e (shaded, K, scale to right) from 72-hr AMPS forecast shown. Output from 30-km AMPS domain analyzed. Forecast initialized at 00 UTC 27 Aug 2002, valid 00 UTC 30 Aug 2002.

because of the dangers of forced landings in adverse conditions. The costs of a mission which has been given a go-ahead, but which must abort and return to Christchurch run approximately $85,000. As for recalled Pole flights, the cost is about $35,000 each. Thus, by avoiding turn-backs by rescheduling flights on the basis of accurate forecasts, AMPS works for the efficient use of resources and helps to pay for itself.

3.2 *Support of field programs and international science*

In addition to flight and operation forecasting, AMPS has supported scientific field programs. The first of these was the GLOBEC (Global Ocean Ecosystem Dynamics) Program: an international effort to address the question of how global climate change may affect the abundance and production of animals in the sea. In part, GLOBEC includes sailings of research vessels, such as the National Science Foundation's *Laurence M. Gould*, to the Antarctic Peninsula and the Marguerite Bay region (see Fig. 2(b)). In support of this, AMPS has provided a suite of products covering this area for requested periods. Figure 4 offers an example of a GLOBEC 72-hr prog of surface θ_e and wind.

AMPS's supporting of international science in Antarctica also takes the form of providing products to the Italian National Antarctic Research Program (PNRA). PNRA maintains a station at Terra Nova Bay (TNB) (Fig. 2(c)) and requested a subset of AMPS products for its forecasting operations, which support both supply flights conducted by the Italian Air Force and research activities in the area. The reduced product set is ftp'd to the TNB facility because it has only limited satellite Internet connectivity (approx. 30 min twice a day).

In addition to the TNB support, AMPS provides a special product suite for the British Antarctic Survey at Rothera and Germany's Neumayer Station (Fig. 2(b)). Furthermore, posted on the web are products tailored for the Australian Bureau of Meteorology's Casey, Davis, and Mawson stations, as well as time series for bases of Russia (Novolazarevskaya), Japan (Syowa), and Norway (Troll) (see Fig. 2(b) and caption).

A planned international field campaign that AMPS stands poised to support is RIME, the Ross Island Meteorology Experiment (Parish and Bromwich 2002). A primary goal of RIME is to explore the atmospheric processes over Antarctica and their interactions with lower latitudes through the Ross Sea sector. Because it is already focussed on the Ross Island area, AMPS could readily provide flight or ground operation forecasts for RIME. Second, existing high-resolution AMPS datasets from the archive could be used to identify locations where observations may be valuable for revealing local terrain-induced phenomena and instrument siting. Third, the AMPS MM5 can be used to assimilate field data collected during intensive observing periods, and thus provide high-resolution mesoscale gridded datasets for analysis.

The AMPS goal of stimulating collaboration between forecasters, modelers, and researchers in part has been achieved through visits by BPRC students/researchers to McMurdo each field season to interact with forecasters and get feedback on the Polar MM5 and the AMPS interface. Workshops have also advanced this objective. These have taken the form of the AMPS Users' Workshop in June 2001 and the Antarctic Numerical Weather Prediction and Forecasting Workshop in June 2002, both held at NCAR. Most recently, the Workshop on Antarctic Numerical Weather Forecasting for Operations in October 2002 focussed on AMPS. This workshop was held to stimulate international collaboration in AMPS and in Antarctic forecasting and modeling.

3.3 *Assisting in emergencies— Rescues*

3.3.1) SHEMENSKI SOUTH POLE RESCUE OF APRIL 2001

In April 2001, an unprecedented late-season flight was attempted under international coordination to rescue an ailing American doctor from the South Pole. Although originally intending to winter over (i.e., remain for the February–October period), Dr. Ronald Shemenski, the staff physician at Amundsen-Scott Station, came to exhibit pancreatitis and was suffering from gallstones. In light of the advancing calendar and the risks of being locked in with untreatable complications, NSF initiated an effort to get a plane to the Pole to evacuate Dr. Shemenski. The mission was daunting, however, with the dangers of landing at that time of year being frequent blowing snow conditions, marginal aircraft operating temperatures, and darkness and absence of a lighted runway. Ultimately, two small, twin-prop Twin Otter aircraft were dispatched to the British Antarctic Survey's Rothera Station on the Antarctic Peninsula (Fig. 2(b)). There they awaited the forecast of a favorable weather window for the 10-hour flight to the pole; the landing, crew rest, and loading; and the take-off and return to Rothera.

It was primarily during the over-continent stage that AMPS served in the flight forecasting and rescue planning. The 5-day Global MM5 runs provided long-range outlooks, while the shorter 30-km AMPS domain (the finest grid over the Pole at the time) gave more detailed views along the flight route and over the Pole. The most important forecasting concern was the prediction of blowing snow at the Pole. Both AMPS and the ECMWF global were found to have accurately predicted the cessation of the blowing snow event on 24 April, which signaled the beginning of the evacuation window (Monaghan et al. 2003). In addition to forecast time series of surface winds, AMPS's horizontal plots also indicated acceptable conditions over the area.

After waiting out the unfavorable period, one of the planes departed Rothera at 1434 UTC 24 April and after 9.5 hours arrived safely at Amundsen-Scott. With Dr. Shemenski safely aboard, the aircraft took off at 1647 UTC on 25 April and returned to Rothera safely. The return journey to the U.S. was without incident.

In commending the multinational rescue team, Dr. Karl Erb, Director of NSF's Office of Polar Programs, referred to the contributions of the SPAWAR forecasters, AMPS (run at NCAR), and other meteorologists involved in the effort thusly:

> "[As] in any operation in Antarctica, where weather cannot be ignored, the Space and Naval Warfare Systems (SPAWAR) Center in Charleston, S.C., was instrumental in providing up-to-the minute weather forecasting, that optimized the chances for success. The National Center for Atmospheric Research (NCAR), meteorologists at the University of Wisconsin, and on the ground at McMurdo and South Pole station as well as British meteorologists also helped accomplish the difficult task of evaluating complex weather patterns during a continental flight." (Erb 2001)

3.3.2) MAGDALENA OLDENDORFF RESCUE OF JUNE–JULY 2002

In June 2002, the German supply ship *Magdalena Oldendorff* was servicing research stations along the Queen Maud Land coast when it became trapped in thickening sea ice. Headed for Cape Town, South Africa from the Russian base of Novolazarevskaya, the ship became ice-bound with a crew of 28 and a complement of approximately 79 Russian scientists. Ultimately, the *Oldendorff* sat stuck at 69.93^{o}S, 1.43^{o}W (location shown in Fig. 2(b)) in Muskegbukta Bay.

Upon a call for assistance, South Africa sent its ice-strengthened Antarctic supply and oceanographic research vessel *Agulhas* to rescue the scientists and crew. It left Cape Town on June 16 and by the end of June was in position to use its helicopter to pluck the scientists and crew from the *Oldendorff*.

Aware of the effort of the South African Weather Service in forecasting for the *Agulhas*, NCAR expanded AMPS's 90-km grid northward to South Africa. In addition, AMPS generated special products. A window of model output focussed on the *Oldendorff* showed the local conditions in detail, while time series of surface weather for the location of the *Oldendorff* were also produced.

On its southward voyage, the *Agulhas* encountered rough weather from a low that was accurately forecast by AMPS. This is reflected in Fig. 5, which shows the 39-h forecast from the 00 UTC 22 June initialization (valid 15 UTC 23 June). In a statement of 26 June 2002, the South African Weather Service announced:

> "The passage and intensification of the low pressure system which caused much discomfort aboard the *Agulhas* was very well predicted by the regional model [AMPS]. The ship at this time was positioned just to the north-west of the 934 hPa vortex [marked by 'X' in plot]. The [shading] indicate[s] precipitation— in this case snow. The *Agulhas* reported heavy snow in its

18h00 UTC observation with the wind backed into the south-west." (Hunter 2002)

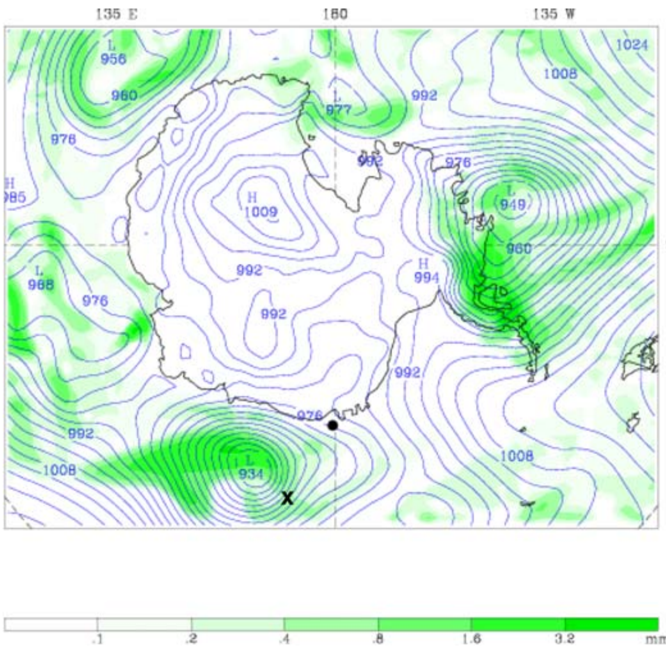

Fig. 5: Sea level pressure (contoured, interval= 4 hPa) and 3-hourly precipitation (shaded, mm) for Hr 39 of 00 UTC 22 June 2002 forecast. 90-km grid output plotted; window of full grid shown. Forecast valid 15 UTC 23 June 2002. Dot marks position of Magdalena Oldendorff, while "X" marks the position of the Agulhas. Deep low 934 hPa southeast of Agulhas seen.

Blizzard conditions hampered the rescue mission on several occasions. While AMPS did forecast such conditions, it also predicted a brief window of favorable weather for July 1, allowing for the final helicopter airlifts to remove the last of the scientists and crew. The *Agulhas* successfully returned to Cape Town on July 10. The *Oldendorff* herself, however, remained in the ice for the duration of the winter.

4. SUMMARY

Under support from the National Science Foundation (NSF), the Antarctic Mesoscale Prediction System (AMPS) has been providing real-time mesoscale model forecasts for Antarctica since September 2000. The principals have been NCAR and the Byrd Polar Research Center (BPRC) of The Ohio State University. The system is built around the Polar MM5, a version of the Fifth-Generation Pennsylvania State University/NCAR Mesoscale Model adapted at BPRC for better performance in polar environments. AMPS's configuration consists of grids of horizontal spacings of 90 km, 30 km, 10 km (two domains), and 3.3 km. The products posted to the AMPS web page (http://www.mmm.ucar.edu/rt/mm5/amps) cover a broad spectrum.

AMPS was originally developed as an experimental system to assist meteorologists at McMurdo Station forecasting for McMurdo–Christchurch and McMurdo–South Pole flights. Over time, however, AMPS has grown to serve many international scientific and logistical activities: these include the Italian Antarctic Program at Terra Nova Bay, the GLOBEC Program around the Antarctic Peninsula, and the operations of British, German, and other stations around the continental margin. Moreover, it has repeatedly assisted in emergency rescue operations: the medevac of Dr. Ronald Shemenski from the South Pole in April 2001 and the mission of the South African ship *Agulhas* to retrieve the crew and scientists aboard the *Magdalena Oldendorff* in June/July 2002.

AMPS is a resource available to all with interests in Antarctic NWP and forecasting. The AMPS community encourages international collaboration in all facets of this system, and, more generally, in polar NWP and meteorology. It is envisioned that AMPS and its collaborations will continue to provide high-resolution mesoscale guidance to Antarctic forecasters and to support field campaigns, scientific operations, and emergency efforts.

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