REAL-TIME MESOSCALE MODELING OVER ANTARCTICA

The Antarctic Mesoscale Prediction System*

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A real-time, high-resolution forecast system serves Antarctic science efforts and emergency operations, while advancing polar numerical weather prediction.

Logistical and scientific operations in Antarctica are critically dependent on numerical weather guidance. The extreme, unforgiving environment amplifies the risks stemming from poor forecasts, while the sparse observing network often leaves forecasters heavily reliant on numerical weather prediction (NWP). To the operation of real-time mesoscale (i.e., limited area) models, Antarctica likewise presents unique challenges. The difficulties 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.

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In September 2000, the Antarctic Mesoscale Predication System (AMPS; Powers et al. 2001) began providing numerical forecasts for Antarctica (see Fig. 1)

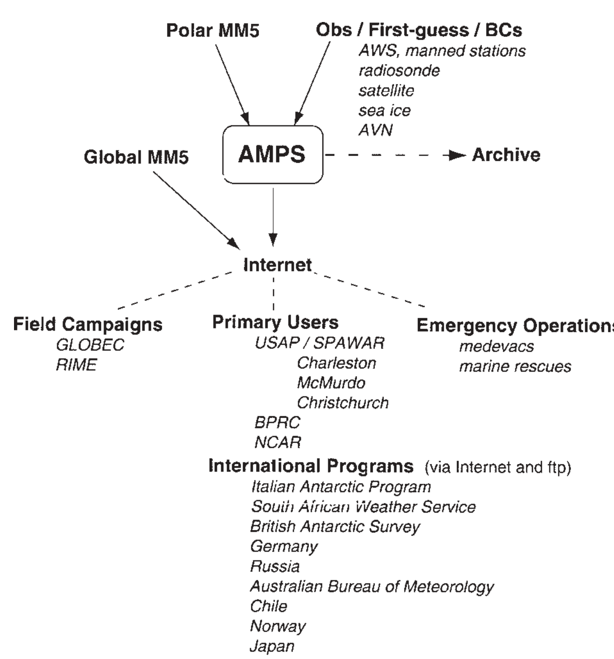

FIG. 1. Schematic of AMPS: input, output, and users and programs (e.g., meteorological services, field programs, installations, etc.) served; Obs = observations; BCs = boundary conditions. For other abbreviations, see text.

and, in particular, the McMurdo Station area (see Figs. 2a and 2d). Funded by the National Science Foundation, AMPS has been an experimental real-time mesoscale modeling system in which the Polar MM5 [fifth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model; Grell et al. 1995] has been generating forecasts in support of the United States Antarctic Program (USAP) and a broad range of international activities.

While efforts to tune the MM5 for polar conditions had been initiated earlier, AMPS itself was conceived

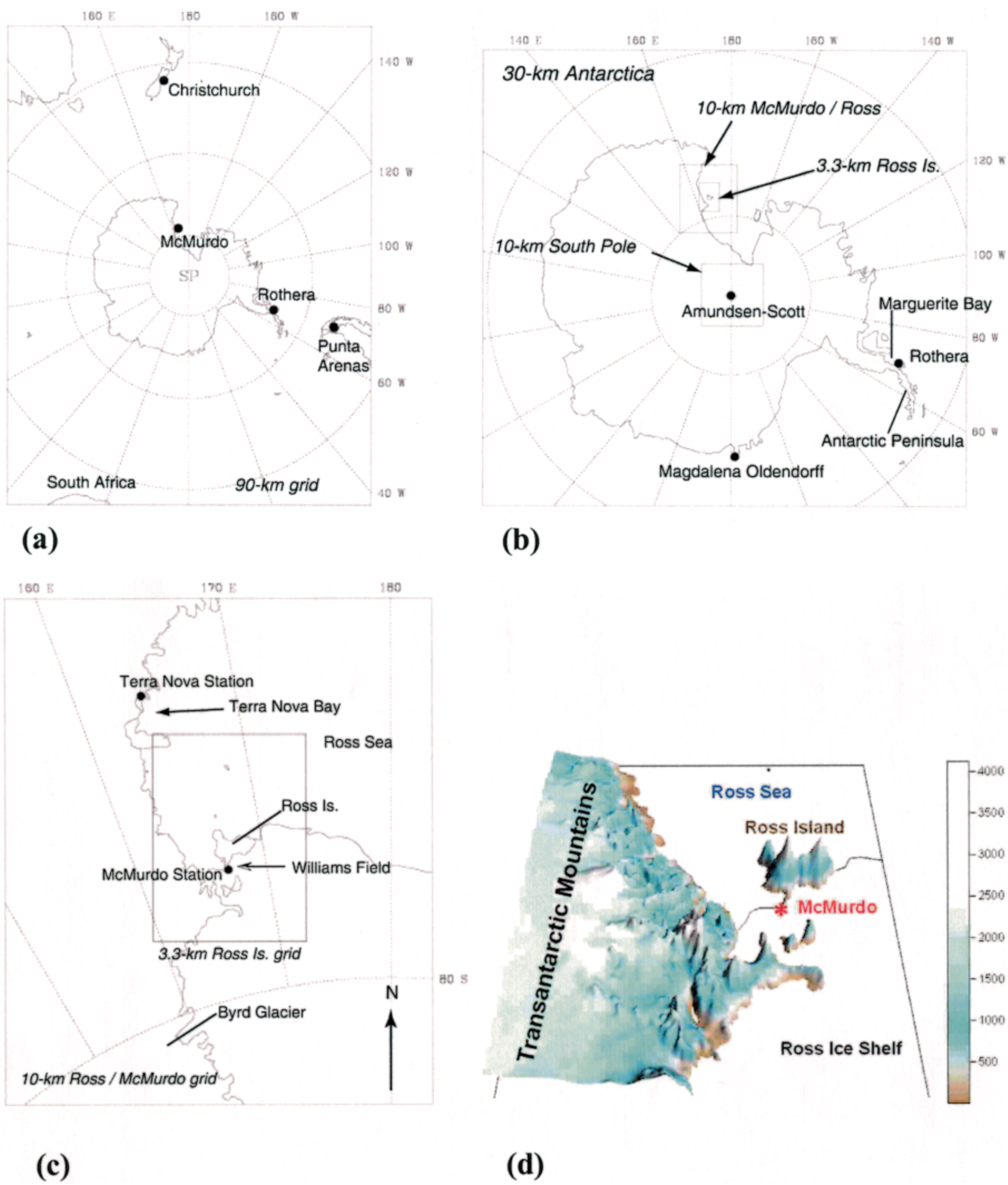

Fig. 2. AMPS domains and Antarctic locations: (a) 90-km grid; (b) 30-km grid (outer frame), 10-km McMurdo/Ross grid, 10-km South Pole grid; (c) 10-km McMurdo–Ross grid and 3.3-km Ross Island grid; (d) 3D depiction of topography (m) of the Ross Island region. The Transantarctic Mountains exceed 2000 m, while the two main peaks of Ross Island each exceed 3200 m. East–west dimension of Ross Island is approximately 75 km.

from the recommendations of the May 2000 Antarctic Weather Forecasting Workshop held at the Byrd Polar Research Center (BPRC) of The Ohio State University. Workshop participants formally recognized that NWP was critical to forecasters at McMurdo Station (see Fig. 2c), who provide forecasts for USAP flights to and from McMurdo and over the continent. At this time (the 1999–2000 field season), forecasters at McMurdo had been consulting two versions of the MM5, run in real time at BPRC and the Air Force Weather Agency (AFWA). The former utilized the Polar MM5 (described below); its development by BPRC was stimulated by a medical emergency at the South Pole in October–November 1999 (Nielsen 2001). Global models, also available, were felt to be of limited utility because of (i) horizontal resolutions inadequate to resolve mesoscale features crucial to short-term (6–24 h) 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 workshop'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 size of ≤ 15 km; Bromwich and Cassano 2000). This concern over resolution stems from the inherently mesoscale nature of the phenomena to be forecast in McMurdo, where elevations run from sea level to greater than 3000 m over distances of tens of kilometers (see Fig. 2d). Figure 3 presents a surface analysis of a cyclonically forced barrier wind event at Ross Island (from O'Connor et al. 1994) in which the scales of the lows are on the order of 200–250 km, with the smaller mesohigh having a scale of 60 km. The workshop also addressed needs for (i) a robust modeling capability with the flexibility to tailor products to the evolving requirements and preferences of the forecasters, (ii) research to improve model physical parameterizations for use in the Antarctic, and (iii) verification.

AMPS was originally designed as a 2-yr experiment, with the system based at NCAR in Boulder, Colorado. The principals have been the Mesoscale and Microscale Meteorology (MMM) Division of NCAR and the Polar Meteorology Group of BPRC. Since September 2000, AMPS has been furnishing twice-daily numerical guidance for Antarctica and the McMurdo area. Foremost, it has served guiding flights between Christchurch, New Zealand; McMurdo; and the South Pole. The AMPS project has aimed to

1) provide real-time mesoscale and synoptic model products for Antarctica, tailored to the needs of field forecasters at McMurdo Station;
2) improve and incorporate model physical parameterizations suitable for the Antarctic region;
3) perform qualitative and quantitative system verification; and
4) stimulate close collaboration between forecasters, modelers, and researchers by providing model output to the community through a Web interface, an archive, and workshops.

AMPS has been eagerly received by the forecasters at McMurdo, and their crucial feedback has led to regular system upgrades. In addition, special applications have figured prominently. These have included a South Pole evacuation, a marine rescue, and an international field campaign. Now that the first phase of AMPS is complete, this paper aims to describe these developments in Antarctic NWP and sci-

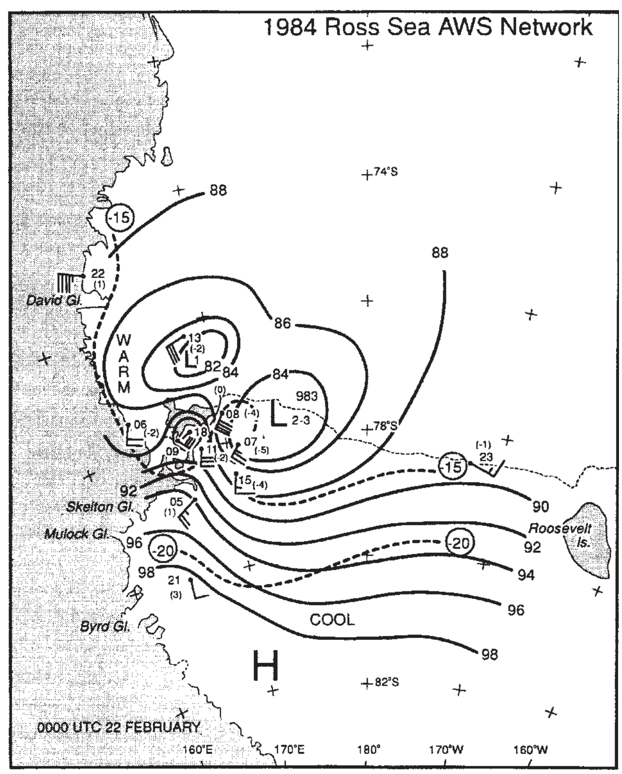

FIG. 3. Example of mesolows and highs in the Ross Island region from analysis by O'Connor et al. (1994). Sea level pressure (hPa, 88 = 988) and surface isotherms (°C, dashed) from AWS observations at 0000 UTC 22 Feb 1984. Number at observations corresponds to AWS station number. Pressure changes (hPa) during the preceding 24 h are given in parentheses next to each AWS site. (Reproduced with the permission of the American Meteorological Society.)

entific support and to document some of the challenges and lessons of real-time mesoscale modeling for the Antarctic. We hope to enhance the community's understanding of real-time polar mesoscale prediction and stimulate new collaborations in polar modeling and meteorology.

THE MODELING SYSTEM.

Configuration. The MM5 (Grell et al. 1995) setup used in AMPS currently features five grids, with horizontal spacing of 90, 30, 10 (2 grids), and 3.3 km. The 90-km domain (Fig. 2a) includes New Zealand, the origin of flights to McMurdo. Amid the *Magdalena Oldendorff* rescue (described below), this grid was permanently enlarged to include the southern tip of South Africa. Covering Antarctica, the 30-km domain (Fig. 2b) reflects the users' desire that the entire continent be contained in a mesoscale grid with better resolution, topographic data, and land use information than available in other models when the system was created. The first 10-km grid (Fig. 2b) was designed to cover the McMurdo Station area with, when the project began, the highest resolution practicable for real-time forecasting.

Another 10-km grid was added (Fig. 2b) to cover the South Pole, which handles several hundred flights annually. Last, 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 Island domain (Fig. 2c). Under forecasts of strong southerly flow, this grid can produce von Kármán vortices shed north of the island, as seen in Fig. 4.

All nesting is two-way interactive. The vertical resolution reflects 31 σ levels between the ground and the model top at 50 hPa. Model initializations are at 0000 and 1200 UTC. Forecast lengths are 72 h for the 90-km and 30-km grids, and 36 h for the 10-km and 3.3-km grids.

The AMPS MM5's initial and boundary conditions are derived from the National Centers for Environmental Prediction (NCEP) global spectral model global forecasting system (GFS). The GFS first-guess field is objectively reanalyzed with the available observations using a multiquadric technique (Nuss and Titley 1994). The data in the Antarctic region include reports from manned surface stations, surface automatic weather stations (AWSs), and upper-air stations. Sat-

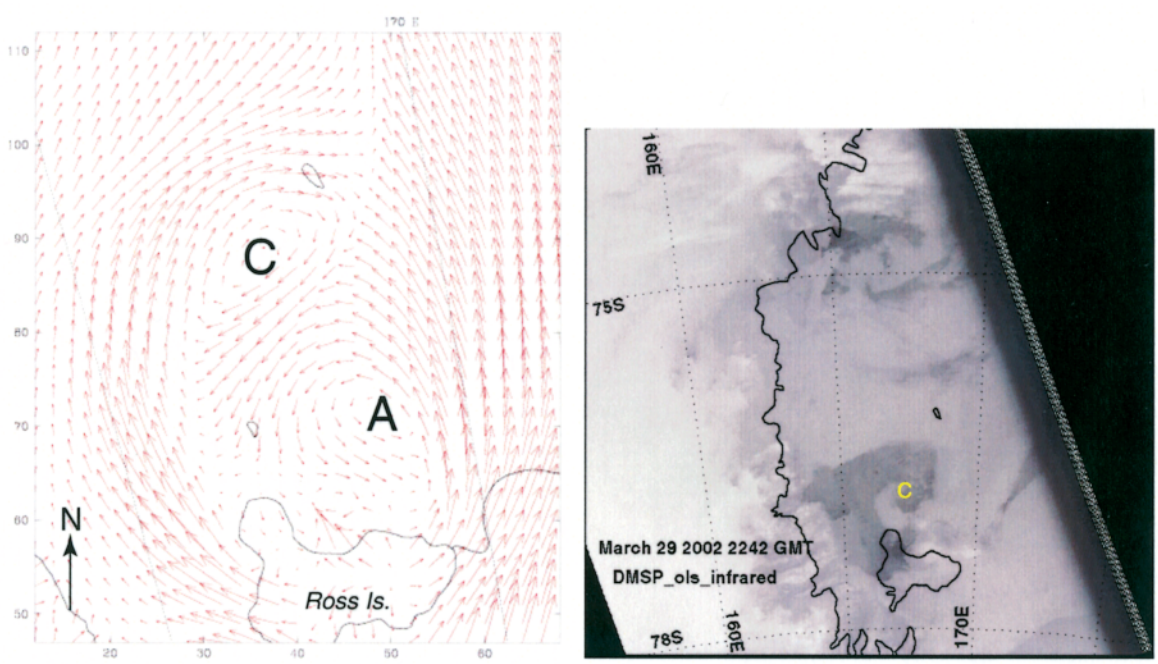

Fig. 4. 3.3-km AMPS domain output showing von Kármán vortices north of Ross Island and corresponding IR satellite imagery. (a) AMPS hour 23, valid 2300 UTC 29 Mar 2002. 200-m AGL winds shown, plotted every other grid point. Vector length = 8.5 m s^{-1}/grid interval, "C" = cyclonic circulation center, and "A" = anticyclonic circulation center. (b) IR imagery for 2242 UTC 29 Mar 2002. Panel (b) captures a cyclonic vortex, roughly coincident with "C" in (a). A sequence of images indicates that cyclonic vortex ("C") has spun up off the western end of Ross Island and moved northward. Analysis of other available surface observations, however, has suggested that the model may have overpredicted the strength of the southerly flow here, and thus may have overdeveloped the series of lee features present in its output. Thus, as in all high-resolution mesoscale model applications, plausible features in AMPS must be considered with care. (Satellite image courtesy of Arctic and Antarctic Research Center.)

ellite-derived cloud-track winds are also captured in the 90-km grid. The system ingests sea ice data daily from the National Snow and Ice Data Center for initializing its fractional sea ice depiction.

Analyses of AMPS simulations suggest that the model's original objective reanalysis scheme may not be exploiting the observations as much as possible because it takes a single-level, univariate approach as compared to a multivariate analysis involving vertical correlations. Furthermore, it is limited to the ingestion of direct (i.e., model prognostic) variables. Measurements of indirect variables, particularly those provided by satellites, may significantly benefit Antarctic forecasts through variational assimilation. One example is the GPS radio occultation sounding (Kuo et al. 2002). Thus, we are implementing a three-dimensional variational data assimilation (3DVAR) system.

Associated with AMPS is a global version of the MM5 (the GMM5; Dudhia and Bresch 2002); its 5-day forecast produced twice a day provides a longer-range outlook for the continent. AMPS employs the "Polar MM5" (PMM5; Bromwich et al. 2001; Cassano et al. 2001), a version of the model developed by BPRC. For this variant of the MM5, a number of key physical schemes were modified for polar regions and to capture features unique to extensive ice sheets, such as steep coastal margins and the lack of conventional soil and vegetation. Modifications for the PMM5 include:

i) accounting for sea ice 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 flux over ice surface, and assuming ice saturation when calculating surface saturation mixing ratios over ice;
iv) modification of the CCM2 (Community Climate Model 2; Bath et al. 1992) radiation scheme to include the radiative properties of clouds as determined from the model's microphysical species (as opposed to relative humidity);
v) modified thermal properties of snow and ice (e.g., modified thermal diffusivity for snow-covered, permanent ice, and sea ice grid points); and
vi) more levels in the MM5's soil model (to better represent heat transfer through ice sheets).

Verification studies have found the impacts of the polar modifications to be positive (Cassano et al. 2001; Guo et al. 2003). Further performance analysis and parameterization development of the PMM5 is part of ongoing system development.[1]

Figure 1 shows AMPS in relation to inputs and users. Tight coordination is maintained with the primary user, the Space and Naval Warfare Systems Center (SPAWAR), headquartered in Charleston, South Carolina. SPAWAR forecasts for the USAP, primarily from its weather office at McMurdo Station, Antarctica. SPAWAR also provides feedback on desired products, enhancement priorities (e.g., new grids), and model performance in significant weather events (e.g., high winds, fog).

System performance. Analyses of objective verification statistics are beyond the scope of this overview. (For verifications details on AMPS or the PMM5, the reader may consult the references cited below.) Nonetheless, to summarize aspects of system performance, we offer some illustrations of the evaluation of AMPS.

System performance is monitored and evaluated in four 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 that become apparent with experience. Second, systematic verifications are undertaken. These have been both event-based (Bromwich et al. 2003; Monaghan et al. 2003) as well as seasonal. Users thus far find that AMPS's fine resolution captures the flight-critical, near-surface variations in temperature, humidity, and wind (Cayette 2002). During the 2001–02 field season at McMurdo, for example, AMPS significantly contributed to operational forecasts on 44 of the 53 occurrences of "poor weather" (i.e., fog, snow, blowing snow, and/or low cloud layers that hamper or threaten flight operations; Cayette 2002). This represents a capability and a level of assistance not previously available.

Third, AMPS has a real-time verification capability that presents forecast error statistics for recent periods on the Web. This allows users to see the current biases, rms errors, etc., for forecast parameters such as temperature, wind, and geopotential height. The AMPS verification page offers plots of error distributions as well as tables of statistics. Information on the plots is available on the verification page (see online at "Verif" icon on main AMPS page or at www.mmm.ucar.edu/rt/mm5/amps/verif directly).

Last, case verification is also undertaken. Mesoscale cyclogenesis is troublesome in the Ross Island region

[1] The Polar MM5 options have been put into the standard MM5 release and thus are available to the broad MM5 community. A Polar MM5 Web page may be found at http://www-bprc.mps.ohio-state.edu/PolarMet/pmm5.html.

because it can produce conditions hazardous to McMurdo flight operations and threaten "turn backs" (when McMurdo-bound aircraft are forced to retreat to Christchurch due to bad weather). The western Ross Sea may be the world's most prolific breeding ground for these mesoscale low pressure systems (Carrasco et al. 2003): on a yearly average, two cyclones per week form near Terra Nova Bay and one per week forms near Byrd Glacier (Fig. 2c; Carrasco and Bromwich 1994). In fact, cyclogenesis peaks in the austral summer when Antarctic operations are in full swing.

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[2] 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 (see, e.g., Fig. 3). They also found, however, that the AMPS first-guess field (from the GFS) could have a particularly lasting impression on the forecast. The lack of conventional observations over Antarctica—an impediment to correcting or improving the first guess through reanalysis—was seen to be influential (Bromwich et al. 2003). The findings thus suggested that variational data assimilation would better utilize the available surface observations and support the ingestion of satellite measurements. Partly as a result of such work, 3DVAR is a key element of AMPS's next phase.

AMPS's performance during a rescue has also been analyzed. In April 2001 a small aircraft embarked on an emergency flight from Rothera Station to the South Pole to remove an American physician, Dr. Ronald Shemenski, in need of medical attention. At the time, the AMPS 30-km grid (not the 10-km grid) was running over the South Pole. For the critical flight forecasting period of 21–25 April 2001, Monaghan et al. (2003) verified a number of key variables, which included: 500-hPa wind speed and direction, geopotential height, and temperature; surface wind speed and direction, pressure, and temperature; and South Pole cloud fraction. The verification considered AMPS's PMM5, plus three other models available to the forecasters for this crisis: the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, the "Aviation" (AVN) global spectral model (NCEP), and the GMM5 (NCAR). The ECMWF model, with approximately 28-km resolution at 75°S (and increasing resolution toward the pole), performed with the highest overall skill, as defined by generally having the lowest bias and rms errors and the highest correlations for the examined fields. AMPS's PMM5 exhibited the next best skill, with the AVN and GMM5 the least.[3] It was found that the spatial resolution of each model exerted an important influence on accuracy, particularly in the complex topography of the coastal regions. In addition, in testing done with AMPS, a significant sensitivity to the first-guess and boundary conditions was again noted (*accord* Bromwich et al. 2003). The ECMWF's skill in part reflected its advanced data assimilation system, including 4DVAR (four-dimensional variational data assimilation) and use of satellite infrared and microwave radiances from polar orbiters—improvements that benefit the data-sparse high latitudes (see Simmons and Hollingsworth 2002; Mahfouf and Rabier 2000).

Feedback on system performance has been continuous from SPAWAR, as the forecasts are assessed daily in the crucible of flight operations. In addition, emergency forecasts have prompted appreciation for AMPS from the broader community. The following section explores these special AMPS applications.

SPECIAL APPLICATIONS. *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 forecasters at McMurdo Station and flights to and from McMurdo and across the continent (e.g., McMurdo–South Pole) that the USAP oversees. The latter are conducted by the Air Force Air Mobility Command (AMC), the New York Air National Guard's 109th Airlift Wing, Kenn Borek Air Ltd., and Petroleum Helicopters, Inc. Prior to AMPS, SPAWAR's forecasts for USAP relied upon the global models such as NCEP's AVN, NCEP's Medium-Range Forecast Model, and the U.S. Navy's NOGAPS. These provided relatively low horizontal resolution (e.g., 1° lat–lon) and did not well represent the terrain or polar environment. Furthermore, quality control checks frequently discarded the South Pole upper-level observations. During the 1999–2000 field

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

[3] Although the ECMWF global model statistically did better than AMPS in this case, SPAWAR and other users want AMPS for a number of reasons. Among these are, first, that the ECMWF global does not always provide better forecasts over all forecast areas of concern. Second, the availability of ECMWF forecasts to SPAWAR and other AMPS users is limited to only certain products at certain frequencies. Third, AMPS provides tailored products that specifically reflect the input of the forecasters (e.g., fields shown, vertical levels offered, plotting parameter used, etc.).

season, SPAWAR did receive forecasts from the Air Force Weather Agency, reflecting a 45-km MM5 grid over Antarctica, but polar physics modifications and horizontal meshes of 10-km or less were considered more advantageous for the western Ross Sea/ McMurdo area. Similarly, starting in January 2000, BPRC supplied the USAP with forecasts from a 60-km version of the PMM5 (a predecessor of the AMPS PMM5). Currently SPAWAR has found that AMPS allows longer range forecasts with greater accuracy.

Ongoing tailoring of products for SPAWAR (and other) users has been a pillar of the project. In practice this has been easy because the system is still "experimental" and thus flexible enough to stay in step with new ideas and needs. For instance, we can readily add surface time series plots for stations or camps that may vary depending on operational needs.

One place for which detail is constantly needed is Williams Field, the USAP airstrip McMurdo uses most.[4] Products tailored for the activity there include time series of surface temperature, wind, and pressure (Fig. 5a) and moisture and wind parameters (Fig. 5b). One of the special products is the cross-field wind component at Williams (Fig. 5b). Crosswinds above 15 kt preclude landing and take off for aircraft with skis. AMPS supports both the main season 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.

Fog in the McMurdo area scares forecasters and pilots alike. Because of a vast cold surface and the availability of moisture, dense fog can rapidly envelop the region and reduce visibility from "unrestricted" to less than 50 m in less than 1 h. Moreover, with only one touch-down area and white surface, even light fog makes navigation and landing perilous. In this setting AMPS has proved to be a valuable tool in the prediction of moisture patterns and temperature trends. For example, SPAWAR found that without AMPS's highest resolution, it would have been too difficult to dis-

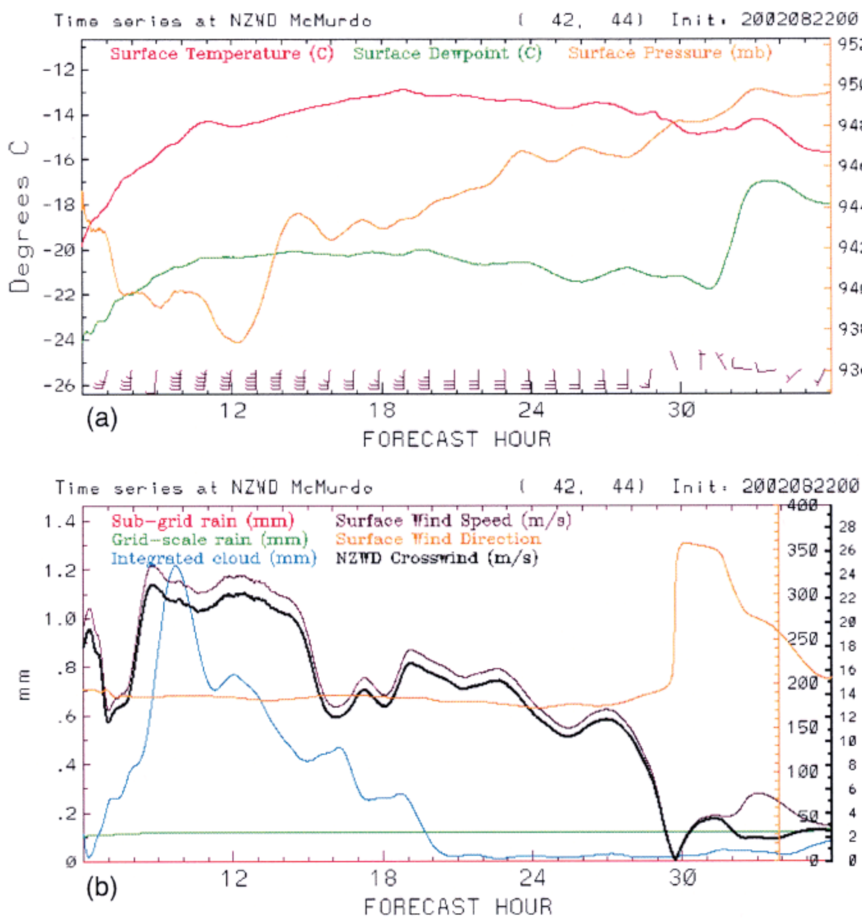

FIG. 5. Surface time series at Williams Field from 3.3-km grid for forecast initialized 22 Aug 2002. The 3.3-km grid operating at this time ran for hours 6–36. (a) Temperature (red, °C, scale to left), dewpoint (green, °C, scale to left), pressure (orange, hPa, scale to right), and wind (barbs). (b) Wind speed (purple, light, m s^{-1}, scale to right), crosswind component at Williams Field (black, heavy, m s^{-1}, scale to right), surface wind direction (orange, deg., scale to right), and integrated cloud water and ice (blue, mm, scale to left). Accumulated subgrid-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 (b) are actually to precipitation that falls as snow.

[4] Another strip, used in the early season, is the Ice Runway. This is located south-southeast of McMurdo Station on the frozen McMurdo Sound. A third, located south of the Ice Runway, is called Pegasus.

cern the location, onset, and duration of fog at McMurdo on 27–28 September 2002. To err on the side of caution, forecasters would have otherwise had to cancel a flight. Instead, the 3.3-km grid's predictions indicated the fog would be patchy and confined to areas away from the Pegasus runway (Fig. 6). As noted in the Pegasus observations listed in Table 1, fog did form to the northwest and came within one mile of the airfield by 2255 UTC 27 September. Here, the AMPS output assisted the forecasters in an accurate call that allowed operations on a day that would have otherwise been wasted.

The stakes are high in forecasting for the flights from New Zealand, and not only because of the dangers of forced landings in adverse conditions. A flight that must abort and return to Christchurch costs approximately \$85,000 (Capt. C. A. Souza, New York Air National Guard, 2002 personal communication). Recalled Pole flights cost about \$35,000. By helping avoid these situations, AMPS makes Antarctic operations more efficient, and in part, helps to pay for itself.

Assisting in emergencies—Shemenski Pole Rescue of April 2001. The rescue of Dr. Shemenski was an unprecedented late-season flight involving international coordination. Although originally intending to winter over until October, Dr. Ronald Shemenski, the staff physician at Amundsen-Scott Station, came to exhibit pancreatitis and began suffering from gallstones. As winter made access to the station impossible, and Dr. Shemenski needed treatment, NSF decided on an evacuation. This meant a daunting flight, however, at a time of year with frequent blowing snow, marginal aircraft operating temperatures (down to −75°C), and darkness without a lighted runway.

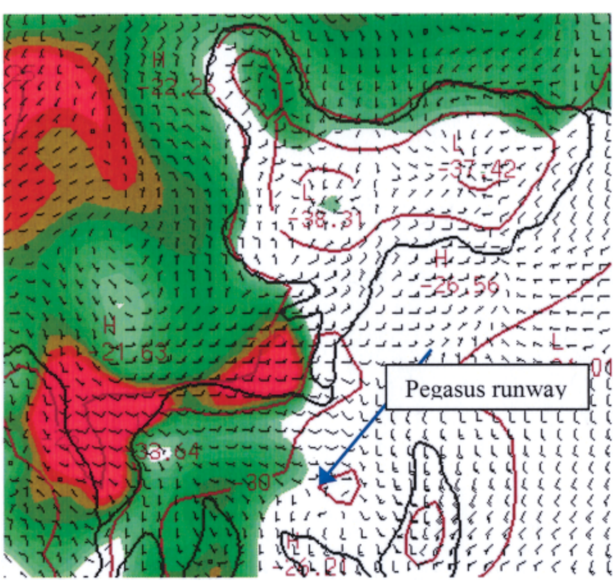

Fig. 6. AMPS 3.3-km 24-h forecast of surface RH (0000 UTC 27 Sep 2002 initialization). RH with respect to ice shaded: green = 75%–80%, dark green = 90%–100%, red = 110%–120%. Surface wind barbs: full barb = 10 kt, half barb = 5 kt.

Kenn Borek Air, Ltd. of Canada dispatched two twin-prop Twin Otter planes to Punta Arenas, Chile, and thence to the British Antarctic Survey's Rothera Station on the Antarctic Peninsula (Fig 2a) to await the forecast of a favorable weather window for the 10-h flight to the pole, crew rest and loading, and the 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 30-km AMPS grid gave more detailed views along the flight route and over the Pole. The most important forecasting concern was the prediction of blowing snow at Amundsen-Scott. Both AMPS (30-km) and the ECMWF global accurately predicted a cessation of blowing snow on 24 April, and thus an evacuation window (Monaghan et al. 2003). For forecasts covering the times after 0000 UTC 24 April, the AMPS runs show the decrease of the wind to the approximate threshold of 6 m s^{-1} for an aircraft landing in blowing snow (Fig. 7). In addition to such time series, AMPS's horizontal plots also indicated acceptable conditions over the area.

One of the planes at Rothera departed 1434 UTC 24 April and after 9.5 h arrived safely at Amundsen-Scott (Fig. 8). With Dr. Shemenski safely aboard, the aircraft took off at 1647 UTC on 25 April and reached Rothera without problem at 0052 UTC 26 April.

In commending the multinational rescue team, Dr. Karl Erb, Director of NSF's Office of Polar Programs, referred to AMPS (run at NCAR) and the meteorologists involved as follows:

> [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).

The evacuation of Dr. Shemenski in April 2002 was not the only crisis test of AMPS.

Table 1. METAR observations from Pegasus Air Field (NZPG) taken on 28 Sep 2002 from 0055 to 1508 LST (0308 UTC). Fog in the vicinity with sector visibility to 1 mile are observed during the time of landing the C-17. Note: visibility "9999" = unrestricted, weather "VCBR = mist in vicinity, clouds "SKC" = clear; for further details on abbreviations, consult METAR.

Day (Sep 2002)	Time (UTC)	Wind Dir. (degrees)	Wind Speed (kt)	Visibility (m)	Weather (METAR)	Remarks	Clouds (1000s ft)	Temperature (°C, M = minus)
27	1255	100	3	9999			SKC	M38
27	1355	0	0	9999			SKC	M39
27	1455	80	3	9999			SKC	M39
27	1555	30	11	9999			SKC	M41
27	1655	360	6	9999			SKC	M41
27	1755	0	0	9999			BKN065	M39
27	1855	360	5	9999			SCT065	M39
27	1955	150	3	9999			SCT065	M38
27	2055	100	8	9999			SCT065	M40
27	2125	110	6	9999			SCT065	M41
27	2155	110	7	9999			SCT065	M41
27	2225	130	3	9999	VCBR		SCT065	M42
27	2255	110	8	9999	VCBR	Vis NW1600	SCT065	M42
27	2355	110	8	9999	VCBR	Vis NW3200	SCT065	M39
28	0055	100	6	9999	VCBR	Vis NW3200	FEW065	M38
28	0155	60	5	9999	VCBR		FEW065	M39
28	0255	70	4	9999	VCBR		FEW065	M39
28	0308	70	4	9999	VCBR		FEW065	M39

Mandalena Oldendorrf Rescue of June-July 2002. In June 2002, the 21 000-ton German supply ship *Magdalena Oldendorff* was servicing research stations when it became trapped in thickening sea ice. Aboard the ice-bound ship (Fig. 9) were a crew of 28 and approximately 79 Russian scientists. Ultimately, the *Oldendorff* sat stuck at 69.93°S, 1.43°W (as of 8 August 2002; see Fig. 2b) in Muskegbukta Bay.

In response to the *Oldendorff*'s call for assistance, South Africa sent the *Agulhas,* an ice-strengthened research vessel, to retrieve the scientists and crew. By the end of June it was in position to send its heli-

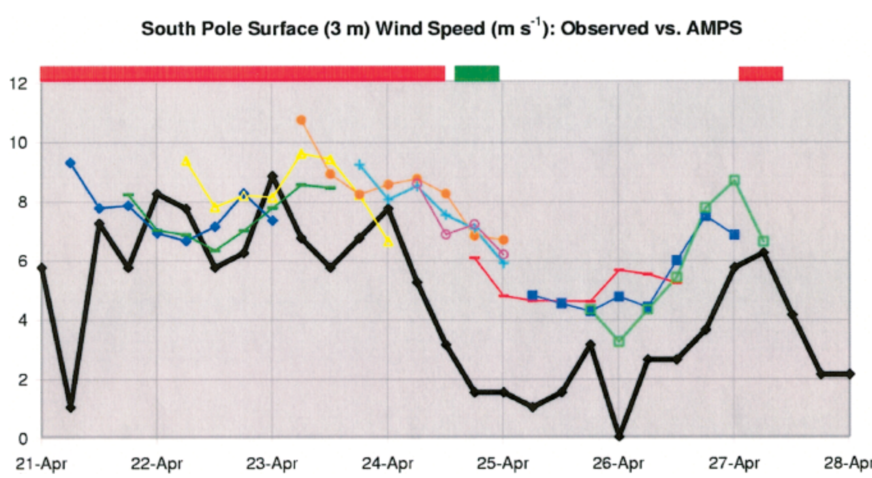

Fig 7. Observed vs forecast surface (3 m) wind speed (m s^{-1}) at South Pole, 21–27 Apr 2001 for all forecasts out 6–48 h from the initial time. Observations (thick line) are from the AWS at 90°S, °E. The green horizontal bar indicated the duration of the flight to the Pole. The forecast values are from the AMPS 30-km grid. The red horizontal bars represent times when blowing snow conditions were reported at the Pole. (AWS data courtesy of University of Wisconsin Antarctic Meteorological Research Center.)

the wind backed into the south-west. (Hunter 2002a)

Blizzard conditions hampered the rescue mission on several occasions. On the morning of 30 June, for example, easterly winds at the *Oldendorff* were averaging 33 m s^{-1}, while blowing snow reduced the visibility to less than 50 m, grounding the *Agulhas*'s helicopters. While AMPS did forecast such conditions, it also accurately predicted a brief window of favorable weather for 1 July, allowing for the final helicopter airlifts to remove the last of the scientists and crew. Hunter (2002b) noted: "A brief weather window on Monday July 1 was well-predicted by the US model and the last non-essential personnel were ferried across to the *Agulhas* before the weather set in again." The *Agulhas* successfully returned to Cape Town on July 10.

FIG. 8. Twin Otter aircraft on the snow at Amundsen-Scott Station, South Pole, during the Shemenski rescue.

copter to pluck the scientists and crew from the *Oldendorff*. To aid the rescue, NCAR expanded AMPS's 90-km grid to South Africa. In addition, AMPS generated special products. A window of detailed model output focused on conditions in the *Oldendorff* area, while time series of surface weather for the location of the *Oldendorff* were also produced. The AMPS forecasts were used heavily by the South African Weather Service. For example, on its southward voyage, the *Agulhas* encountered rough weather from a low that was accurately forecast by AMPS (Fig. 10). On 26 June 2002, the South African Weather Service announced the following:

> 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 observations with

As the *Oldendorff*'s personnel were being secured by the *Agulhas*, Argentina was directing its icebreaker *Almirante Irizar* to free the *Oldendorff*. The AMPS forecasts continued through this mission as well. The *Almirante Irizar* reached the *Oldendorff* on 19 July, and for 10 days both vessels tried to break out (see

FIG. 9. (left) View of the *Magdalena Oldendorff* in the ice, with the (right) *Almirante Irizar* alongside. (Photo courtesy of Argentine Navy available via Santiago L. Aversa/FuerzasNavales.com.)

Fig. 9). However, the ships as a pair were unable to make safe headway because of the thickness of the ice. On 30 July, the *Almirante Irizar* left to return to Argentina and the *Oldendorff* spent the winter locked in the ice.

Field program support and community outreach. AMPS has also supported scientific field programs. The first of these has been the GLOBEC (Global Ocean Ecosystem Dynamics) Program, an international inquiry into how global climate change may affect the abundance of animals in the sea. As part of GLOBEC, the National Science Foundation's *Laurence M. Gould* and other research vessels have sailed to the Antarctic Peninsula and the Marguerite Bay region (see Fig. 2b). AMPS has provided a suite of products for this area (see, e.g., 72-h program of surface equivalent potential temperature (θ_e) and wind in Fig. 11).

AMPS also provides products to the Italian National Antarctic Research Program (PNRA). PNRA maintains a station at Terra Nova Bay (Fig. 2c) and requested AMPS products for its forecasting operations, which support supply flights conducted by the Italian Air Force and research activities in the area. Using ftp, we provide a reduced product suite to Terra Nova, since that facility has limited satellite Internet connectivity (approximately 30 min twice a day).

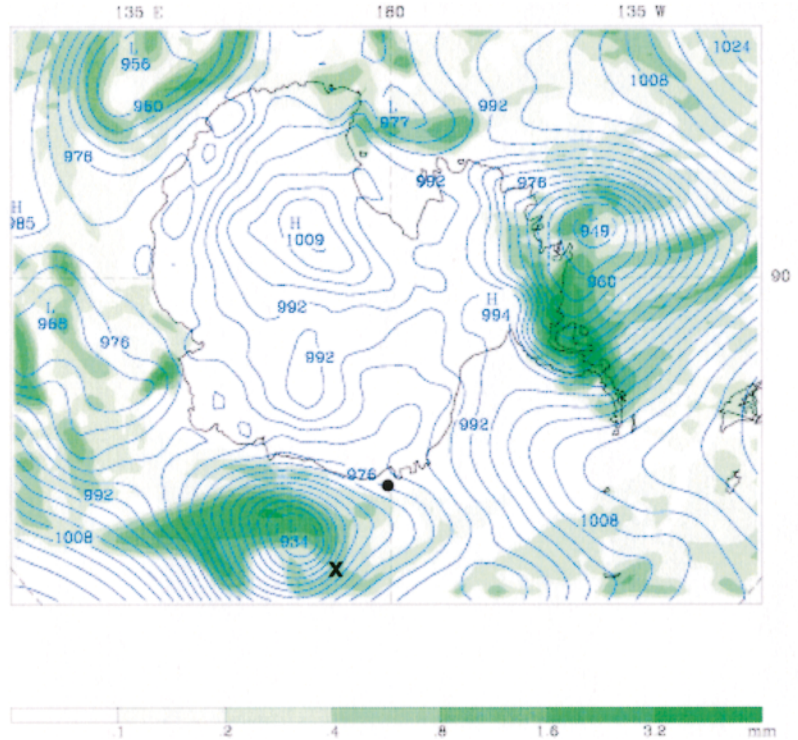

FIG. 10. Sea level pressure (contour interval = 4 hPa) and 3-hourly precipitation (shaded, mm) for hour 39 of 0000 UTC 22 Jun 2002 forecast. 90-km grid output plotted; window of full computational grid shown. Forecast valid 1500 UTC 23 Jun 2002. Dot marks position of *Magdalena Oldendforff,* while "X" marks the position of the Agulhas. Deep low of 934 hPa southeast of Agulhas seen.

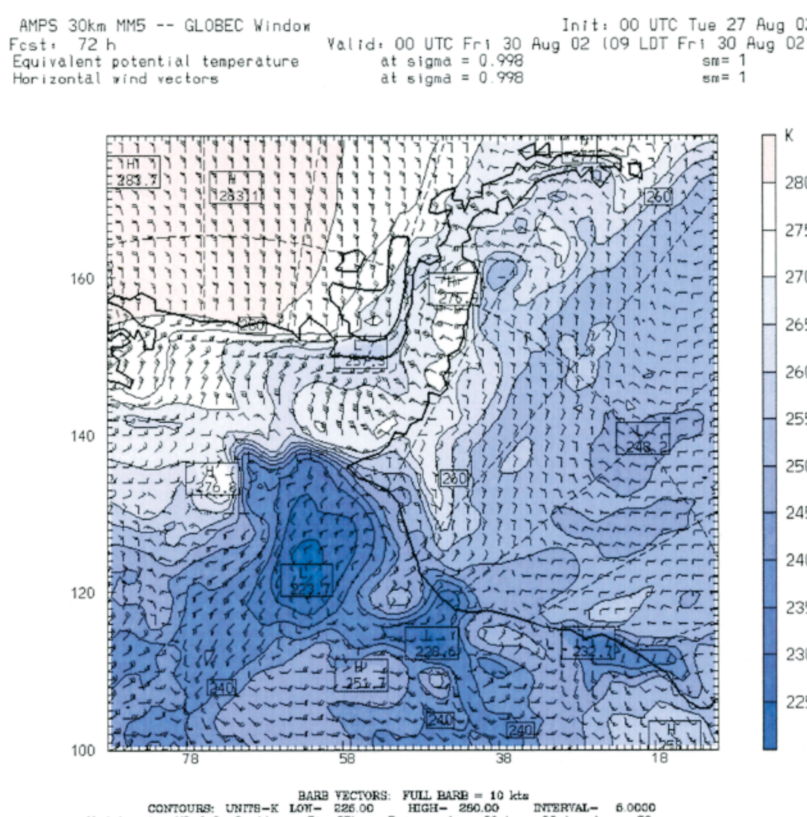

FIG. 11. Example of GLOBEC plot window and forecast. Surface wind (barbs, full barb = 10 kt) and θ_e (shaded, K, scale to right) from 72-h AMPS forecast shown. Output from 30-km AMPS domain analyzed. Forecast initialized at 0000 UTC 27 Aug 2002, valid 0000 UTC 30 Aug 2002.

Another opportunity for scientific collaboration is RIME, the Ross Island Meteorology Experiment (Parish and Bromwich 2002), which will explore atmospheric processes over Antarctica and their interactions with lower latitudes through the Ross Sea sector. Regional observations (including those from aircraft) made in conjunction with numerical modeling efforts will be geared toward understanding the Antarctic transports of heat, water vapor, and mass along with their modification by topographic and mesoscale processes (Parish and Bromwich 2002). AMPS is poised to help in several ways. First, because it is focused on the Ross Island area, AMPS could readily provide flight or ground operation forecasts for RIME. Second, archived high-resolution AMPS datasets could be used to identify locations where observations may be especially valuable for revealing local terrain-induced phenomena. 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. Fourth, the PMM5's physical parameterization (e.g., boundary layer schemes) could be scrutinized and improved through verification from the campaign's datasets. One planned byproduct of RIME is better NWP in the Ross Sea region (Parish and Bromwich 2002).

Among its goals, the AMPS Project seeks to stimulate collaboration between forecasters, modelers, and researchers. In part, this 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. The goal of collaboration has also been advanced through workshops. These have taken the form of the AMPS Users' Workshop in June 2001 and June 2003 and, with broadened scope, the Antarctic Numerical Weather Prediction and Forecasting Workshop in June 2002. In addition, AMPS was the focus of the October 2002 Workshop on Antarctic Numerical Weather Forecasting for Operations. This was held to stimulate international collaboration in AMPS and in Antarctic forecasting and modeling, and the list of international users shown in Fig. 1 largely reflects its success in expanding the activities served by AMPS.

FUTURE DIRECTIONS. 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. The products posted to the AMPS Web page (www.mmm.ucar.edu/rt/mm5/amps) cover a broad spectrum, but reflect the primary user needs in flight forecasting. Since 2000 AMPS clearly has grown to serve science operations beyond those of NSF and forecasts for USAP flight operations. Moreover, it has repeatedly assisted in emergency rescue operations.

Challenges for AMPS include the improvement of initial conditions, which is being addressed through the implementation of 3DVAR. In addition, verification and analysis of the Polar MM5 and tuning of physics parameterizations are ongoing. A polar physics working group for the MM5 has been established to share developments and ideas geared toward improving the polar performance of the model (see online at www.mmm.ucar.edu/pmm5). While originally organized to exchange information about Polar MM5 physics, the group's developments should apply to a range of mesoscale models, in particular the new Weather Research and Forecasting (WRF) model (Michalakes et al. 2001).

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, to improve polar physics parameterizations, and to support field campaigns and emergency operations.

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ACCESSING AMPS

The range of AMPS products is available online at http://www.mmm.ucar.edu/rt/mm5/amps. The page contains links with details on the model setup and products. An archive of AMPS forecasts supports verification work, as well as research. The AMPS archive is open to the public, and the Web page provides information on it, including materials archived, locations, and access.

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