meeting summary

Report on the First International Symposium on Operational Weather Forecasting in Antarctica

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ABSTRACT

The First International Symposium on Operational Weather Forecasting in Antarctica was held in Hobart, Australia, from 31 August to 3 September 1998. There were 40 attendees at the meeting from Australia, Belgium, Brazil, China, France, Italy, Russia, and the United Kingdom. In recent years there has been considerable growth in the requirement for weather forecasts for the Antarctic because of the increases in complex scientific research activities and the rapid growth of tourism to the continent. At many of the research stations there are now sophisticated forecasting operations that make use of the data available from drifting buoys and automatic weather stations, the output from numerical weather prediction systems, and high resolution satellite imagery. The models have considerable success at predicting the synoptic-scale depressions that occur over the ocean and in the coastal region. However, the many mesoscale systems that occur, which are very important for forecasting local conditions, are not well represented in the model fields and their movement is mainly predicted via the satellite data. In the future it is anticipated that high resolution, limited-area models will be run for selected parts of the continent. The symposium showed that great advances had been made during recent years in forecasting for the Antarctic as a result of our better understanding of atmospheric processes at high latitudes, along with the availability of high resolution satellite imagery and the output of numerical models. Outstanding problems include the difficulty of getting all of the observations to the main analysis centers outside the Antarctic in a timely fashion, the lack of upper air data from the Antarctic Peninsula and the interior of the continent, and the poor representation of the Antarctic orography and high latitude processes in numerical models. An outcome of the symposium will be a weather forecasting handbook dealing with the entire continent.

1. Introduction

In recent years there has been a huge increase in the number of people visiting the Antarctic continent for scientific research activities, on vessels resupplying the research stations, as part of private expeditions, on tourist vessels, and even on aircraft conducting tourist over-flights. All these activities require weather forecasts to ensure that their visits are safe in what is a harsh and dangerous environment, even in the summer months when most visits occur. Although weather forecasts have been attempted since the very first voyages to Antarctica took place, the increasing complexity of modern logistical activities on the continent means that ever more specialized and accurate forecasts are required. For example, many operators use small fixed-wing aircraft equipped with both skis and wheels to deploy and recover field parties at isolated locations in the interior of the continent. The fuel for such flights has to be brought into the Antarctic via ship and, for flights well away from the research stations, has to be placed in depots at more southerly locations. With accurate forecasts of upper winds and the weather at the destination, the timing of such flights and the route/flight level used can be optimized to conserve the fuel required. Of particular importance is the need to avoid flights that are aborted close to the destination because of bad weather, since the cost in wasted fuel will be considerable. The consideration of weather analyses and forecasts is therefore an important part of planning field activities in the Antarctic.

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Although in recent decades there have been many conferences concerned with meteorological research in the Antarctic, there has never been a meeting dealing exclusively with the practical aspects of weather forecasting for the continent, despite the internationalization of many aspects of work in the Antarctic over recent years. It was therefore decided that such a conference would be of great value and enable those concerned with forecasting for the continent to review the methods used to prepare forecasts, to assess the new forms of data becoming available, to discuss the strengths and weaknesses of model output at high southern latitudes, and to identify areas where improved techniques are required. A major goal of the meeting was to ensure that the many advances in our theoretical and practical understanding of Antarctic meteorology that have emerged in recent decades through the research community were being translated into improved forecasting techniques and methods.

The interest in forecasting for the Antarctic resulted in the First International Symposium on Operational Weather Forecasting in Antarctica being held in Hobart, Australia, over the period 31 August–3 September 1998. The symposium was organized by the Australian Bureau of Meteorology (ABOM) and the British Antarctic Survey (BAS), with the meeting being cosponsored by the American Meteorological Society, the Australian Meteorological and Oceanographic Society, the Scientific Committee on Antarctic Research (SCAR), and the World Meteorological Organization (WMO). A list of acronyms used in the paper is given in the appendix. There were 40 attendees at the meeting from Australia, Belgium, Brazil, China, France, Italy, Russia, and the United Kingdom. Those attending had a wide range of skills and consisted of practicing forecasters with Antarctic experience, administrators responsible for providing forecasting services for Antarctic operations, developers of numerical models, and researchers with a close interest in weather forecasting.

The meeting was opened by the governor of Tasmania, Sir Guy Green, who commented on the long association between Hobart and those involved in the study and exploration of the Antarctic, the sub-Antarctic, and the Southern Ocean. He also emphasized the value of the symposium in encouraging a global view of the field and reinforcing the ethos of the Antarctic Treaty. This was followed by a welcome on behalf of the Australian government from Senator the Hon. Ian Macdonald, parliamentary secretary to the Minister of the Environment, delivered by J. Zillman, director of the Australian Bureau of Meteorology and permanent representative of Australia with the WMO. The final introductory speech was given by E. Sarukhanian (chief, Observing Systems Division, WMO) on behalf of G. O. P. Obasi, secretary-general of WMO, who said that WMO considers this event very important, particularly toward the development and continuance of quality forecasting and warning services for Antarctica.

2. The forecasting requirement and particular problems in forecasting for the Antarctic

The first presentations considered the needs of the user community for forecasts at high southern latitudes and the particular problems of making predictions for the continent. J. Sayers (executive secretary of the Council of Managers of National Antarctic Programmes) gave a summary of current inter- and intracontinental flights and discussed the need for aviation forecasts for flights such as those undertaken by both national and commercial operators. The council plays an important part in developing procedures for aircraft operations in Antarctica and has published an Antarctic Flight Information Manual set of rules, plus an Antarctic Telecommunications Operators Manual. During his talk J. Sayers dealt in particular with the development of an East Antarctic Air Network (EAAN). It is planned that this will link Cape Town, Dronning Maud Land, the Larsemann Hills (69.4°S, 76.2°E), and Hobart (see Fig. 1 for places referred to in the text). The proposed Dronning Maud Land landing site is a blue ice strip, "Blue One," at about 1000 m ASL near Novolazarevskaya (70.8°S, 11.8°E). The proposed Larsemann Hills site is a compressed snow/ice strip immediately inland of the Larsemann Hills. Flights would be conducted in both directions, originating in Cape Town and Hobart. Such an enterprise would obviously require accurate weather forecasts and it is envisaged that EAAN would need an outlook two to three days prior to flight; a further outlook including route winds and Terminal Airfield Forecasts (TAFs) 24 h prior to takeoff; detailed route forecast and diversion route forecasts, satellite pictures, TAFs, and alternate TAFs 2–5 h prior to flight; continual weather watch and phone contact with meteorological personnel during flight, plus hourly Meteorological Aerodrome Reports (METARs), aerodrome reports when special (adverse)

FIG. 1. A map of Antarctica showing places referred to in the text.

criteria are met, and Trend Type Forecasts (or landing forecasts); update information and METAR and Trend Type Forecasts 30 min before the point of no return. In addition, the minimum landing conditions for an Ilyushin 76, one of the aircraft being considered for use on this route, are 5000-m visibility, 600-m ceiling, no blowing snow, and less than 12 m s^{-1} cross wind. A trial of EAAN is proposed for the year 2000, but this may be a little optimistic. In response to questions regarding whether the weather forecasting community is able to provide the meteorological forecasting support for EAAN, the members of the weather services considered they were.

The forecasting requirements of tourism operators, the Australian Antarctic Division and aviation/shipping was considered by M. Betts (Australian Antarctic Division) and J. Dennis (QANTAS). Mr. Betts described the rapidly increasing number of tourist operations working in the Antarctic and the large number of private expeditions arriving on the continent. For the first time in recent years the number of tourists has exceeded the number of government-sponsored expeditioners with there currently being about 10 000 tourists per year. Tourism operators expect the number of Antarctic tourists to reach 14 000 per annum very shortly and demand for meteorological forecasting support in the future will be increasingly from the tourism operators rather than from the government-sponsored expeditions. Critical weather parameters that effect tourist operations are wind, cloud, surface definition, sea state, and sea ice cover. Captain Dennis described the tourist overflights of the Antarctic that QANTAS operates. These start at Melbourne, Sydney, Adelaide, or Perth, pass over various parts of the continent, including Dumont d'Urville, the McMurdo area, the Trans-Antarctic Mountains, Casey, or Davis (68.6°S, 78.0°E), and then return to Australia. The aircraft used are Boeing 747-400 series aircraft and the primary aim is to maximize time over the continent in clear sky conditions. Operating procedures dictate that the aircraft must, at all times, be able to return to an airport (in Australia, New Zealand, or South Africa) with simultaneous failure of two engines and loss of cabin pressure. Upper winds and the choice of route are critically important for these flights so as to maximize the tail wind for as much of the journey as possible. Meteorological analyses and forecasts are obviously very important in the preflight planning of these journeys and during the flights the pilots are in radio contact with meteorologists both in Australia and on the Antarctic research stations. In the future pilots hope to be able to receive satellite imagery for themselves to aid the identification of cloud-free areas of the continent.

W. Budd [Australian Antarctic Cooperative Research Centre (CRC)] considered the peculiarities of Antarctic meteorology relevant to forecasting. He identified a number of factors that are important, including the effects of the topography (in particular the intensity of katabatic winds and frequency of hydraulic jumps), the frequency of hazardous snow drift, blizzards, blizzard electricity, extremes of low temperature, the strength of the surface inversion (where temperature lapse rates of 30°C per 30 m are not uncommon), low water vapor content, the high frequency of cloud cover in the coastal region (which can be difficult to identify in satellite imagery over ice surfaces), the severity of icing, sparseness of data coverage, isolation, and poor telecommunications. All these factors conspire to make the forecasting process very difficult. Yet there is evidence that higher resolution models are starting to give more accurate fields, such as a better representation of the low-level wind conditions.

H. Phillpot (ABOM, retired) also presented an overview of the forecasting problem. Following his extensive study (Phillpot 1997) of the relationship between the Antarctic continental weather behavior and the movement or development of synoptic systems, Phillpot again stressed the value of detailed analysis at the 500-hPa level using the available radiosonde data and estimates of the height of the 500-hPa surface made from automatic weather station (AWS) observations of pressure and temperature (Phillpot 1991). He provided good examples of strong wind events at East Antarctic stations, and presented cases of single station forecasting techniques based primarily on the relationship between surface wind and its vertical structure.

The history of the activities of the ABOM in Antarctica was considered by G. Love [deputy director (Services), ABOM]. He discussed the improvement in service over time and the increase in bureau activity in Antarctica, from the pioneering days of the International Antarctic Analysis Centre through to the establishment of the Australian Antarctic Meteorological Centre at Casey in 1991. Australian meteorologists have regularly traveled to the Antarctic since 1975 on science expeditions in support of Australian National Antarctic Research Expedition activities. Previously this only occurred on an infrequent basis. An important step forward in the provision of meteorological services was the availability of satellite imagery, especially the installation of a receiver for 1.1-km resolution NOAA High Resolution Picture Transmission (HRPT) data. An example of an image showing the range of the Casey HRPT facility, and in particular a synoptic-scale depression off Casey, is shown in Fig. 2.

3. Observations

The lack of observations across the Antarctic continent has always been a problem for forecasters, although the arrival of satellite imagery in the 1960s greatly aided the forecasting process, and in recent years drifting buoys over the ocean and in the sea ice zone, and AWSs on the continent itself have proved of immense value. At this meeting we had a number of presentations about the current and planned observing network. E. Sarukhanian described the WMO observations network in the Antarctic and stated that at present there are 31 staffed stations, 2 of which are in the interior of the continent (down from 9 during IGY), 14 upper air stations, and approximately 65 AWSs. A list of current Antarctic observing stations, along with maps of their locations is available online

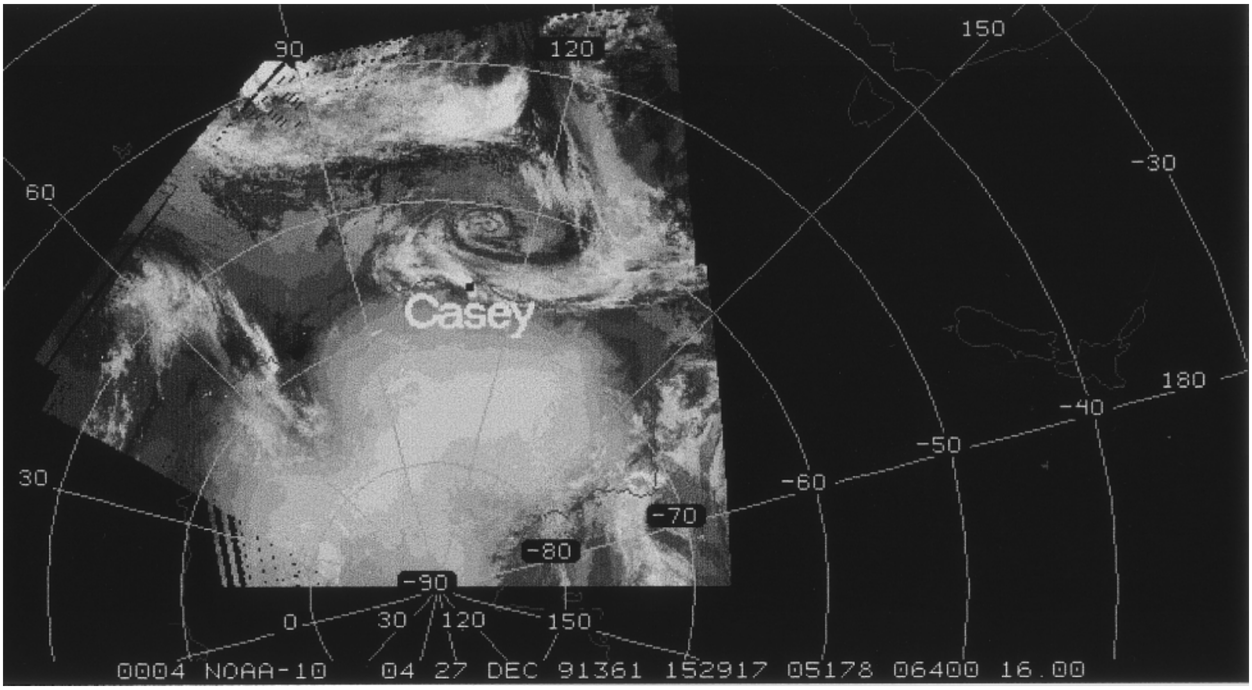

FIG. 2. A satellite image of a depression off Casey.

(http://www.nerc-bas.ac.uk/public/icd/stations/). Although observations are sparse in the interior of the continent the lack of data is not particularly bad in comparison with the continents of South America and Africa. Assessments of the performance of the Global Telecommunications System suggest that 74% of observations get through to analysis centers. This represents an area where improvement should be possible given recent advancements in communication systems used in Antarctica, and work is under way at WMO toward addressing this problem. The SCAR Antarctic First Regional Observing Study of the Troposphere (FROST) project (Turner et al. 1996) similarly found that most observations got out of the Antarctic, although they found that there could be large differences in the data received at particular nodes of the GTS. E. Sarukhanian encouraged member nations to "share" in the responsibility of maintaining Antarctic stations to save on logistics expenditure and suggested this could potentially lead to the reopening of some closed stations, for example, Leningradskaya (69.5°S, 159.4°E). The distribution of ships and buoys south of 60°S is only equal to 1% of the total global (February) coverage and is far worse during other months. The spatial distribution is also poor but it is predicted that the number of buoys will rise substantially in the future. J. Shanklin (BAS) noted that typically 80% to 85% of data reach the United Kingdom, with difficulties being experienced with HF communications, data collection platform problems, satellite failures, ground station failures, and communication failures at analysis centers (i.e., computer outages).

Shanklin described the provision of data for forecasting activities at the BAS stations. He noted the lack of any radiosonde ascents from the Antarctic Peninsula, despite this area having many research stations. The ability to download local area ARGOS data via the NOAA satellite HRPT broadcasts was cited as being of particular value.

I. Allison (Australian Antarctic CRC) described the Australian activities with AWSs and drifting buoys in the Antarctic. Synoptic meteorological data from both the AWSs and buoys are input to the GTS via CLS Argos. Allison provided a history of the Australian Antarctic Division's efforts in placing AWSs in eastern Antarctica. A number of stations have been placed to the south of Casey and about the Lambert Glacier, typically at elevations around 2000 m. Various designs have been used over the years, with the most recent being helicopter deployable and featuring an acoustic surface detector to sense the accumulation of snow. As most of these stations are not revisited, considerable effort is taken to validate the data received. The systems do seem to be robust since one station has operated continuously for more than 14 years, and a temperature of –80°C had been recorded at another station. Metadata for these AWSs, and summary data from them, are in the process of being made available via the Australian Antarctic Division online (http://www-aadc.antdiv.gov.au/Metadata/). It was suggested during questions after the talk that in the future AWSs might be placed by low-altitude parachute deployment or other "drop and forget" techniques, but current AWS designs do not permit this type of deployment.

Allison also described ice buoy deployments carried out by the Australian Antarctic Division since 1985. Buoys deployed from ships in the Antarctic sea ice tend to survive only 6 to 9 months, in contrast to buoys deployed in Arctic waters which remain in the land-locked ice for much longer periods. Nevertheless, data from nearly 40 buoys have been collected from the pack ice between 20°E and 160°E and used to produce an ice drift climatology for the region. Peaks in the ice drift energy are found at low frequencies (days to weeks), apparently associated with synoptic-scale weather events, and also at the inertial period. Data from these buoys are currently being transferred to WDC-A (Glaciology)/National Snow and Ice Data Center, in Boulder, Colorado.

In his talk Budd stated that an important factor affecting the accuracy of the numerical weather prediction (NWP) systems out to seven days is thought to be the distribution of Southern Ocean data, including observations from drifting buoys. The question of how many extra buoys would be required to make substantial improvements to NWP products was posed, and it was decided that we need to reach the point where redundancy exists, thus necessary distribution is linked to model resolution.

Satellite imagery has been available on many research stations for a couple of decades or more but it is only in recent years with the availability of cheap HRPT receivers that the data could provide information on mesoscale phenomena and fog/cloud on the scale of a few kilometers. However, other satellite data are also proving to be of value in the data-sparse Antarctic region, such as surface wind vectors over the ice-free ocean from scatterometers and products derived from passive microwave measurements such as precipitation rates, integrated water vapor, ice edges, and cloud liquid water. Although these quantities cannot be derived from satellite data received in the Antarctic, the information can be computed within a few hours of collection with the geophysical parameters being assimilated into numerical analysis schemes or sent to the Antarctic stations.

4. Analysis and diagnosis

The NWP analyses prepared for the Antarctic and Southern Ocean are not as accurate as those for more northerly areas, yet studies are under way to maximize the value of the available data and to try and improve analysis methods used. The FROST project has assembled a comprehensive dataset of Antarctic observations, analyses, and satellite products for three one-month periods (July 1994, mid-October to mid-November 1994, and January 1995). These data have been used to assess our capability to analyze the atmospheric conditions across the continent and over the Southern Ocean. The high resolution satellite imagery available to the project showed a spectrum of weather systems at the latitude of the circumpolar trough from minor vortices a few tens of kilometers in diameter to major depressions. Many of the mesoscale and small synoptic-scale disturbances are extremely important in weather forecasting and J. Turner (BAS) reported that within FROST it was found that many of these systems were poorly resolved in numerical analyses. Most FROST data are now available on a Web site operated by BAS (http://www.nerc-bas.ac.uk/public/icd/FROST/).

K. Jacka (Australian Antarctic CRC and ABOM) considered the question of analysis around the Antarctic and drew attention to studies of the impact of isolated observations on Southern Ocean analysis, showing that drifting buoys tended to have the highest impact. Analysis systems using a broad combination of different observing systems were believed to be of greatest reliability. Jacka gave examples of improvements in ABOM Global Assimilation Prediction (GASP) analysis quality following assimilation of both drifting buoys and scatterometer wind data in combination. The inclusion of such data from the Southern Ocean had positive impacts on the forecasts for more distant regions, such as Australia. PAOB (pseudo observations generated by meteorologists on the basis of hand analyses) were shown to also have a positive impact.

Satellite data allow a number of aspects of the Antarctic environment to be observed beyond simply the location and type of the cloud, and K. Michael [Institute of Antarctic and Southern Ocean Studies (IASOS)] and R. Massom (Antarctic CRC) discussed satellite remote sensing of katabatic winds and polynyas, using visible, thermal infrared, and microwave imagery. Polynyas are nonlinear areas of open water, reduced ice concentration, or thin ice that tend to persist and recur in areas normally expected to be ice-covered. Passive microwave radiometers, of which the Special Sensor Microwave/Imager is currently operational, provide a daily overview of global sea-ice extent (distribution) and concentration, uninterrupted by cloud and darkness. Monitoring the presence or absence of sea ice is of great importance in forecasting since the ice provides a very effective high-albedo cap on otherwise strong fluxes of heat and moisture between ocean and atmosphere (particularly in winter). Passive microwave data have been used to map polynya extent and variability in East Antarctica. Such data are not suitable for detailed studies, however, due to their poor spatial resolution (pixel size 25 km × 25 km). Higher resolution data from, for example, synthetic aperture radars such as that on Radarsat provide more detailed information on polynya extent and behavior. Katabatic winds play a significant role in both forming and maintaining coastal polynyas. Such cold and persistent strong winds lead to both the heavy formation of sea ice within, and its removal from, polynyas. Katabatic winds leave a thermal signature on the underlying ice sheet/ice shelf which can be detected in thermal infrared imagery. An example, from the Ross Sea, is given in Fig. 3. A major limitation on the use of visible and thermal imagery alone to detect and monitor surface features in Antarctica is persistent cloud cover (and polar darkness for visible imagery). Examples were also given of experimental techniques designed to help discriminate between the different large-scale sea-ice regimes constituting the East Antarctic pack, and between wind-roughened open water and first-year ice. Such techniques have great potential in aiding ships attempting to reach the research stations early in the short summer season.

Expert systems can also be of value for automatic sea ice analysis, and S. Pendlebury (ABOM), R. Williams (School of Computing, University of Tasmania) and K. Hill (IASOS) described one system for discriminating sea ice and clouds using NOAA Advanced Very High Resolution Radiometer (AVHRR) data, which are readily available on many research stations. The technique involves the use of the first four channels of AVHRR imagery and operating on them to produce numerical combinations (e.g., the difference between AVHRR bands 1 and 2). These combined products are then used in a decision tree to determine the type of surface conditions. While the current system operates in a pixel-by-pixel mode, it is hoped that future versions will take into account such factors as texture. Several case studies were presented, showing good agreement between the output of the system and that of ice analysts.

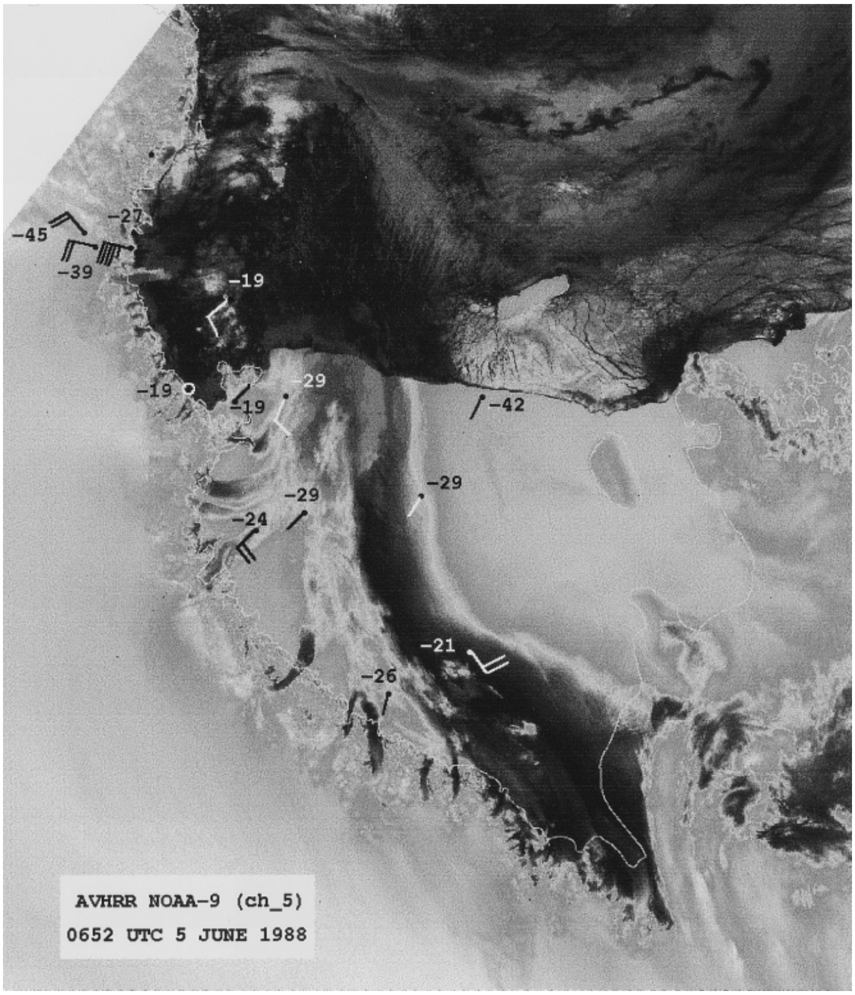

FIG. 3. Thermal infrared satellite image (from the Advanced Very High Resolution Radiometer, channel 5) from 5 June 1988 showing katabatic winds (dark signature) from West Antarctica (in the lower right) propagating about 1000 km across the flat Ross Ice Shelf (in the center) to the Ross Sea (in the top left). These winds blow along the regional isobars associated with a synoptic-scale cyclone to the northeast of the Ross Ice Shelf. Simultaneous automatic weather station observations of wind and air temperature are plotted. The AVHRR image from *NOAA-9* was collected at McMurdo Station on Ross Island by U.S. Navy personnel and archived at Scripps Institution of Oceanography. Image courtesy of Dr. D. Bromwich and the Byrd Polar Research Center.

The analysis techniques employed at a number of Antarctic stations were described during the meeting. Turner (BAS) discussed the procedures in use at Rothera where model analyses and forecasts from the United Kingdom Meteorological Office are available, along with high resolution satellite imagery and AWS observations. The satellite data are very important for verifying the accuracy of the model fields and for analysis of the many mesoscale weather systems that affect the area. Conventional frontal/mean sea level pressure (MSLP) analyses are still prepared manually every six hours since the model data lack the small-scale structure that is very important in forecasting. Over the interior of the continent, where there are few conventional observations, a nowcasting approach is taken with short “movies” of satellite images being analyzed to determine the motion of clouds. By far the most valuable form of satellite imagery during the daylight hours is the 3.7-μm data, which allow a good discrimination to be made between cloud composed of water droplets (often supercooled) and the ice surface. Such data are also of great value in preparing the surface frontal analysis.

T. Gibson (honorary research associate, IASOS) discussed the identification of tropospheric jet streams over Antarctica, a subject that he felt had received too little attention in recent years. Tropospheric jet streams affect synoptic developments, and high temperatures and other anomalous surface conditions can occur over the high plateau in association with strong jet streams inland, for example, at Vostok with a strong jet stream and warming aloft the inversion can break down. The jets are associated with two fronts; the polar front, which is located climatologically around 50°S, and what is often called the “Antarctic front,” which is usually in the zone 60°–70°S.

Gibson thought that numerical models analyzed jet streams well, although other data, such as water vapor imagery and cloud drift winds, can also be of value in identifying the jets. In the absence of conventional data, jet streams are often located using characteristic values of thickness, as recently outlined in Phillpot (1997). However, Gibson believes that another closely related parameter—the layer–mean value of the moist static energy (m)—is an even better indicator of jet locations. Some examples were presented, showing close correspondence between the polar jet and an isoline of the mean "m" value for the 500–300-hPa layer.

In recent years attempts have been made to produce high quality reanalysis datasets of operational data, with both the U.S. National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) preparing multiyear global reanalysis datasets. In a talk by D. Bromwich (presented by Turner) it was shown that the ECMWF products have some problems over the interior of Antarctica (neither Vostok nor South Pole data were fitted as well by the reanalyses as by the original operational analyses). In particular, differences appear to be positive over East Antarctica and negative over West Antarctica. Although the sources of all the differences are not yet fully explained, it is understood that ECMWF has been using an incorrect height for Vostok Station. In discussion, reference was also made to the problems of finding the elevation of AWS stations in the interior of Antarctica and the possibility of errors arising from that source. Some AWS elevations are well known, but there are old stations whose locations may have changed during the course of the last 40 years, with attendant changes in elevation. Even when changes in location have not occurred, there remain problems in updating station histories to match the available data.

G. Mills (ABOM Research Centre) discussed strategies for numerical diagnosis in high latitudes, including objective identification of fronts and the impact of ship-launched radiosondes on NWP. The models can resolve the structure of many weather systems and represent a significant resource to the Antarctic forecaster provided they are prepared to use them in verifying the existence (or nonexistence) of the expected forcing and response, given the specific conceptual model that the forecaster thought appropriate for the particular situation. He felt that the tendency to use conceptual models to correct model output is an example of improper use of both numerical and conceptual models. He drew attention to the utility of high resolution models in detecting upper-level forcing preceding cyclogenesis, and showed an example of detection of a front using model output, pointing out that the wide divergence between manual frontal analyses could be reduced with the use of objective guidance.

5. Numerical model prognosis

N. Adams (ABOM) and D. Campbell (ABOM) reported that at the Antarctic Meteorological Centre (AMC) at Casey, numerical guidance from ECMWF, the ABOM GASP system, and NCEP (aviation run) were used. The ECMWF products are held in high esteem for their general accuracy; however, the AMC only receives a subset of the ECMWF data, which comprises 5 degree × 5 degree grid-point MSLP and 500-hPa height data received once each 24 h. This poor spatial and temporal resolution, plus lack of diagnostics, is a serious limitation to the overall utility of an otherwise useful product. On the other hand, a comprehensive set of fields and diagnostics is received from the GASP model each 12 h, but the spatial resolution is still relatively poor at 2.5 degrees × 2.5 degrees.

The NCEP (aviation run) model output is the most useful numerical guidance at the AMC, with full diagnostics every 6 h at 1-degree resolution on numerous sigma levels. However, the receipt of NCEP model data was not reliable and so GASP information was most often used.

Software has been developed to extract flight information for both the QANTAS operations (described by Captain Dennis earlier) and low-level helicopter operations, allowing a pictorial representation of winds, temperatures, and relative humidity. Forecast nephanalyses (cloud charts) are also produced from the NCEP data and are popular with users. Simulated radiosonde flights are also created from the forecast data, with good vertical resolution.

As part of a Ph.D. thesis, Adams is adapting the ABOM's Limited Area Prognosis System (LAPS) model for use over the Antarctic and hopes to have this model quasi operational by the summer of 1999.

K. Batt (ABOM) and L. Leslie (University of New South Wales, Australia) reported on the performance of a high resolution numerical weather prediction model over the Southern Ocean. Their model is not dissimilar to the current ABOM's LAPS model: both are essentially described in Leslie and Skinner (1994). Briefly, the model can be run at resolutions of between 50 and 15 km and 16 to 31 vertical levels, 6 hourly cycling, and 2′ by 2′ orography; higher resolution topography is being experimented with over New South

Wales, Australia. The model is designed to be nested in any global model. Referring to testing of the model, Batt reported on its use in the Auckland-to-Cape Horn-to-Brazil leg of a recent Whitbread Round the World yacht race. Comparing the model results with yacht observations suggested that model performance is reasonable. Further testing over the Southern Ocean was carried out with the mesoscale model nested in the ABOM's GASP model and run to 7 days. Australian National Meteorological Operations Centre Indian Ocean analyses were used for verification using a geostrophic wind scale to simulate observed wind speeds. The domain used was 40°S to the Antarctic coast and the model was run at both 50-km and 15-km resolutions with the results for the latter resolution being the more accurate. On the other hand the finer resolution runs showed a lot of detail that would be difficult to verify in a data-sparse area. In the future, the model will be run during periods when Antarctic resupply vessels are operating in order to obtain some real-time observations for verification purposes. The presenters would also like to run the model over coastal Antarctica in areas where observations are more plentiful.

6. Forecasting

It was evident from papers delivered at the symposium that considerable attention is being given by nations to the problem of weather forecasting for the Antarctic. Forecasting strategies varied from being climate based, through use of a conceptual model in conjunction with numerical guidance, to a single station nowcasting approach.

a. Climate studies

I. Barnes-Keoghan (ABOM) and D. Shepherd (ABOM) highlighted the utility of climatology as a tool for seasonal planning and as a "first guess" for forecasts for Antarctic operations. However, these contributors cautioned that there will usually be some errors in climatological datasets. Moreover, site changes such as the relocation of the Casey site in 1969 invariably give rise to inhomogeneous data. Nevertheless, much effort is being devoted by nations to maintaining viable databases. For example, the ABOM has developed an Australian Data Archive for Meteorology. This presently includes only Australian stations (in Australia and in the Antarctic), but some non-Australian Antarctic stations may be included in the future. The data stored in the database include synoptic reports, typically at 3-h intervals, along with daily values (such as minimum temperature or sunshine hours) together with monthly summaries.

Barnes-Keoghan showed monthly statistics for Davis (data available from 1957), Mawson (1957), Casey (1969), and Macquarie Island (1950). For intercomparison purposes, statistics were produced for each of these stations for the period 1969 to 1997. Elements presented were snow days, fog days, visibility at 3000 m or less, sunshine hours, cloudiness, high and low air temperatures, wind roses, wind gusts, and aircraft ceiling limits (taken as more than 4 octas of cloud below 1500 ft). The visual observations (visibility, cloud, etc.) were taken from 3-hourly observations.

By examining such data the presenters argued that decisions could be made on basic planning for operations. For example, for aviation purposes the sub-Antarctic Macquarie Island was the most difficult of the Australian operated stations with frequent problems with cloudiness and reduced visibility. On the Antarctic continent itself, Casey is least favorable for aviation operations due to a relatively high prevalence of onshore moist airflow. Mawson enjoys good visibility but is very windy, although with a fairly consistent wind direction. Davis is the best Australian Antarctic station for aviation, with best overall visibility and lowest average wind. Severe wind gusts are common at all stations.

Another climatological tool of use in the forecasting process was the analysis of synoptic features such as the locations of high and low pressure systems. R. Leighton (ABOM) and I. Simmonds (University of Melbourne, Australia) illustrated this point by discussing the variations in July cyclonicity across the Southern Hemisphere for the years 1973 to 1994. Using ABOM analyses, Leighton extracted by hand the frequency of closed centers in 5 degree × 5 degree squares. When a low first appeared on a chart it was retraced to where the wave first appeared. This process has led to conclusions such as the following: there are six main cyclonicity maxima around the Antarctic coast; on mean MSL charts Indian Ocean pressure gradients are tighter than in the Pacific Ocean; the Pacific Ocean is the most marked blocking region for the Southern Hemisphere (there is nearly always a block in it somewhere); blocking is rare in the Indian Ocean; but another region of pronounced blocking is the western Atlantic Ocean. Blocks in the Pacific and Atlantic Oceans will produce ridges south of Tasmania and just east of South America. These ridges may link via the Antarctic and may form a pulsing dipole in which high pressure cells wax and wane alternately within the Pacific and Atlantic Ocean ridges.

Simmonds has undertaken similar studies using an automatic vortex detection technique (Jones and Simmonds 1993). Simmonds et al. (1999, manuscript submitted to *Aust. Meteor. Mag.*) report on a comparison between the manual and computer methods, with the latter leading to more synoptic centers than the manual method. During the symposium Leighton and Simmonds also cautioned that climate change may alter the currency of climate-based forecasting techniques. They reported, for example, that preliminary work has shown the following variations in cyclonicity; the 1980s had less cyclonicity than the 1970s along the Australian sector of the Antarctic coast but increases in cyclonicity have occurred near latitude 55°S. In particular, at 55°–60°S cyclonicity increased from 1985 in the Eastern Hemisphere with the greatest increase in the Indian Ocean sector.

b. Real-time weather forecasting

There were a number of talks that dealt with forecasting techniques and procedures used on the Antarctic research stations. Here we present a summary of these presentation groups by meteorological element or forecasting problem.

1) FRONTAL DEPRESSIONS

M. de Keyser (Belgium) discussed frontal depressions crossing the Antarctic Peninsula. He prefaced his remarks by noting that numerical modeling of high southern latitude fronts seemed not to be as reliable as that of their Northern Hemisphere counterparts and so the 500-hPa and 1000–500-hPa charts were used to characterize the southern fronts. Over the ocean areas the classic "Norwegian" frontal model could be applied to many fronts. Typically such a classic front would be associated with considerable warm advection ahead of the front with rain and drizzle commencing when the 500-hPa ridge ahead of the front passes the station. In the warm sector water droplets in the warm air mass fall through the cold air mass ahead of the warm front, hence the drizzle and rain comprise supercooled droplets and freeze on contacting any object. This is a particular hazard for aviation as the process may lead to 3–4 cm of icing on an aircraft within 5 min.

De Keyser felt that in the high latitude areas of the Southern Hemisphere fronts tended to develop more rapidly than those in the Northern Hemisphere. It is surmised that cold Antarctic continental outflow increases horizontal temperature gradients and hence baroclinic instability. Certainly fronts often intensified while crossing the Antarctic Peninsula, giving rise to considerable snowfall at Rothera.

2) MESOSCALE WEATHER SYSTEM

Turner (BAS) discussed mesoscale cyclonic activity around the Antarctic noting that he was referring to cyclones with a length scale of less than 1000 km and systems that usually, but not always, lasted less than 24 h. More particularly, he noted that many such systems had diameters in the range of 300 to 500 km, with mesocyclones near 1000 km being much less common. Turner noted that mesocyclones occur poleward of the polar front with most being found over the ocean, although some systems form over the larger ice shelves (e.g., the Ronne ice shelf). Mesocyclones can have a significant effect on regional weather; for example, such lows are reported to be responsible for 40% of snowfall at McMurdo (Rockey and Braaten 1995), while cold outflows on the western flank of mesolows over ice shelves may lead to polynya formation.

T. Yates (ABOM) also discussed mesoscale lows and spoke on shallow mesolow development. He noted that such lows are often observed in the Prydz Bay region and tend to be unrelated to obvious large scale forcing. Although small in scale (of order 100-km diameter, see Fig. 4) these lows are significant to aviation operations as they are associated with surface winds of 15 to 20 m s^{-1} and with low cloud. Yates proposed a conceptual model of these lows:

- preexisting surface vorticity due to the climatological cyclonic curvature of flow over the Amery Ice Shelf;
- there may be a weak trough aloft, identified at, say 500 hPa;
- the mesolow formation was argued to result from katabatic surge exiting the Amery/Lambert Basin; and
- the baroclinicity resulted from warm air advection due to northeasterlies over the coastline near Davis and cold air advection due to southerlies along the western side of the Lambert Glacier.

3) ATMOSPHERIC BLOCKING

M. Pook (Antarctic CRC) linked the broad-scale climatic approach to the regional scale through a discussion of how blocking affects storm tracks over East Antarctica. Several examples were discussed, which involved significant effects of blocking on Antarctic weather. The first example occurred in 1952 and was described in Schwerdtfeger's seminal book (Schwerdtfeger 1984) on the climate and weather of the Antarctic. This example of blocking was over the Weddell Sea, southeast of South America. The second event, while not of blocking per se, did involve a slow-moving ridge downstream of the Casey area in the summer of 1983/84, which was instrumental in steering synoptic systems onto the coast. The third example occurred in the winter and early spring of 1989 when major blocking was present over the southwestern Pacific. The effect of this blocking was evident in the record from ice cores drilled in Law Dome (close to Casey Station) showing up as an anomalously warm period of enhanced precipitation in September 1989. In other words it resembled a summer signature in the ice core record.

Another example of how blocking has a significant effect on Antarctic weather occurred during the FROST period of July 1994. In this case satellite imagery illustrated how intense and persistent blocking in the eastern Pacific steered lows toward the Antarctic coast just eastward of the Ross Ice Shelf. This was followed by a westward shift in the blocking in the latter part of the month when rare examples of vortices over the continent were identified by their cloud signature and identified at the surface by AWS data (Pook and Cowled 1999).

4) Forecasting for aviation and field activities

L. Cowled (ABOM) discussed forecasting for aviation in the Vestfold Hills/Davis area, Southern Prince Charles Mountains (72°S, 67°E), and Mawson. In particular he concentrated on the forecasting of gales for Davis and Mawson and the forecasting of

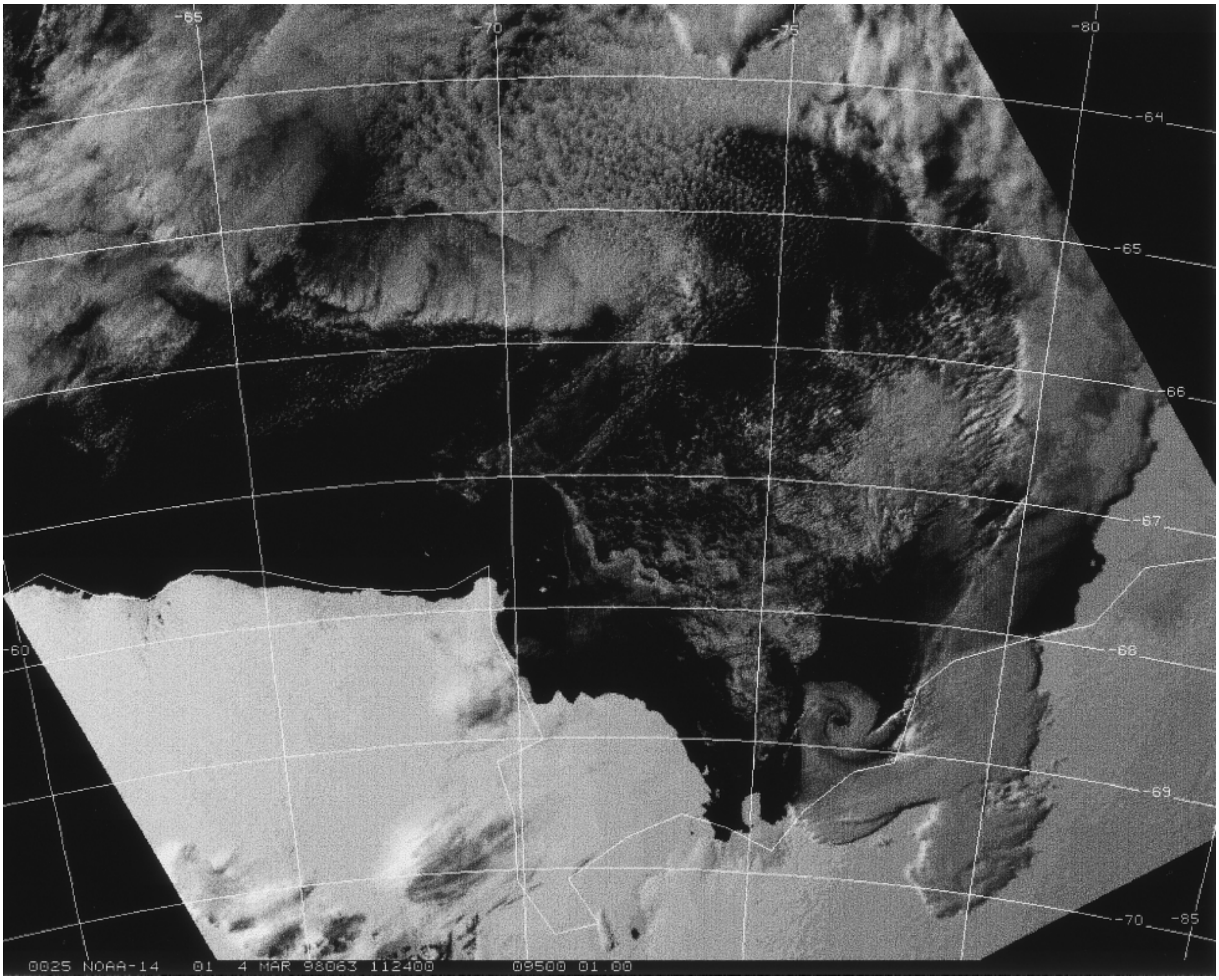

FIG. 4. A shallow mesolow in Prydz Bay.

cloud over the Prince Charles Mountains. A route census was performed during the 1997/98 summer season, employing afternoon NOAA imagery to estimate whether flights were possible each day from Davis to Mawson, Casey, and the Prince Charles Mountains. The results indicated that an average delay of one week due to weather could be expected for a flight to Mawson and two weeks for a flight to Casey.

Gales at Davis were often caused by synoptic-scale lows that were generally well forecast by global models. However, a significant fraction were caused by mesoscale lows. On one occasion, gale force winds could not be attributed to anything other than a continental outflow (possibly in the form of a katabatic jump). AVHRR infrared imagery at the time of the outflow showed katabatic outflow signatures. For Mawson, the anecdotal wisdom for gale forecasting was recounted: arrival of a frontal cirrus band generally indicates rapid strengthening of the surface wind to become strongly supergeostrophic. Although a rapid pressure fall generally leads to gales with the passage of a depression close to the station, gales often occurred without significant pressure falls.

While in Cowled's experience wind appeared not to be a major problem over the Southern Prince Charles Mountains during the summer, cloud certainly provided difficulties with maintaining a visual horizon reference. Cowled showed ECMWF composite charts (aggregation of many case studies) indicating northerly flow at 500 hPa over the Lambert Glacier at the time of deterioration in weather over the southern Prince Charles Mountains. Such inflow was difficult to detect on individual charts. During discussion, I. McCarthy cautioned against the assumption of light winds over the Prince Charles Mountains in summer as the surface wind characteristics may vary between seasons.

J. Nairn (ABOM) reported on a season of forecasting at Edgeworth David, which was an Australian summer camp established in the Bunger Hills (66.2°S, 100.9°E) for seven weeks in the summer of 1985/86. It was only accessible by helicopter and was some 70 km inland from the ice shelf edge. Forecasts were mainly for helicopter and field party operations. The main elements forecast were whiteout, cloud cover, snow, blowing snow, rain, wind velocity, and turbulence. The weather during the season was fairly poor and only about two days out of seven were especially good for helicopter operations. The main cause of the poor weather was passing synoptic-scale systems.

Nairn suggested that for single station forecasting techniques at a field camp the forecaster required portable AWSs (up to three); radio transmitter and facsimile receiver; pilot balloon wind finding; equipment for observation of temperature; dewpoint, and pressure (digital and barograph); and Automatic Picture Transmission equipment for satellite imagery reception.

5) FORECASTING FOR THE MAWSON–DAVIS AREA

J. Callaghan (ABOM) presented two broad-to-regional-scale-based conceptual models of weather effects in the Mawson–Davis area (67.6°S, 62.9°E) of the Antarctic. First, blizzard conditions at Mawson may be associated with a longwave ridge at 55°S just downstream of the Mawson–Davis longitudes. Typically a frontal cloud band approaches Mawson from the northwest with winds above 500 hPa veering to the north and with low-to-middle-level warm air advection occurring approximately 12 h before the onset of blizzard conditions. Second, if the ridge is farther east, say east of Casey for example, and there is a long-wave trough near Davis–Mawson then westward moving cloud bands can occur over the Mawson–Davis area (Callaghan and Betts 1987). This second conceptual model envisages that, typically, the long-wave ridge east of Casey would steer lows southward toward the Casey coast. Frontal cloud bands associated with these synoptic-scale cyclones would approach the Mawson–Davis area from the east, circulating around the lows blocked or slowed by the ridge.

Callaghan concluded by linking the broad-scale pattern with the mesoscale when he noted that with a long-wave trough over the Prydz Bay area (69°S, 76°E), and strong upper-level northeasterlies over Davis, low-level mesovorticies often occurred over Prydz Bay. Some of these, he surmised, might approach tropical cyclones in wind strength near their center.

M. Jones (ABOM) also explored synoptic/mesoscale aspects of cyclonicity in the Prydz Bay/Mawson region. Jones reported that from her experience, the ECMWF analyses agreed well with features that were identified on satellite pictures. She also reported that when a 500-hPa trough is to the west of the area mesocyclogenesis is common. Figure 5 shows a small low that has developed while moving into a preexisting upper trough located over Mawson longitudes. Moreover, she indicated that a weak 500-hPa trough or a closed 500-hPa low to the north of latitude 60°S is particularly favorable for mesoscale development along the coast to the south.

Jones reported that the weather associated with fronts at Davis depends on their direction of approach. Those approaching from the Antarctic plateau often produce virga but no snow, while those approaching from the sea had relatively stable uplift ahead and convective activity behind. She also indicated that at Mawson most fronts that approach from the sea almost invariably bring blizzards and blowing snow. On the other hand, fronts approaching Mawson from the east usually have lost most of their moisture and arrive as fragmenting cloud bands.

Jones joined Pook and Callaghan in drawing attention to the importance of the broadscale control on regional weather by discussing various characteristic 500-hPa patterns in the Mawson Coast/West Ice Shelf region. In doing so a number of sequences of satellite imagery were shown of the East Antarctic area. One situation involved a major long-wave trough upstream of Mawson–Davis. The trough intensified while moving slowly eastward. The imagery showed intense cyclonic activity and fronts unfurling over the continent. Gale to storm force winds occurred at Mawson.

Another sequence involved a major long-wave ridge over the Mawson–Davis area with the imagery showing clear skies over the region. A return to relatively zonal flow near and south of 60°S in a third sequence showed lows moving rapidly eastward with very little development or decay, and, again, clear skies over the continent.

6) Katabatic winds

P. Pettré (Météo-France) reported on his work on the forecasting and forcing of strong katabatic events and hydraulic jumps at Dumont d'Urville station (Gallée and Pettré 1998; Pettré and André 1991). Noting that there had been discussion on the definition of katabatic wind in the Antarctic, Pettré indicated that he considered katabatic flow to be wind blowing

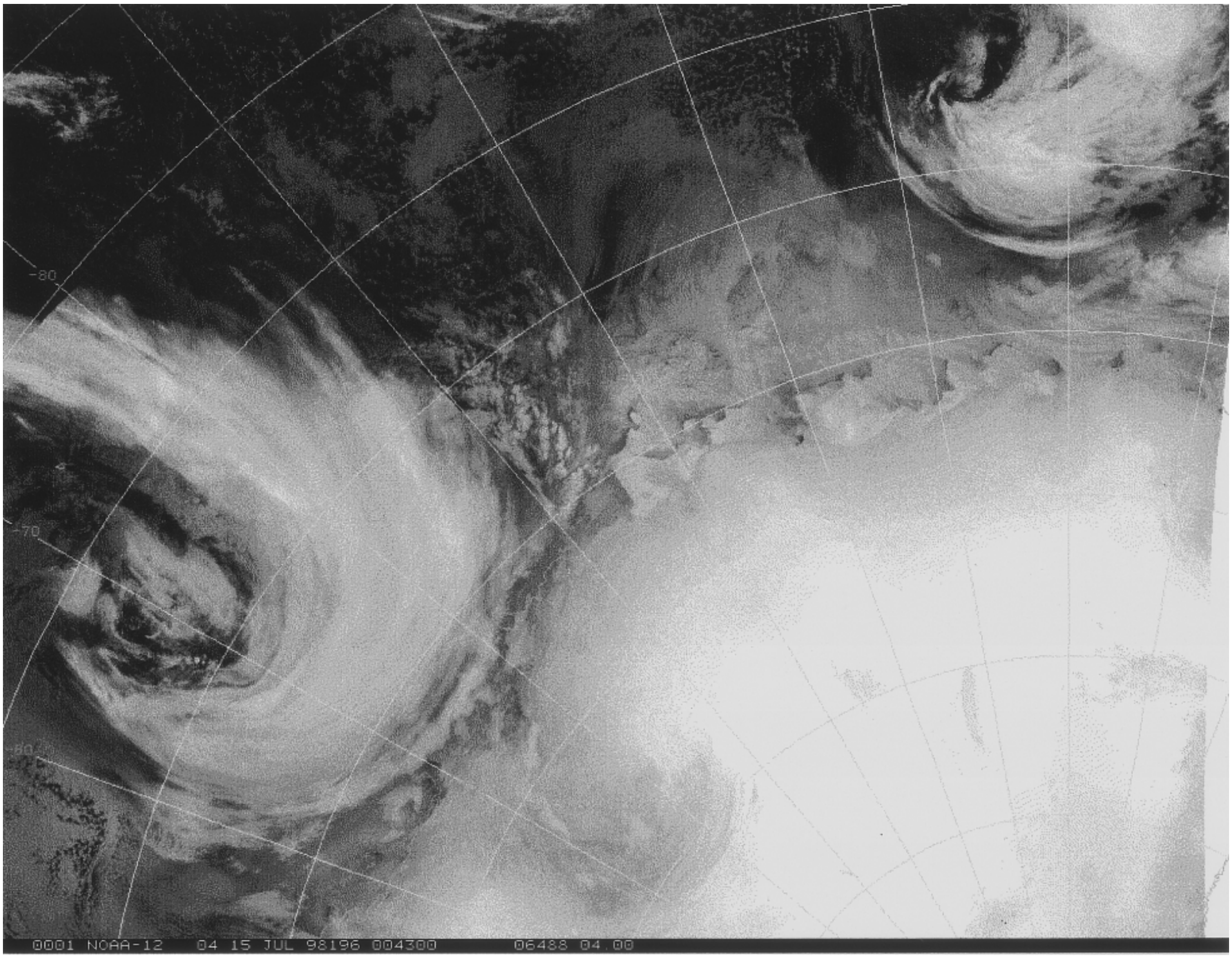

Fig. 5. A mesoscale low north of Mawson.

down a slope under a temperature inversion where the wind is caused by gravity, the air near the slope being more dense than that at the inversion height. The hydraulic jump is a transition zone between Froude number > 1 and < 1. The jump zone may move upslope or downslope and gives a mixing of a warm air intrusion with katabatic layer.

Pettré noted that the katabatic wind strength may depend on the slope of the surface, the horizontal pressure gradient within the inversion layer, the large-scale pressure gradient, and turbulence. Each term may be of similar order of magnitude. For operational use Pettré has proposed a katabatic forecasting index using three parameters: (i) the large-scale pressure gradient due to synoptic systems, (ii) the temperature at Dome C (75°S, 125°E) (a lot of cold air inland is a requirement), and (iii) wind speed at Dome C (indicates penetration of systems into the continent).

P. Targett (ABOM) discussed hydraulic jumps and the wind regimes over the Vestfold Hills (68.5°S, 78.2°E). He reminded the symposium of the work of Lied (1964), who reported one to two hydraulic jumps per week near Platcha (68.5°S, 78.5°E) over a 4- to 5-month period. One of the most extreme of these events involved a pressure discontinuity of about 20 hPa. Targett reported two events of similar intensity over a comparable period of time. On the other hand, Phillpot, during discussion, reported to the meeting that he had only found one significant jump at the nearby Davis station in 12 months of data. This begged the question as to whether there was marked spatial variability of jumps in the Davis–Vestfold Hills area, or whether there is a large interannual variability of hydraulic jumps in the area. It may be inferred from the case studies presented by Targett that there does appear to be marked spatial variability in the presence or strength of hydraulic jumps over the Vestfold Hills. In particular, Targett showed one example of a 10-hPa jump that decayed between Brookes and Davis, 12 to 25 km from the plateau ice edge, while another 10-hPa jump was observed at Davis some 25 km from the plateau ice edge.

In common with Pettre's view, Targett indicated that strong winds over the Vestfold Hills were most often associated with an oceanic low or meso low. In the case of the Vestfold Hills, Targett speculated that perhaps the hills trapped large amounts of cold air, the inertia of which takes a lot of wind to overcome.

7) Fog and low stratus

De Keyser discussed fog and low stratus formation around the Antarctic Peninsula but in doing so summarized a number of generally applicable processes of fog formation. In one of these processes moist air crossing sea ice may cool to saturation resulting in the formation of an inversion and fog formation beneath the inversion. Often rapid formation of thick fog resulted. The source of moisture may be the open ocean while air flow from over nearby polynyas is also a common source.

Fog is also generated from the melt pools that form on the ice shelves. At the end of summer, temperatures above zero extend as far south as Fossil Bluff (71.3°S, 68.2°W) in King George VI Sound. While the ice surface temperature is about −6°C the melt pools are about 0°C, so evaporation from the "lake" to the colder air above produces stratus in the unstable layer below the inversion. Continued advection of air from over the colder ice may produce fog from the inversion level to the ground. If a front crosses at the same time enhanced precipitation results due to the saturated lower levels. Moreover, in light wind situations, fog formed from the melt-pool moisture source may persist for days.

Regarding the formation of stratus, de Keyser identified three mechanisms for its formation: topographic lifting, turbulent mixing, and the thermal contrast across the Antarctic convergence. As an example of the topographic effect de Keyser referred to the Sky Hi (74.6°S, 70.5°W) summer station, which is on the side of a topographic ridge. Where the air flows up the ridge it cools adiabatically and while generally no precipitation results, condensation often leads to stratus at the ridgetop. Stratus so formed persists as long as the air trajectory and air mass remain. On the other hand, in a weather situation where the Sky Hi station is in the lee of the ridge the base enjoys good weather.

In relation to the formation of stratus due to turbulent mixing, stratus may form in the mixed layer beneath the inversion formed by the mixing. If mixing extends upward, for example with a strengthening wind, the stratus dissipates as the inversion vanishes. Fog close to the Antarctic Convergence has its basis in the convergence's strong gradient of sea surface temperature. Fog or stratus forms where this gradient is strongest. Two peninsula stations [Marsh (62.4°S, 58.9°W) and Marambio (64.2°S, 56.7°W)] are very close to the Antarctic Convergence so they have frequent stratus problems.

McCarthy described three interesting fog-type occurrences observed during Antarctic field operations in the western parts of East Antarctica. The first occurred at Mount King (69.9°S, 69.5°E), the site of an

Australian field camp at an elevation of 1120 m, located 120 km from the nearest coast. Even when the sea ice was present, it contained some leads and open water, which provided a moisture source. On occasions, usually during the mid to late afternoon, a light westerly set in, as opposed to the usual easterly. This resulted in warm moist air being advected upslope from around the coast. The rising air cooled to saturation and formed a low stratus/stratocumulus cloud bank, which when advected farther upslope became fog. Although air temperatures were typically −5° to −8°C on fog afternoons, the Tula and Scott Mountains nearer the coast recorded temperatures as high as +8°C giving plenty of potential for moisture uptake. The deposition of rime icing in such situations was very pronounced and on one occasion got into the helicopters' turbines causing two in-flight helicopter engine failures. Figure 6 shows a difficult forecasting situation as fog developed at the Mount King, Enderby Land, summer camp at around midnight just prior to a Pilatus Porter aircraft landing.

The second event occurred over the Lambert Glacier/Manning Nunataks area in 1990. On this occasion three helicopters flying eastward across the Lambert Glacier toward Manning Nunataks on the eastern escarpment of the glacier encountered fog about 10 km west of the escarpment edge. The moisture source was thought to originate from a series of large melt lakes that had formed on the surface of the glacier the previous day. The morning following this fog event, most of the previously observed melt lakes had disappeared.

The third event occurred over the pack ice in August 1995, at 64.8°S, 140.8°E. This event, while not quite reaching the official fog criteria of visibility less than 1000 m, did, however, curtail aircraft operations because of reduced visibility. An ice crystal haze would probably be the best description of this phenomenon. The pack ice at the time was estimated at 10/10ths, wind speed was 10–12 m s^{-1}, and the temperature was around −24°C. As the morning progressed a haze developed around the ship producing spectacular optical effects of halos, arcs, parhelia, sun

FIG. 6. A Pilatus Porter aircraft landing downwind (note wind sock suggests a 10–15-kt easterly), as stratus/fog begins to stream in from the west (i.e., westerly starting to replace the easterly). The picture was taken during the 1976/77 summer season at the Mount King, Enderby Land, summer camp at around midnight.

dogs, and reduced visibility. No frost deposition occurred, suggesting supercooled water droplets were not present, but at times very fine ice crystals (“diamond dust”), could be seen in the sunlight. The “fog” was observed from helicopter reconnaissance to be 600 m thick.

7. Centers for Antarctic forecasting

Much of the Antarctic weather forecasting knowledge outlined above has been obtained through work at the various centers that have a focus on high southern latitude weather services. The symposium heard about meteorological forecast operations at stations operated by Australia, Brazil, China, France, Italy, South Africa, and the United Kingdom.

a. Australia

Adams and Campbell described the operations and systems at the Casey Antarctic Meteorological Centre and reported that the AMC is staffed during summer operations of the Australian National Antarctic Research Expedition. The AMC undertakes 6-hourly MSLP analyses and 12-hourly 500-hPa analyses, transmitting them via radio facsimile. Ice analyses are prepared at the AMC for limited areas on a weekly basis. During winter, products are also transmitted by radiofax, generally supplied by the National Meteorological Operations Centre in Melbourne. Because of limitations of data availability, model fields are usually used as a first guess, then modified in the light of AVHRR imagery and observations. Figure 7 shows the layout of part of the AMC.

Forecasts are provided to Casey personnel, also to Mawson and Davis stations in the absence of a forecaster at Davis. Support is provided for helicopter operations, usually on routes from Davis to Mawson, Casey, or into the Prince Charles Mountains. Shipping forecasts are prepared for all shipping between 60° and 160°E, with special forecasts available on request. A significant client is the Australian airline QANTAS, for whom specialized flight forecasts are provided for sightseeing flights from Australia.

Heavy reliance is placed on AVHRR data, as well as GMS and Meteosat data. Some difficulty is experienced with a data void near Davis and Mawson because of the gap between GMS and Meteosat coverage, and with the long period during the day between morning *NOAA-12* passes and the afternoon *NOAA-14* passes. As mentioned earlier, considerable use is made in the AMC of public domain GRADS display facilities, using the output of the ECMWF, Australian Bureau of Meteorology, and the U.S. NCEP models.

A full historical observations dataset is available at the AMC for Casey, with 10-s resolution radiosonde data collected for all Australian Antarctic stations. From this dataset a single-station analog forecast system has been developed for Casey, Davis, and Mawson stations. Given current surface and upper air conditions, a search is made of analogues within the station database. Analogs are displayed and rated as to the degree of fit and a forecast time series is prepared. Assessment of the system during the 1997/98 summer showed fair results for temperature but poor results for wind. Further work is in hand.

The ABOM usually staffs Davis station over the summer with one forecaster whose main concern is with S76 long-range helicopter operations (usually two machines) based at Davis. Services also provided by the Davis forecaster include local forecasts for Davis and Mawson, as well as for field parties in the southern and northern Prince Charles Mountains and Law Base (69.4°S, 76.4°E). The Davis forecaster is also available for consultation via HF radio by shipping in Prydz Bay. While the Davis forecaster is supported by an on-site Automatic Picture Transmission receiver, and on-site weather analysis, support is also provided in the form of AMC (Casey) produced satellite pictures, numerical products, manual analyses, and forecast discussions.

B. Southern (ABOM) outlined the role of the Australian National Meteorological Operations Centre (NMOC), with a focus on the utility of the Australian GASP model for Antarctic forecasting. He said that NMOC is responsible for the maintenance (and to a lesser extent development) of the Australian numerical forecast models, as well as the continual hemispheric-scale analysis program in support of all Australian meteorological offices. A staff of 40 people provide round-the-clock analysis and prognosis products, oceanographic products and real-time data management. Pseudo observations (PAOBS) are generated for insertion into global models, alleviating data limitations over oceanic areas.

In regard to modeling, NMOC expends significant resources, both staff and machines, in maintaining the reliability and timeliness of the models they run. They can supply boundary conditions for local area models and remote users can run models on the NMOC’S SX-4 computer. Local area modelers (within the Australian Bureau of Meteorology) should therefore coordinate their efforts with NMOC for best results.

NMOC can also supply many forecasts on demand from its model output, for example, route forecasts for Antarctic operations to and from the continent. GASP is the appropriate model for such efforts, since the domain of the higher resolution model (LAPS) ends at 65°S.

It is acknowledged that relative humidity fields are poorly represented over the Antarctic continent in the GASP model, resulting in spurious maxima in precipitation ("bull's-eyes"). In view of the low humidity over the Antarctic, this is not seen as a serious limitation at present. Forecasters should use the Australian Wave Model sea and swell forecasts near Antarctica with caution. Although GASP sea ice fields are updated weekly, there is no consideration of sea ice in the sea-state model resulting in unrealistic propagation of swell waves south of the ice edge.

b. Brazil

C. Hungria (Antarctic CRC but representing Brazil) described the meteorological activities in the Brazilian Antarctic program and noted that they have four main objectives.

1) Meteorological research related to the region north of the Antarctic Peninsula. The main investigations at present relate to various chemical, meteorological, and human impact studies.
2) Operation and maintenance of a small meteorological unit at Comandante Ferraz Station (62.1°S, 58.2°W) for unattended data collection to supply the needs of the program and to provide weather forecasts for logistic/scientific operations.
3) Maintenance of AWSs in remote sites with direct data reception at Comandante Ferraz station and also at the Brazilian Navy support/research vessel *A. Rongel* using NOAA–Argos retrieval.
4) Technical developments.

Hungria indicated that the Brazilian program was committed to the following future developments: dissemination of real-time historical data through a Web site; the development of a new meteorological laboratory in the summer of 1998/99 at Comandante Ferraz including the installation of a year-round HRPT satellite receiver; input of AWS data to the WMO network in real time; and the installation of new AWS at Peter I Island (68.8°S, 90.6°W) and Elephant (61.1°S, 55.1°W) Islands.

c. People's Republic of China

B. Lingen (Chinese Academy of Meteorological Sciences) outlined aspects of the meteorology and weather service of relevance to the Chinese stations of the Great Wall (62.2°S, 59.0°W) and Zhongshan (69.4°S, 76.4°E). He indicated that although radiofax broadcasts from other nations have been employed in the past, they have been insufficient to allow accurate forecasting for shipping and land operations near the two Chinese stations. Accordingly, HRPT facilities have been installed at Zhongshan and the Great Wall. Moreover, there are plans to improve communications links at Zhongshan and to place AWSs in the interior of Antarctica via ice traverses.

Lingen said that strong wind forecasts remain the most important element for Chinese activities and several classes of MSLP analysis have been identified as being significant for gales at the Great Wall station. Two of the classes appear to involve either the intensification of a high pressure system over Antarctica or over South America, leading to strong gradients over the Drake Passage. A third class involved strong ridging from a high centred to the northwest in the southeast Pacific. At Zhongshan, strong winds are most commonly due to katabatic winds, which are not as easy to predict as large-scale phenomena, but which are well resolved by model output.

FIG. 7. The Antarctic Meteorological Centre at Casey.

d. Italy

F. Coppola (Italian Weather Service) presented information on the Italian Antarctic weather forecasting service by outlining meteorological operations at Terra Nova Bay (74.7°S, 164.1°E). Antarctic operations commenced at this station in 1985 with weather services being provided by the Italian Air Force. They operate from Christchurch, New Zealand, using two Squirrel and one Twin Otter aircraft.

At the Terra Nova Bay station the forecast service is based on HRPT facilities using NOAA and DMSP satellite data and on ECMWF analyses and prognoses. For the wider area prognoses a 3 degree × 3 degree grid is used. For the Victoria Land/Ross Sea area a 1 degree × 1 degree grid is used. The ECMWF fields that are available consist of wind, height, and temperature data at the 850-, 700-, 500-, and 300-hPa levels and at MSLP.

Coppola reported that the Trans-Antarctic Mountains affected communications in the early years of operation, requiring a larger antenna. The Twin Otters and helicopters have different weather requirements and on the base they can choose the mode of transport according to the expected weather. The Italians work with the French in Dome C operations by providing aviation services. They fly from Terra Nova to Dome C and then to Dumont d'Urville enclosing an area of 65 000 km^2. Fuel dumps lie halfway along each leg of the journey. The wind at Dumont d'Urville is often lighter between 0200 and 0800 UTC so flights are often planned for this period.

Great interest was shown in Coppola's report that the AWS at Dome C not only measures wind velocity, air temperature, relative humidity, and station-level pressure but also visual parameters such as cloud cover and ceiling, vertical and horizontal visibility. Moreover, the AWS provides the observations in special criteria/METAR format.

e. South Africa

While not attending the symposium, I. Hunter [South African Weather Bureau (SAWB)] supplied some written information on the SAWB's involvement in Antarctica. He wrote that a new South African National Antarctica Expedition base (SANAE IV) was completed at Vesleskarvet during 1997–98. [Vesleskarvet is a nunatak (rocky outcrop) at 71°40′S, 2°50′W, altitude 862 m, and some 170 km inland of SANAE III. The name of the nunatak has given rise to SANAE IV being affectionately known as "Vesles."] This is the first SANAE station on land and the first without meteorological personnel. However, an AWS at SANAE IV provides real-time data, which are available from the South African Antarctic Program online (http://home.intekom.com/sanae/weather.html) along with historical data in the form of monthly time series.

Moreover, the SAWB's Central Forecasting Office in Pretoria provides a weather forecasting service to the meteorologists on board the two vessels, which resupply SANAE IV. This service includes the relay of U.S. National Ice Center analyses and daily updates of five day forecasts of wind, weather, sea, and swell based on the ECMWF and U.K. Meteorological Office data, with the Bracknell wave model output also utilized.

Hunter indicated that the two resupply vessels deploy drifting buoys en route to the Antarctic and that SAWB has local user terminals on Gough and Marion Islands for the downloading of the drifting buoy data.

f. United Kingdom

Turner outlined the weather forecasting service for BAS logistical operations. The BAS operates five aircraft, including a Dash-7 (a four engined turboprop aircraft) and four Twin Otters. Flights are undertaken by the Dash-7 between the Falklands Islands and Rothera station in the early part of the Austral summer to help get researchers into the field. From Rothera, Twin Otters are used to move passengers farther south, for example to field sites at the base of the peninsula.

A forecaster is flown to Rothera early in the season, with a weather observer stationed at Fossil Bluff to the south. Daily briefings are provided to aircrew to aid in optimizing flying activities in light of the expected weather.

The Dash-7 operations are highly weather sensitive, as the aircraft does not have skis and few alternate landing sites are available. Twin Otter operations are not quite as sensitive in that the aircraft can be landed on ice. Forecasts are also provided for the two BAS research/supply ships.

Forecasts and synoptic data are extracted from a computer system in Cambridge (United Kingdom) twice each day. MSLP charts are hand analyzed using AVHRR channel-3 data and local AWS data collected via ARGOS.

In the future it is hoped that model precipitation fields can be made available and to include better orography for the Antarctic Peninsula in the operational models and, in the longer term, to possibly run a local-area model.

8. The weather forecasting handbook

In recent years a number of organizations have produced weather forecasting handbooks, including the ABOM, BAS, and the U.S. Naval Support Force, Antarctica. These have proved of great value to forecasters working in particular sectors of the continent, although they have not been widely circulated since they all deal with fairly limited areas of the Antarctic. They tend to be used in conjunction with textbooks on Antarctic meteorology, which contain some material relevant to forecasting (Schwerdtfeger 1984; King and Turner 1997). A major outcome of this symposium will therefore be a new Antarctic weather forecasting handbook that will hopefully be of value to all those concerned with weather prediction at high southern latitudes. The handbook will be split into two halves. The first will cover topics such as the accuracy of numerical model output over the Antarctic, interpretation of satellite imagery, and the mechanisms behind phenomena such as fog and katabatic winds. The second half will consist of forecasting information specific to locations across the continent and give details of local forecasting rules that are used. The handbook is being written by many forecasters with experience of working in the Antarctic and should be available (online and in hardcopy format) during the second half of 2000. Details on the progress and availability of the handbook can be obtained from the authors.

9. Future requirements and prospects

The symposium showed that great advances have been made during recent years in forecasting for the Antarctic as a result of our greater understanding of atmospheric processes at high latitudes, along with the availability of high resolution satellite imagery and the output of numerical models. However, there is still progress to be made in terms of collecting and making better use of data, and in improving the performance of models in the region.

Although the distribution of the research stations is adequate in some sections of the continent, there are still problems in West Antarctica where there are no observations between the Antarctic Peninsula and McMurdo. If a station cannot be established here then one or more AWSs should be deployed to fill this serious data void. It was also acknowledged in the introductory speech of Obasi that the lack of surface data from East Antarctica is a handicap to forecasting in the Antarctic as is the slowness in data transmission out of the Antarctic to the main analysis/forecasting centers. This may improve in the near future with the development of new satellite communications systems.

Although the resolutions of the global models run by the major weather services are gradually being improved they are still poor at representing the rapidly varying orography in areas such as the Antarctic Peninsula and in some parts of the Antarctic coastal zone. There is therefore a need for high resolution, limited-area models to be run for sections of the continent, either at centers outside the Antarctic or on the research stations themselves.

10. Conclusions

This First International Symposium on Operational Weather Forecasting in Antarctica proved very successful and the organizers were pleased that forecasters from so many countries could attend. It was unfortunate that no one from the United States could attend the meeting since, in addition to operating a large number of AWSs that are used in the forecasting process by many forecasters, the United States has a sophisticated weather forecasting operation at McMurdo Station in support of its aviation, marine, and field activities. However, it is hoped that U.S. forecasters will be able to make a very valuable contribution to the handbook.

In his farewell address H. Hutchinson (regional director, ABOM, Hobart) observed the growing maturity of Antarctic forecasting and forecasters' ability to relate their techniques and practices. It is hoped that the forecasting handbook that will come out of the meeting will be of value in improving international cooperation in weather forecasting in the Antarctic.

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Appendix: List of acronyms

ABOM	Australian Bureau of Meteorology
AMC	Antarctic Meteorological Centre

AVHRR	Advanced Very High Resolution Radiometer
AWS	Automatic weather station
BAS	British Antarctic Survey
CRC	Cooperative Research Centre
EAAN	East Antarctic Air Network
ECMWF	European Centre for Medium-Range Weather Forecasts
FROST	First Regional Observing Study of the Troposphere
GASP	Global Assimilation Prediction
HRPT	High Resolution Picture Transmission
IASOS	Institute of Antarctic and Southern Ocean Studies
LAPS	Limited Area Prognosis System
METAR	Meteorological Aerodrome Reports
NCEP	National Centers for Environmental Prediction
NMOC	National Meteorological Operations Centre
NWP	Numerical weather prediction
SAWB	South African Weather Bureau
SCAR	Scientific Committee on Antarctic Research
TAF	Terminal Airfield Forecasts
WMO	World Meteorological Organization

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