Antarctic Weather Forecasting Workshop
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Operational Antarctic Numerical Weather Prediction
72 h Forecast of Sea Level Pressure
Valid 12 UTC 12 January 2000

BYRD POLAR RESEARCH CENTER

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Columbus, Ohio 43210
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Current state of Antarctic weather prediction

George Howard
Lead forecaster, McMurdo Station, Antarctica

Space and Naval Warfare Systems Center, Charleston (SPAWARSYSCEN) assumed responsibility for operational weather support to the U.S. Antarctic Program from the United States Navy in October 1997. Mac Weather (McMurdo Station, Antarctica) and Deep Freeze Weather (Christchurch, New Zealand) provide year-round support to a wide array of customers including fixed- and rotary- wing aircrews, ocean-going ships’ crews, operational commanders and their staffs, mission planners, as well as the working and off-duty populace of McMurdo Station. In providing continuous austral summer support, Mac Weather and Deep Freeze Weather employ 16 people. Austral winter support requires only two individuals at McMurdo Station. Collected data includes satellite imagery, surface observations from weather observers and automated sensors, upper-air soundings, and retrieved forecast model products. Observational data amounts to less than 10% of that available to stateside forecasters.
Structure of forecasting within the U.S. Antarctic Program

George Howard
Lead forecaster, McMurdo Station, Antarctica

Aircraft, ship operations, and science projects in support of the United States Antarctic Program (USAP) cannot be carried out without timely and accurate environmental forecasts. The McMurdo Weather Office is the sole forecasting facility supporting USAP operations on the Antarctic continent. It acts as a central hub providing multiple terminal forecasts for operating stations and camps on the Antarctic continent, marine forecasts, flight forecasts for continental and intercontinental missions, and forecasts and warnings providing for safety of personnel. This presentation details how the McMurdo Weather Office supports a host of customers and provides a brief description of the forecasts provided. These include: Terminal Aerodrome Forecast (TAF), Flight Forecasts (DD Form 175-1), Horizontal Weather Depiction (HWD), En-route Weather Forecasts (WEAX), Point of Safe Return (PSR) Forecasts, Helicopter Forecasts, Local Area Forecast, Conditions of Readiness, Ice Forecasts and Special Weather Forecasts.
Data sources and their utility in Antarctic weather prediction

Art Cayette
Forecaster, McMurdo Station, Antarctica

U.S. Antarctic Program (USAP) weather data is gathered at the McMurdo Station, Antarctica office in various forms. It is collected to support a single forecasting hub for the USAP. Surface and upper-air observations are taken at McMurdo Station and the South Pole. McMurdo’s active runway(s), outlying camps, USAP ships, and automated weather sensors provide surface observations. Orbital and geostationary satellite data is collected and displayed on a SeaSpace TeraScan system and composite imagery loops are accessed via the Internet. Accessible computer models are reanalyzed with these data and used to construct forecasts for all required and requested USAP operations.
Operational Weather Forecasting for the British Antarctic Survey
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Introduction

The British Antarctic Survey (BAS) undertakes a wide range of atmospheric, biological and earth sciences research into the southern most continent and surrounding seas. This is carried out from three permanently manned research stations, by field parties in remote locations, from aircraft and from a research vessel. Their locations are shown in Figure 1, along with other areas mentioned in the text. Rothera, on Adelaide Island, is the centre for BAS deep field operations and from where field parties are deployed into the more remote areas of the continent. There is also an extensive diving program and associated small boating activity. Halley, on the Brunt Ice Shelf, is the most southerly of the bases and carries out meteorological and upper atmospheric research. Twin Otter aircraft are based there for all or part of each summer season carrying out logistic operations, field party deployments and survey work. Bird Island, on the north west tip of South Georgia is concerned with biological research. Access is only possible by ship. A summer only base is maintained at Signy Island and is involved in terrestrial and life sciences research. Access again is only possible by ship. Fuel depots at Fossil Bluff and Sky Blu are manned during the summer season.

In support of these bases BAS operates two ice strengthened vessels, the RRS Ernest Shackleton and the RRS James Clark Ross, with the former being mainly concerned with the re-supply of the stations and the latter having a dual research and re-supply role. BAS also operate four Twin Otter aircraft, which are fitted with both wheels and skis and a Dash 7 aircraft which provides an airlink between Rothera and the Falkland Islands. The Dash 7 also carries out aerial survey work and is used to ferry fuel drums and supplies to the depot at Sky Blu, where there is a blue ice runway. This aircraft is not fitted with skis and hence requires hard surfaces on which to land.
The Forecasting Requirement

A single forecaster is deployed to Rothera at the start of the summer season to provide forecast advice for all the Survey's activities in the Antarctic. Forecasts for the ships concern wind, weather and visibility and on occasions, sea state. These are issued once per day and are for the following 24 hours with an outlook for a further 24 hours. Detailed forecasts of wind, weather, visibility, cloud, contrast and icing conditions are required for the Air Unit. Personal briefings are provided early each morning with further briefings over the radio to any units deployed in the field. An ongoing watch is maintained throughout the day. Forecasts are also supplied to the Station Support Manager both at Rothera and Halley. Field party forecasts are also supplied once per day during their routine radio schedule. Forecasts are for wind, weather and likely cloud cover for the next 24 hours with an outlook for two days. Occasionally there are requests for forecasts from other national programs and also commercial operators.

Data Sources

Model guidance is from the UK Meteorological Office Global Model and is received twice per day from the 0001 UTC and 1200 UTC runs. These data are received from Bracknell via BAS HQ at Cambridge in GRIB code, with processing and re-mapping onto a polar stereographic map being carried out at Rothera. Charts are received of MSLP at T+0, T+12, T+24, T+36, T+48 and T+72, also 1000-500 hPa thickness charts and wind feather and contour charts at 850 hPa, 700 hPa, 500 hPa and 400 hPa. High resolution satellite imagery is also received from the NOAA satellites with around 14 passes a day being obtained. Resolutions of up to 1 km are available in the IR Channel 4, the near IR Channel 3 and visible Channel 2. Surface observations are also available from Bracknell via Cambridge covering parts of South America, the Falklands and the Antarctic Continent around the Peninsula and as far east as Neumayer. In addition 5 AWS observations from around the Peninsula are received plus field party reports.

The Forecasting Process

General Weather of the Area

The Peninsula is affected by many large depressions, a significant number of which become slow moving to the west of Alexander Island. Lows are reluctant to cross the Peninsula, although a new centre often develops to the east and may eventually affect Halley. The area around Sky Blu is often a 'graveyard' for fronts sweeping south across the Peninsula and hence cloudy conditions may persist for a considerable length of time. Mesoscale lows are common not only around the Peninsula but also on the Ronne Ice Shelf and in the area around Halley. Precipitation is variable from year to year and is mainly in the form of snow although rain does occur at Rothera and also on occasions at Fossil Bluff.
Practical Forecasting

The UK Meteorological Office Global Model provides excellent guidance around the Peninsula and even further south across the Ronne Ice Shelf and towards the Ellsworth Mountains. Large depressions are handled well and changes of type are generally well forecast. It is not expected that a global model will pick up or handle mesoscale features particularly well but nevertheless hints with regard to their possible formation and movement can be picked up from use of the 1000-500 hpa thickness and 500 hpa charts.

Although there are many local winds, particularly in the mountainous areas, it was found that realistic advice on surface winds could be given for many areas using the MSLP output from the model. Even at Sky Blu, at an altitude of approximately 1500 metres, the MSLP was a better guide to strong winds than the 850 hpa field. However the model pressure field did appear to be in error at times in this area, although most strong wind events were indicated by the model output. During the last season, a model forecast of a small low development in the south western Weddell Sea and subsequent movement towards the Ellsworth Mountains enabled a forecast of strong winds for a field party in the area to be correct. On another occasion the model guidance suggested a deep low to the N.W. of Rothera with a very strong pressure gradient over Rothera and as far south as Sky Blu. However winds remained light at Rothera and initially at Sky Blu, although actual data and model data suggested that the strong pressure gradient did indeed exist and forecasts continued to reflect this fact. Subsequently Fossil Bluff reported gusts of 65 knots and Sky Blu also reported winds of 60 knots after the initial light winds. Aircraft encountered severe turbulence and very variable winds. The pressure gradient was indeed strong, as intimated by the model, but the flow was severely distorted by the topography, hence the persistent light winds at Rothera. It is in these sorts of cases that despite local evidence to the contrary, the forecast and warning of severe winds and turbulence can be maintained using model guidance and eventually actual data. Even at Halley the model proved to be good guidance in wind forecasting although mesoscale features in this area can be significant in this respect and are not usually forecast explicitly by the model. There are many local winds amongst the mountains, but even here useful guidance can be given to field parties camped in these areas, in the sense that the winds that they may be experiencing can be identified as being local or not and advice can be given that if travel is contemplated, then a different wind regime may exist within a short distance. Although katabatic and foehn winds are a feature of the area, strong katabatics seem to be very limited in their extent and many of the significant winds are pressure gradient driven and hence, to a degree, predictable.

Cloud cover is probably one of the most difficult parameters to predict. As mentioned Sky Blu tends to be a graveyard for fronts and the persistence (or not) of this cloud is forecast using model guidance relating to the reinforcement of cloud by further fronts and whether any upper level features, such as cold pools or troughs, are likely to help maintain cloud cover. A current problem regarding frontal cloud at Rothera is that on relatively rare occasions a cold front crossing the Peninsula leaves a 'cut off' of cloud in the west which maintains precipitation for a number of hours after a clearance might have been expected. We have, as yet, no method for identifying these fronts.
Much cloud cover forecasting is done taking a nowcasting approach and using 1 km resolution imagery to detect movement, development and decay. Model guidance is also used to determine any likely changes in trajectory and hence possible changes in moisture content of the air.

The model thickness field is the main tool for forecasting precipitation, both the type and form, although in the short term imagery also plays an important part. A subjective determination has to be made of the likely intensity and it's affect on visibility. Account also has to be taken of the wind and the likely addition of blowing snow to reduction of visibility.

Many of the forecasting problems in this area of the Antarctic are similar to those encountered in more temperate regions but without the density of observations. Nevertheless useful guidance can still be given to operators by the careful study of basic model output and imagery in an effort to detect implied trends.
The First International Symposium on Operational Weather Forecasting in Antarctica

The First International Symposium on Operational Weather Forecasting in Antarctica was held in Hobart, Australia from August 31-3 September 1998. The symposium was organised by the Australian Bureau of Meteorology and the British Antarctic Survey, with the meeting being co-sponsored by the American Meteorological Society, the Australian Meteorological and Oceanographic Society, the Scientific Committee on Antarctic Research and the World Meteorological Organisation. There were 40 attendees at the meeting from Australia, Belgium, Brazil, China, France, Italy, Russia and the UK.

The attendees had a wide range of skills and included practising 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 began with a review of the forecasting requirement and particular problems in forecasting for the Antarctic region. There was a review of current inter- and intra-continental flights and discussion of the need for aviation forecasts for flights, such as those undertaken by both national and commercial operators. The forecasting requirements of tourism operators was also covered since this activity has grown considerably in recent years.

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 lows 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. However, there are a number of outstanding problems:

**Data** - the lack of observations from some sectors of the continent is still a concern as is the difficulty of getting all of the observations to the main analysis centres outside the Antarctic in a timely fashion. The lack of data from West Antarctica is of particular concern since 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 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 centres. This may improve in the near future with the development of new satellite communications systems. Further problems include the lack of upper air data from the Antarctic Peninsula and the interior of the continent, where we now have far fewer observations than during the IGY.

**Model performance** – 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 centres outside the Antarctic or on the research stations themselves. Although we now have a much better understanding of the physical processes taking place over the Antarctic this has not always been translated into improvements of these processes in the atmospheric models.
A full report on the symposium has been published in BAMS (Turner, 2000).

The International Antarctic Weather Forecasting handbook

A major outcome of the First International Symposium on Operational Weather Forecasting in Antarctica was the decision to produce an International Antarctic Weather Forecasting Handbook. This volume is being edited by the author and Mr. Stephen Pendlebury of the Australian Bureau of Meteorology and will be available by the middle of 2000. The requirement for the Handbook came from the fact that a number of different national operators and weather services had Antarctic weather forecasting manuals, but they were always concerned with the agencies’ limited areas of operation and particular forecasting activities. With the greater internationalisation of Antarctic operations and cooperation it was felt that a handbook covering the whole continent and the full range of forecasting activities would be of great value. The volume has been produced with the help of many agencies and individuals who have experience of forecasting for the continent, as well as researchers who could provide valuable background to the forecasting problem.

The Handbook consists of two parts. The first presents an overview of the meteorology and climatology of the Antarctic and considers the various types of weather systems encountered, the forecasting requirement, the data available and its characteristics, analysis techniques and the forecasting process.

The bulk of the Handbook contains detailed information about the analysis and forecasting techniques that can be applied at specific locations around the continent. For each location information is provided on topography and the local environment, operational requirements and activities relevant to the forecasting process, data sources and services provided, important weather phenomena and forecasting techniques used at the location.

A series of appendices contain maps showing the locations of most of the research stations and AWSs, climatological data for many stations, data on the Antarctic ‘representative atmosphere and a suggested Antarctic training programme for Antarctic weather forecasters.
The Handbook will be published on CD-ROM in PDF format. This will reduce the cost of publication, allow the use of colour and high resolution satellite imagery, enable it to be updated at regular intervals and allow users to print only the sections that they require, while still having access to the full volume. It is anticipated that the Handbook will also be available on the World Wide Web via the Home Page of the Council of Managers of National Antarctic Programmes (COMNAP) (http://www.comnap.aq/).

Further details on the Handbook can be obtained from the author at the above address.

Reference

1. Introduction

Ball's pioneering work (e.g., Ball 1960) has had a major influence on how the Antarctic surface wind is viewed. Ball (1960) considered the surface wind regime over the ice sheet as a steady-state flow in response to the balance of horizontal pressure-gradient, Coriolis and friction forces. The forcing of the wind is primarily the result of two processes: (1) the horizontal pressure-gradient force (PGF) arising from a temperature inversion over sloping terrain and (2) the PGF in the free atmosphere. The former is often referred to as the katabatic force (KF), and the latter the synoptic force (SF). The interplay between KF and SF is thus critical toward understanding the Antarctic surface wind regime.

Antarctic surface winds are among the most persistent on earth, reflecting clearly the influence of the underlying ice topography (Parish 1982). Annual resultant wind directions are generally 20-50° to the left of the fall line, consistent with Coriolis deflection of gravity-driven flows. There appears to be conflicting testimony regarding how KF and SF interact to create the Antarctic surface wind field. Ball (1960) noted that the strongest surface winds would tend to occur on the western side of the trough for coast-parallel moving cyclones. Loewe (1974), however, noted that the strongest winds along Adélie Land (67°S, 140°E) are associated with pressure falls in advance of cyclones. Bromwich (1989), Parish et al. (1993), Murphy and Simmonds (1993) and Yasunari and Kodama (1993) and Neff (1999), among others, have commented on the role of synoptic forcing on the Antarctic surface wind regime.

An analysis has been conducted to infer the relative roles of KF and SF in forcing the surface wind regime over Antarctica during a case of strong cyclonic forcing near Adélie Land in March 1993. The emphasis in this paper will be on output from Fifth Generation Penn State/NCAR Mesoscale Model (MM5) Version 2.9. Details of MM5 can be found in Grell et al. (1994). The simulations shown here consist of a nested grid of 30-km grid spacing (61 x 61 grid) in the outer domain and a 10-km grid spacing (82 x 82 grid) in the inner domain. For brevity, only the results from the inner grid will be discussed.

2. A case study of synoptic forcing

During the two-day period commencing 0000 UTC 23 March 1993 a major cyclone developed to the west of Adélie Land and moved eastward along the coast. Adélie Land was subject to dramatic shifts in the ambient PGF as the intense the cyclone passed to
north. The focus here is to depict the changes in KF and SF accompanying the movement of the cyclone.

Figure 1 illustrates the wind vectors at the lowest sigma level of 0.999 (approximately 5 m above the surface) at 0000 UTC 25 March 1993. This represents a 48-hr forecast from the initial 0000 UTC 23 March 1993 model start time. By this time, the cyclone had passed to the east of Adélie Land and had a central pressure of approximately 976 hPa. The position of the cyclone at this time was approximately 65°S, 160°E, as can be inferred from the airflow pattern in Fig. 1. Near-surface winds showed little directional change as the cyclone moved along the coast. Despite pronounced changes in the intensity and direction of the PGF associated with the cyclone, Antarctic surface winds retain a downslope component and, hence, resemble typical katabatic flows. This directional persistence is in agreement with data collected at automatic weather stations (AWSs) situated along Adélie Coast (Keller et al. 1994). This also suggests that significant adjustment must take place between the large-scale PGF associated with the cyclone and the Antarctic orography since the PGF just offshore undergoes significant changes in intensity and direction. Simulated near-surface winds over the Antarctic continent are strong throughout the cyclone passage. As can be seen in Keller et al. (1994), AWSs recorded very strong winds during the period as well. The intense wind conditions associated with passage of this cyclone destroyed three AWS units.

Numerical models such as MM5 are useful in diagnosing the dynamics of atmospheric flows since the actual forces are known. Figure 2 illustrates the total PGF from MM5 for 0000 UTC 25 March 1993 at \( \sigma = 0.999 \). The vectors in Fig. 2 have been scaled by the Coriolis force and thus the arrow lengths correspond to the magnitude of the geostrophic wind. Most striking is the strong topographic control of the PGF. Despite strong cyclonic forcing, the PGF vectors are still directed nearly downslope. Results from the previous 48 hours show the same terrain-following characteristics of the PGF. This topographic control implies that the stable air mass associated with the cyclone must undergo an adjustment adjacent to the Antarctic terrain. Such an adjustment is similar to the “barrier wind” dynamics alluded to first by Schwerdtfeger (e.g., 1975). It is only through topographic modification of the large-scale PGF that enables the low-level wind field to attain such a high degree of directional constancy.

To understand the forcing of Antarctic surface winds, the PGF must be resolved into KF and SF components. Cassano (1998) has discussed the momentum balance of gravity-driven flows, noting that the horizontal pressure-gradient in the downslope direction can be expressed:

\[
PGF = g \frac{d}{\Theta_o} \sin \alpha - \cos \alpha \frac{g}{\Theta_o} \frac{d(\bar{\Theta}h_i)}{ds} - \frac{1}{\rho} \frac{dp}{ds_{SYN}} \tag{1}
\]

This formulation is similar to that proposed by Ball (1960) and Mahrt (1982). Here, \( d \) is the potential temperature deficit, the difference in potential temperature at any point in the katabatic layer between the radiatively cooled layer and the ambient atmosphere. The term \( \alpha \) refers to the terrain slope, \( h \) is the height of the diabatically cooled layer, \( \Theta_o \) is a reference potential temperature, and \( s \) refers to a horizontal distance. Other symbols have their usual meteorological meaning. The first term on the right represents KF. The
second term represents the effects of the change in the depth and/or cooling of the katabatic layer in the downslope direction on the acceleration, and the third term is SF.

Cassano (1998) has shown that it is possible to infer each of these terms from numerical model output, and thereby depict the momentum balance of katabatic flows. In this study, a diagnosis of all three terms has been made using output from MM5. The process of determining KF is schematically represented in Fig. 3. The dashed line refers to the potential temperature profile in the free atmosphere above the radiatively-cooled lowest layer. The vertical profile is determined by fitting a line to the potential temperatures in a layer between 1500 and 5000 m above the ice surface. Such a profile is thought to represent the synoptic or ambient environment. The difference between the sigma level potential temperature and the inferred potential temperature in the ambient environment is the deficit. For the MM5 simulations, the potential temperature deficit is calculated at each grid point. The KF term can then be easily determined since the terrain slope is known from the terrain data set used in MM5. The second term in (1) can be shown to be smaller than either KF or SF for the scale of the MM5 simulations (Ball 1960; Cassano 1998). The following discussion will thus focus only on KF and SF.

Estimates of KF are illustrated in Fig. 4. The direction of KF is down the local fall line and the vectors have again been scaled by the Coriolis force. KF vectors are large near the coast, but decrease rapidly away from the steep terminal ice slopes at the continental margin. Comparison of KF with the total PGF shows that the katabatic component is only a fraction of the atmospheric forcing at this time. It can be readily observed that the KF vectors are considerably smaller than the total PGF vector in Fig. 2. Estimates of SF (Fig. 5) can be obtained by taking the vector difference between the total PGF and KF. The close coupling between SF and the Antarctic terrain is apparent in Fig. 5. Similar results were observed for previous time periods (not shown). It can be concluded that SF is the dominant force throughout the case study period.

3. Summary

The technique proposed by Cassano (1998) enable estimates of SF and KF to be made from gridded output. MM5 simulations of a case study from 23-25 March 1993 were used to describe the interactions of KF and SF in the development of the Antarctic surface wind regime. During the cyclone passage, the Antarctic surface wind field retained a high directional constancy and wind directions were similar to those expected from pure gravity-driven flows. Throughout the simulation period, SF was the dominant force. The direction of SF over the ice sheet at low levels was controlled by the local terrain. Wind vectors of SF are directed primarily down the local fall line throughout the domain. It is proposed that significant adjustment in the PGF must take place between the ambient flows and the Antarctic terrain. Such an adjustment is the only means by which the flows can maintain the high directional constancy values during periods of intense cyclonic activity. This suggests that it is inappropriate to label flows as katabatic based solely on direction. Such topographic control of the wind field is also necessary in order to explain the persistence and direction of the summertime Antarctic surface wind field.
Acknowledgments: This research was funded in part by National Science Foundation grant OPP-9725263.

References:


Fig. 1. Wind vectors at lowest sigma level (approximately 5 m agl) for 0000 UTC 25 March 1993. Antarctic terrain contour heights (m) represented by solid lines.

Fig. 2. Total PGF vectors at lowest sigma level (approximately 5 m agl) for 0000 UTC 25 March 1993. Vector lengths scaled by the Coriolis force and represent a geostrophic wind magnitude.
Fig. 3. Vertical sounding of potential temperature (solid). Dashed line represents potential temperature profile in ambient atmosphere; \( d(z) \) is the potential temperature deficit, \( \theta_0 \) is the reference potential temperature.

Fig. 4. KF vectors at lowest sigma level (approximately 5 m agl) for 0000 UTC 25 March 1993. Vector lengths scaled by the Coriolis force and represent a geostrophic wind magnitude.
Fig. 5. SF vectors at lowest sigma level (approximately 5 m agl) for 0000 UTC 25 March 1993. Vector lengths scaled by the Coriolis force and represent a geostrophic wind magnitude.
The Antarctic Meteorological Research Center (AMRC) at the Space Science and Engineering Center (SSEC), University of Wisconsin – Madison has a large archive of meteorological data. Of the nearly 2 Terabytes in holdings, some of the products such as the Antarctic Composite Infrared Images (ACII) are unique. Other data types in the collection include:

- Satellite data (NOAA HRPT, GAC, LAC and ACII)
- Surface observations (AWS, synoptic, raobs, METARs, ship and buoy)
- Numerical model analyses and forecasts (MRF, WWFM, ECMWF, UKMET)
- Cloud drift and water vapor wind charts

A description of the data archive, include amounts of holdings, dates of coverage, and types of data will be provided. Distribution capabilities will also be discussed in addition to a discussion of future additions and abilities.
### Antarctic Meteorological Research Center Data Holdings

<table>
<thead>
<tr>
<th>Composite satellite data</th>
<th>ACIIIs (Antarctic Composite Infrared Image) at 3 hourly intervals 30 October 1992 to the present</th>
</tr>
</thead>
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<tr>
<td>Polar orbiter satellite data</td>
<td>NOAA satellite data 12 December 1992 to the present. There are some gaps in the data.</td>
</tr>
<tr>
<td>Model analyses and forecasts*</td>
<td>Medium Range Forecast (MRF) from the National Center for Environmental Prediction (NCEP) from 2 July 1993 to the present with forecasts added in late 1994. Wind and Wave Forecast Model (WWFM) from NCEP from 4 December 1998, European Center for Medium Range Forecasting Model (ECMWF) from 5 December 1998. United Kingdom Meteorological Office model from 1 January 2000.</td>
</tr>
<tr>
<td>*This data is an archive of the data that is available from GTS in real-time and not the reanalysis data.</td>
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<tr>
<td>Synoptic observations</td>
<td>Synoptic observations south of 40°S from 1 January 1997.</td>
</tr>
<tr>
<td>Radiosonde observations</td>
<td>Mandatory/significant Antarctic radiosonde levels from 1 November 1996 to present. McMurdo 1956 through 1979, Antarctic region 1980 through 1993, McMurdo and South Pole 1994 to the present (Late 1996 to present all available data south of 35°S have been added).</td>
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<tr>
<td>Water vapor winds</td>
<td>Wind vectors based on water vapor movement from the Geostationary Meteorological Satellite (GMS) satellite, 130°E to 180°, 40°S to 70°S, 27 October 1997 to the present</td>
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<tr>
<td>Cloud drift winds</td>
<td>Wind vectors based on infrared image cloud movement from GMS satellite, 130°E to 180°, 40°S to 70°S, 10 June 1998 to the present.</td>
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<td>USAP Research vessel observations</td>
<td>Meteorological observations from the research vessels, April 1996 to present.</td>
</tr>
<tr>
<td>AWS observations</td>
<td>Antarctic automatic weather station (AWS) data February 1980 to the present, as 3 hourly or 10 minute data.</td>
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<tr>
<td>AGO observations</td>
<td>Automatic Geophysical Observatory (AGO) ten minute meteorological data December 1992 through December 1998.</td>
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<tr>
<td>UK/BAS observations</td>
<td>Six hourly meteorological data from the British Antarctic Survey (BAS) 1957 through 1993 for Faraday, Halley, Rothera, and Signy Island Stations.</td>
</tr>
<tr>
<td>Manned Station Monthly means</td>
<td>Monthly means of air temperature and air pressure 1957 through 1996 for all available Antarctic manned stations</td>
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<tr>
<td>Palmer Station monthly summaries</td>
<td>Monthly summaries for Palmer Station from September 1992 to September 1993 and April 1998 to present. Amundsen-Scott Station (South Pole) January 1996 to present.</td>
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</table>
Table 1 gives the automatic weather station site name, ARGOS identification number, latitude, longitude, altitude, site start date, and the World Meteorological Organization (WMO) number for the Global Telecommunications System. The sites are grouped according to the region where they are installed. Table 2 contains the same information as Table 1 but are sorted according to the ARGOS ID number. Table 3 lists only the sites that have a WMO number and are listed in the order of the WMO numbers. New sites for the year 2000, new ARGOS IDs for the year 2000 and the elevation or altitude determined by UNAVCO are indicated at the bottom of each table.

The United States Antarctic Program (USAP) automatic weather stations (AWS) data have been entered into the Global Communications System starting in 1990. The Fleet Numerical Oceanography Center, Monterey, California and then through Service ARGOS starting in 1997. The use of Service ARGOS to enter the AWS data into the GTS at three hourly intervals appears to be working satisfactorily. Occasional problems arise such as an incorrect location for an AWS unit usually due to incorrect information being distributed in the GTS.

The main problem with the AWS sites is that we do not know the actual elevation of the site above sea level. When we install remote AWS units using the Twin Otter or LC-130 aircraft we may fly several hundred nautical miles and be away from a site with good altimeter information and a well established elevation. The only information about the elevation of the site is the aircraft altimeter. Time and distance can alter significantly the altimeter elevation. Global Positioning System (GPS) are now available through UNAVCO at McMurdo, Antarctica. During the 1998-1999 field season a differential GPS became available and a correction was made to the elevation of Marble Point AWS amounting to −10 m corresponding to about 1 hPa pressure unit. During the 1999-2000 field season a GPS unit supplied by UNAVCO was taken to several sites and a record for determining the elevation was obtained by setting the unit down and turning it on while at the site. The recorded record is usually one hour or more long and appears to be sufficient. About two months later we were supplied with the elevation information which are enter in Table 1, 2, and 3. The largest change was at Siple Dome amounting to +48 m. We will continue to take the UNAVCO GPS units to every possible site in the future and obtain new or additional elevation information. Byrd Station elevation is 1530 m starting in 1957 and it has been snowing there ever since. I wonder if the elevation of Byrd Station should still be 1530 m? The AWS site is some distance from the station and I don't know if we went up slope or down slope when going to the AWS site.

The European Centre for Medium-Range Weather Forecasts (ECMWF) will start the synoptic reanalysis in May 2000 beginning with 1987 and going forward. They will be using USAP AWS data from Antarctica and Greenland. Roy Jenne, National Center for Atmospheric Research (NCAR) is working closely with the ECMWF and has been in contact with Linda Keller about the elevations of the AWS sites. We have supplied the most recent information to him and it may be possible to revise the elevations of AWS sites near to those that have the elevation determined by the GPS. This has not been done yet. We do not know if the U.S. National Center for Environmental Prediction has any plans to use the AWS data in their possible reanalysis.

The network around Ross Island was completed with the installation of an AWS unit in the vicinity of Cape Crozier (Laurie II, Table 1). Cape Bird was installed during the 1998-1999 field season near the New Zealand hut and outside of the protected area. Apparently the guys do not bother the skuas which was a concern of the New Zealanders. At least I have not heard any complains. I did a very poor job of marking the guys with colored streamers.
The AWS network may expand into West Antarctica and possibly the eastern portion of the Ross Ice Shelf. The sector of Antarctica south of 30°S and between 175°W and 85°W is still the largest meteorological void on earth except for the AWS sites. During the 1999-2000 field season an AWS site was established at Noel, Table 1, a possible ice core drilling location. The British Antarctic Survey (BAS) plans to install an AWS at Thurston Island in the near future. The big iceberg event on the edge of the Ross Ice Shelf may result in an AWS located on the iceberg and on the edge of the Ross Ice Shelf in the vicinity of 180°. The International Trans Antarctic Scientific Expedition (ITASE) may install one or more AWS sites on the traverse in West Antarctica in the near future.

The NOAA polar orbiting satellites receive the AWS data then transmit the data in the imagery for reception by the McMurdo Meteorology Office. The AWS data are processed by the Terascan system and made available for forecasting in the McMurdo area. The data are then sent to the University of Wisconsin and to others as needed.
### Table 1. The 2000 Antarctic automatic weather station site name, ARGOS identification number, latituude, longitude, altitude above sea level, sit start date and WMO number for the Global Telecommunications System. Sites with three digits after the decimal point in the latitude and longitude were located using the ARGOS positions for a three day period, aircraft GPS, or hand held GPS.

<table>
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<tr>
<th>Site</th>
<th>ARGOS ID</th>
<th>Lat. (deg)</th>
<th>Long. (deg)</th>
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<th>Date Start</th>
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Table 2. The 2000 Antarctic automatic weather station site name, ARGOS identification number, latitude, longitude, altitude above sea level, site start date and WMO number for the Global Telecommunications System. Sites with three digits after the decimal point in the latitude and longitude were located using the ARGOS positions for a three day period, aircraft GPS, or hand held GPS.

<table>
<thead>
<tr>
<th>Site</th>
<th>ARGOS ID</th>
<th>Lat. (deg)</th>
<th>Long. (deg)</th>
<th>Alt. (m)</th>
<th>Date Start</th>
<th>WMO#</th>
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*# New site for 2000: # New ARGOS ID at the site for 2000: @UNAVCO GPS Location: and Elevation: CRS, 16 MARCH 2000*
Availability and Visualization of Satellite Data in the Antarctic

R. L. Bernstein
SeaSpace Corporation

Through a set of NSF grants to SeaSpace and Scripps Institution of Oceanography initiated in 1986, the initial TeraScan system for receiving, processing, and archiving data from the polar orbiting weather satellites was developed and first installed at McMurdo Station during the 1987-88 season. The U.S. Navy also was a partner in this activity, both in a research and operational sense. Navy forecasters were the operators and users of this system, and a parallel system was also delivered to the Navy Research Laboratory in Monterey, California. All data acquired by this reception system at McMurdo were archived to cartridges, and regularly delivered to the newly organized Scripps Arctic & Antarctic Research Center (AARC).

The initial TeraScan system at McMurdo focused only on the hrpt telemetry stream from the noaa polar orbiters, acquiring and processing avhrr imagery, tovs soundings, and argos-relayed data from the automatic weather stations. Subsequent improvements added rtd telemetry from the dmsp polar orbiters (ols imagery, ssmi, and ssmt-1/2 soundings). Over the years, the system at McMurdo has seen several computer system upgrades, along with additions to create backup and redundancy. Aside from the polar satellite data directly received at McMurdo, SeaSpace has routinely supplied Japanese gms geostationary data to the McMurdo forecasters via internet, from TeraScan systems now located in Japan.

Also over the past 14 years, TeraScan noaa/dmsp systems were established at Palmer Station, at Antarctic stations operated by Italy, Japan, Germany, and Chile, and aboard icebreakers operated by the U.S., Canada, Germany, and Japan.

Outside of the polar regions, several hundred TeraScan systems now operate in 30 countries. The U.S. Navy has systems at nine of its major centers and facilities, and aboard 28 of its aircraft carriers and other big-deck vessels.

As TeraScan software has continued to evolve, with new capabilities added, this heightens the importance of continued training, to encourage users to take advantage of these capabilities. SeaSpace routinely offers training classes, tailored to user needs, at its facility in San Diego, or at the customer site.

New Satellites and Sensors

The period from 1978 to the present has seen remarkably little evolution in the actual sensors aboard the noaa and dmsp satellites. Notable exceptions are the introduction of
ssmi in the mid-80s, and the transition from tovs to atovs with the most recently launched noaa. The next dmsp satellite replaces the ssmi/ssmt sensor suite with the ssmis sensor for microwave imaging and sounding. But all of this is now changing; the pace of development in satellite sensor technology is quickening.

NASA launched its EOS Terra satellite last December 1999, and Terra’s Direct Broadcast was just turned on worldwide on 28 April 2000. In December 2000 EOS Aqua, sister to Terra, will be launched. In a certain sense both Terra and Aqua are the precursors to the next generation of polar orbiters – NPOESS – that will ultimately replace noaa and dmsp, beginning with NPP (NPOESS Preparatory Platform) scheduled for launch in 2005.

Terra and Aqua transmit at X-band (8 GHz), at data rates of about 15 mbps, far in excess of noaa (0.66 mbps) and dmsp (1.024 mbps). Both carry the MODIS sensor, with 36 channels (compared to avhrr’s 5 channels), with spatial resolutions ranging from 1000m down to 250m. MODIS alone will have significant impact on operational forecasting in the Antarctic. In addition, Aqua and Japan’s ADEOS-2 satellite will both carry near identical copies of an advanced microwave imager (AMSR – Advanced Microwave Scanning Radiometer) that dramatically extends the capabilities of ssmi.

Terra, Aqua, and other spacecraft of this new generation create new opportunities and new challenges for Antarctic forecasting. Their sensor data need to be introduced into the operational forecasting world, if for no other reason than they are the precursors to the NPOESS satellites that will take over at the end of this decade.

With support from NASA, SeaSpace has been developing new systems for receiving and processing the directly broadcast X-band data from Terra, Aqua, ADEOS-2, as well as the imaging radar satellites (ers-2, radarsat). This development, just as in the case 14 years ago that led to the initial TeraScan system at McMurdo, involves a partnership with Scripps Institution of Oceanography. A prototype system operates now at Scripps, and SeaSpace is in the process of building and testing several of these new systems, one of which will be installed this August at the University of Wisconsin’s Space Science & Engineering Center. It is important to note that SSEC scientists are leading NASA’s efforts to develop atmospheric algorithms for the MODIS sensor.

Given the history of activities that have occurred over the past 14 years, heavily driven by the needs of operational forecasters in the Antarctic, it would seem that the time is ripe for a renewal and extension of these activities during the next few years, to address certain obvious questions:

What will be the impact of MODIS, AMSR, and the other next-generation polar satellite sensors, when their data is routinely available to forecasters with little or no delay at the moment it is needed the most?

How might the data from these sensors constrain and hopefully thus improve numerical model forecasts in the Antarctic?
Do any of these new sensors exhibit some entirely new capabilities for observing developing weather conditions in the Antarctic, perhaps in ways not anticipated by the scientists and engineers who specified and designed these instruments?

How can the research and operational communities merge their common interests to best advantage, to make fullest use of these new data sources to improve the quality of forecasting in this most demanding environment on the planet?

These are big questions, that will take years to answer, and require the combined efforts of many individuals and organizations. Timely reception and processing of the best available satellite data sources will surely be a critical element in this process.
1. INTRODUCTION

The number of visitors to the vast, isolated Antarctic continent is increasing rapidly, as both tourists and scientists strive to uncover its secrets. While tourist visits are usually fleeting, the permanent human presence on the Antarctic continent is necessary in order to carry out the important scientific work that is undertaken there, particularly in climate change and preserving the fragile environment of the continent. Light aircraft for intra-continental flights and heavy intercontinental aircraft from the more northern continents are being used to facilitate the logistics of these operations. It is in order to safeguard these scientific and tourist operations that substantial efforts are now being directed at forecasting the weather in Antarctica.

While extremes in temperature are expected in the south polar regions, the most complex and dangerous weather phenomenon to forecast, in fact to fully understand, is the wind. Parts of East Antarctica are the windiest near-sea level regions on the planet (Wendler et al. 1997), and the processes leading to these extreme winds are not yet fully understood. The application of katabatic wind theory has successfully reproduced many features of the observed time-average surface flow over the Antarctic continent (e.g. Parish and Bromwich 1987), but the influence of the large-scale circulation needs to be taken into account to better explain extreme events. The problem of forecasting the events therefore cannot be tackled successfully without first understanding the mechanisms behind the weather phenomena that occur.

This work is focussed on determining which forcings are responsible for the extreme wind events and are most important for their prediction. Operational forecasts are not the final aim of this work. We focus on identifying the important characteristics of the events and which forcings bring them about, in particular those that will facilitate their forecasting, as well as a determination of their predictability. In section 2 we examine a typical severe weather event (SWE) and look for features common to SWEs on the East Antarctic coast. Section 3 details the possible use of identified precursors for predicting SWEs.

2. A CASE STUDY SEVERE WEATHER EVENT AT CASEY STATION

Casey station is the site of the Australian Antarctic Meteorological Centre, and is the easternmost Australian station on the continent. It lies on the East Antarctic coast at 66°17'S, 110°32'E. The station surroundings are dominated by the Law Dome. With its height of 1395 m and diameter of some 200 km, the Law Dome has a significant influence on the climate of Casey, in particular in sheltering the station from the predominantly easterly winds. The annual mean wind speed at Casey is only 6.3 ms⁻¹, but the station experiences very severe winds of up to 70 ms⁻¹ (see Figure 1). These events are most frequent in winter, but wind speeds greater than 15 ms⁻¹, a speed at which aircraft operations are in some danger, occur on average about three times per month in summer.

While the last twelve days of 1999 were extreme in terms of the winds experienced at Casey, the time series of station surface pressure, temperature and wind speed shown in Figure 1 demonstrate many of the characteristics of severe weather events there. The onset of the extreme wind events is generally very sudden, and high speeds can be reached only a few hours after calm conditions. The duration of events varies from a few hours to several days, and the cessation of strong winds is almost as sudden as the onset. The extreme event of December 22 lasted only 24 hours, but any aircraft flying or exterior activities at the time would have been in grave danger. It
is clear that associated with the event there were substantial changes in both surface pressure and temperature at Casey. Station pressure was at a maximum at the onset of the event, and then fell very rapidly by 40 hPa in about 12 hours. Temperature, too, was increasing during the period leading up to the event and peaked after the pressure minimum and the wind speed maximum. The same features are seen for the two subsequent events, with pressure maxima before onset and minima a few hours after the strongest winds, while temperatures remained mild throughout the period (the mean December temperature at Casey is \(-0.9^\circ\)C).

The evolution of these surface parameters can be linked to the large-scale circulation that accompanies SWEs at Casey. The ECMWF analysis of mean sea level pressure (MSLP) in Figure 2 shows that the December 22 event was associated with a very intense extra-tropical cyclone that approached Casey from the west and deepened as it did so. Such cyclones are very common to this region, and their general behaviour is to move eastward and southward around the Antarctic coast (Simmonds and Keay 2000). The pressure maximum before onset reflects the high pressure ridge that passed over the station ahead of the cyclone, and the approaching cyclone brought about the sudden pressure fall and drove the very strong winds at Casey. The warming that occurs before and during the events is also due to the approach of the cyclone, as the system advects warm air ahead of it from the north towards the coast. Extreme winds at Casey such as these are due almost entirely to the gradient wind associated with passing cyclones. Strong flow is seen through a great depth of the troposphere during the December 28, 1999 event, which is forced by a large-scale cyclone. Little evidence for katabatic flow, such as a marked drop in wind speed with height close to the surface and a surface temperature inversion (Phillpot 1997), is seen. In winter there is evidence for large-scale gravity-driven flow originating in the continental interior near Vostok (Murphy and Simmonds 1993) but this too is linked to the large-scale circulation.

3. PRECURSORS TO SEVERE WEATHER EVENTS

The characteristics of the SWEs identified above are common to the majority of events at Casey, and also to those at other East Antarctic sites such as Mawson (at 67°36'S, 62°53'E). At Mawson, the surface flow is influenced to a greater degree by katabatic flow than at Casey, but SWEs are intrinsically linked to the passage of cyclones and the associated strong winds they drive. Thus, at many stations on the East Antarctic coast the onset of SWEs comes about as a result of a high pressure ridge sitting over the station for some time before a cyclone approaches. The high pressure ridge often acts as a block to the cyclones' passage, slowing and tending to steer the cyclones towards the coast. The calm weather that ensues while the blocking system extends over the station and into the continental interior can also allow strong surface temperature inversions and cold air supplies to form that feed gravity driven flow that interacts
with the large-scale flow at the coast.

The characteristics common to SWEs and the patterns that emerge during the period leading up to them suggest that there may be several precursors to the onset of strong winds. Investigations of many events at both Casey and Mawson suggest that parameters both at the stations (at the surface and aloft) and surrounding the stations might provide SWE forecasting skill. We consider both possibilities and test their utility as SWE precursors in the following sections. Three different data sources have been used: station observations from 1960 at Casey and 1954 at Mawson to 1996; the NCEP re-analysis of MSLP, surface and 850 hPa temperature and 500 hPa geopotential height; output from the Melbourne University general circulation model (MU-GCM) R21 resolution, perpetual January and July simulations at grid-points best representing Casey and Mawson (see Murphy and Simmonds 1993). The search for precursors involves calculating the correlation co-efficients between different parameters and the observed (or simulated, for the MU-GCM data) station wind speed 24 hours later. Significant correlations allude to a useful precursor at 24 hours lead time.

3.1 Precursors at stations

Here we consider surface parameters that followed definite patterns in the lead-up to events: surface pressure, increasing to a maximum at onset then falling; temperatures rising and above average before and during events. We therefore look at their values and their 24 h tendencies at 24 h before the station wind speed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Casey</th>
<th>Mawson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface pressure</td>
<td>-0.11</td>
<td>-0.19</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>0.18</td>
<td>-0.06</td>
</tr>
<tr>
<td>Pressure tendency</td>
<td>-0.13</td>
<td>-0.16</td>
</tr>
<tr>
<td>Temperature tendency</td>
<td>0.05</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

The weak correlations shown in the above table indicate that none of these parameters is a useful precursor to station wind speed. While they may change before SWEs in the manners described above, these patterns do not necessarily lead to SWEs.

We look now at parameters directly above the stations, taken from MU-GCM output since long time series of these parameters from radiosondes are not readily available. The model has been shown to simulate the Antarctic coastal wind regime and characteristics of SWEs at Casey quite well (Murphy and Simmonds 1993) and so we can use its simulated large-scale fields with confidence. We consider geopotential height and upper-air temperatures that would be expected to vary with the anomalies associated with large-scale systems forcing the surface winds. The correlations over

600 simulated days in January are given in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Casey</th>
<th>Mawson</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 hPa height</td>
<td>0.19</td>
<td>0.11</td>
</tr>
<tr>
<td>500 hPa temperature</td>
<td>0.19</td>
<td>0.08</td>
</tr>
<tr>
<td>200 hPa height</td>
<td>0.18</td>
<td>0.11</td>
</tr>
<tr>
<td>200 hPa temperature</td>
<td>-0.19</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

These correlations are again quite low, indicating that there is substantial variation amongst events in the values of these parameters above the stations. The correlations are higher at Casey, suggesting that winds there are more strongly tied to large-scale anomalies than at Mawson.

3.2 Precursors Surrounding Stations

While point values of parameters at and directly above the stations do not correlate well with wind speed 24 h later, the degree to which the atmosphere is organised on the large-scale suggests that it is necessary to consider patterns in certain fields as precursors rather than point values, which vary greatly with wind speed. We can take advantage of the fact that the changes in large-scale distributions of MSLP, pressure and 500 hPa geopotential height are consistent between events, and the average anomalous distributions (from long-term means) are very different for severe weather events and when winds are weak – 'weak wind events' (WWEs). Figure 3 shows the difference between the mean NCEP reanalysis 500 hPa height fields 24 hours before 20 individual SWEs and the mean for 20 WWEs at Mawson in January. Large differences between these are apparent that are statistically different from zero at the 95% confidence level (such regions are stippled

Figure 3: Difference between NCEP composite 500 hPa geopotential height for days before Mawson SWEs and for Mawson calm days in January (in the plot). These anomalies are greater than
those for the 'composite' of the days before the 20 SWEs alone.

We have used a measure of the degree to which a field matches the composites for 24 h before SWEs and for WWEs as a wind speed precursor. The root mean square (RMS) difference between once-daily fields and each of the two SWE and WWE composites have been calculated with NCEP reanalysis fields from 1977-96 over a given area where relevant anomalies exist. The difference between them has been correlated with observed station wind speeds 24 h later, and the areas varied to produce the highest correlations for each station and each parameter. These correlations are all stronger than those calculated with point-value precursors and are all significantly different from zero at 99%, and so the predictive skill of these 'pattern' precursors appears promising.

In order to use the pattern precursors to forecast station wind speeds 24 hours in advance, regression methods have been used. Least squares linear regression fits of combinations of two or three of the pattern precursors to station winds 24 hours later have been applied. The resulting linear combinations of the precursors have been used to make 'hindcasts' of observed winds at Casey and Mawson in January with a 24 h lead time. The best correlations between so-predicted and observed winds, and therefore the best predictive skill found by this method, were 0.32 for Casey and 0.43 for Mawson.

This method has been used to hindcast 20 observed SWEs at each station. Of the 20, none were predicted (forecast winds stronger than 15 ms$^{-1}$) at Casey, but 13 events were successfully predicted at Mawson. The precursors that produced the best range of forecasts were the distributions of MSLP and surface temperature, plus 500 hPa geopotential height for Mawson.

4. CONCLUSIONS

Analysis of a large number of SWEs at both Casey and Mawson has demonstrated the role played by extra-tropical cyclones in the forcing of strong surface winds on the East Antarctic coast. All events examined have seen the approach of a strong cyclone towards the station, bringing warm air ahead of it and having associated strong flow at the surface and throughout the lower- to mid-troposphere. In winter there is also the influence of gravity-driven flow, which is also linked to the movement of large-scale systems as an off-shore cyclone enhances the downslope pressure gradient and disrupts the stability of the katabatic layer that develops as a high pressure ridge moves over the station in the preceding days.

Many events conform to a definite pattern, with associated large-scale structures of the atmosphere related to strengthening surface winds, and these events seem to be relative straightforward to predict. However, there are other events that are more difficult to predict. During such events, many of the same large-scale features are observed, but the atmosphere occasionally evolves very rapidly (such as blocking systems breaking down suddenly), and therefore prediction is difficult. Also, systems can follow very complicated paths, moving over the ice sheet, for example, and in such situations the onset of strong winds is not obvious since the large-scale flow is weak but strong katabatic winds can develop. The regression analysis of the precursors to strong wind events has shown that in the case of typical SWEs, the forecasting of severe weather is relatively straightforward, while the predictability of other events is much lower, and in these cases forecasters may not recognise the impending onset of severe weather. Forecasters must therefore be aware of these atypical events.

The high degree of variability in the Antarctic and sub-Antarctic regions is at the heart of the unpredictability of many events. Perhaps the most promising prediction method is the use of current numerical weather prediction models. Such models are now capable of predicting the evolution of the large scale atmosphere in the high southern latitudes, and forecasts of severe weather events are possible by applying these synoptic forecasts to the characteristics of severe weather events that we have identified.

References


Boundary Layer Flows near the Antarctic Coast

Hubert Gallée and Olivier Brasseur, LTPE at Grenoble

The Antarctic coastal zone is probably the region where weather is the most influenced by boundary layer circulations. This is mainly due to the strong katabatic airstreams which flow down the steep slopes of the biggest ice sheet of the world. For example, wind speeds larger than 300 km/hr have been recorded at the meteorological station of Dumont d'Urville, in Adélie Land. Katabatic airstreams can propagate for long distances over the Ross Sea, maintaining large areas free of sea ice in the coastal zone, especially along the Ross Ice Shelf and in Terra Nova Bay. It has also been suggested that these airflows are partly responsible for the generation of mesocyclonic activity in the Ross Sea [Bromwich, 1991]. Ross Sea mesocyclones are small, with a typical diameter of about 200 km, and shallow, with a typical thickness of about 3000 m. They influence the weather at McMurdo station.

The mesoscale model MAR (Modèle Atmosphérique Régional) has been extensively used to study boundary layer flows in the Ross Sea Sector [Gallée, 1995, 1996, 1997] and near the coast of Adélie Land [e.g., Gallée and Pettré, 1998]. Physical mechanisms responsible for the propagation or not of katabatic airflows over the ocean have been proposed. Interactions between cold continental air from katabatic origin and relatively mild maritime air over the ice-free Ross Sea have been found to be responsible for the formation of boundary layer fronts and associated mesocyclones. These mechanisms will be discussed.

Strong wind gusts influence markedly the weather in the Antarctic coastal zone. They must be estimated from the outputs of numerical weather prediction models. A new modeling approach for estimating wind gusts is presented here. It has been validated in the context of estimating wind gusts during winter storms over western Europe. It is applied to an Antarctic situation. Typical estimates of wind gusts in a MAR simulation over the Antarctic ice sheet amount to roughly 150% of the wind speed simulated in the lowest layer of MAR.

Figure 1: Simulation of a mesocyclone M1 over the Ross Sea with MAR. Surface pressure anomaly (solid line, only over the ocean) is computed from the initial horizontally uniform surface pressure. Contour interval is 0.2 hPa. Interval of ice-sheet elevation contours (dashed) is 0.2 km. MM refers to McMurdo Station and TN to Terra Nova Bay [from Gallée, 1995].
Numerical studies of mesoscale cyclogenesis near Terra Nova Bay

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1 Introduction

Climatologies and previous studies of Antarctic mesocyclones (MCs) have shown that MCs occur frequently in the Western Ross Sea Region (WRSR) of Antarctica (Bromwich, 1991, Carrasco and Bromwich, 1994). Such MCs are often connected to katabatic storms and can represent a severe problem for operations in the WRSR, but are still a very difficult task for operational forecasting. Carrasco and Bromwich (1993, 1995) investigate series of MCs developing in the vicinity of the Antarctic stations Terra Nova Bay (74.7°S, 164.1°E) and McMurdo (77.85°S, 166.67°E) using observational data. In these areas, large valleys are present leading to a significant channeling of the katabatic winds over the ice slopes. In addition, the ocean close to the ice slopes is ice-free during austral summer resulting in a significant low-level baroclinicity.

In the present study, case studies of MCs are investigated using the mesoscale model NORLAM, in order to elucidate the forcing mechanisms of MCs in the WRSR and in order to identify problems of operational forecasting for the Antarctic.

2 The numerical weather prediction model NORLAM

The limited area model (LAM) used for the experiments is the former operational model NORLAM (NORwegian Limited Area Model, version 9) of the Norwegian Meteorological Institute (DNMI) at Oslo. A detailed description of the model’s numerics can be found in Grønås and Hellevik (1982), while basic information on the model’s physics and on parameterization schemes is contained in Nordeng (1986). For the studies of the present paper, a nesting mode is used. A first run using a grid spacing of 50 km (LAM50) is performed with ECMWF analyses as initial and boundary conditions. A second integration with a 25 km grid (LAM25) is then nested in the LAM50 results. The model domain consists of 121 x 97 grid points, while a vertical resolution of 30 $\sigma$-levels is used with about half of the levels located below 850 hPa.

Figure 1 shows a map of Antarctica comprising the NORLAM domain for the Ross Sea area.

![Figure 1: Map of the Ross Sea region of Antarctica comprising the model domain of the LAM50 with topography (solid isolines every 500 m). The box indicates the LAM25 domain. The solid thick line marks the coastline. Antarctic radiosonde stations are indicated by black triangles.](image)
3 Results

3.1 The case of 18 February 1988

On 18 February 1988, a MC was observed in the WRSR between Station Terra Nova Bay and Ross Island (Figure 2). The MC developed on the rear side of an eastward moving synoptic cyclone, whose associated pressure gradient on its western side led to a period with significantly intensified katabatic winds in the vicinity of Terra Nova Bay.

In Figure 3 the wind vectors, potential temperature and relative humidity (shaded if larger than 90%) at 925hPa of an 18h NOR-LAM forecast are displayed. A clear signal of the MC can be seen in the simulation results, where a spiraliform cloud pattern and a vortex in the wind field are visible. The MC development occurs slightly too late in the simulations. However, simulations started earlier yield less satisfactory results thereby indicating that some synoptic forcing, which is necessary for the MC development, is missing in the earlier analyses.

During the further integration, the modeled cyclone moves to the east and merges with a weaker trough south of Ross Island, thereby intensifying, broadening and finally becoming a larger sub-synoptic system, which is in agreement with observations. In addition, a synoptic cyclone enters the northern part of the Ross Sea area, partially merging with the sub-synoptic cyclone. An additional MC development takes place in the night from 18 to 19 February 1988 in the southeastern part of the Ross Ice Shelf (not shown).

An analysis of the vertical component of the vorticity budget equation on pressure surfaces shows that the stretching term is the dominating term for the production of cyclonic vorticity for the Terra Nova Bay MC during the first 18h of the simulation (not displayed). The vertical stretching of the synoptically supported air flow through Reeves Glacier near Terra Nova Bay appears to be important for this MC development. The high values of the stretching term are not a result of the stretching of the katabatic drainage flow alone. An approaching synoptic low at 700hPa provides
additional relative vorticity for the generation of the MC by vortex stretching.

In sensitivity studies (not shown), the diabatic heating over the open water due to the convergence of the sensible and latent heat fluxes and the impact of latent heat release by NORLAM cloud physics turned out to be of minor importance for the MC development. In another sensitivity study, the topography of the WRSR was removed leading to a suppression of the MC development in the NORLAM simulation, which clearly underlines the importance of the WRSR topography for this MC event.

3.2 The case of 7 January 1988

The second case for the Ross Sea has also been previously investigated by Carrasco and Bromwich (1995) using observational data. A series of MCs developed in the period from 7 to 10 January 1988 in the WRSR, with several MCs merging and forming a larger sub-synoptic system.

Figure 4 contains a regional analysis of the sea level pressure (mainly based on AWS data) for 7 January 1988 taken from Carrasco and Bromwich (1995) and model results of a NORLAM simulation for this case (both valid at 1800UTC, 7 January 1988). Two MCs L1 and L2 are present as well in the regional analysis as in the model results. No cloud structures could be detected on satellite images at that time.

At later stages, however, the agreement of observation and simulation results is very poor. This appears to be a result of a too strong high pressure system over the Ross Ice Shelf in the ECMWF analyses, which prevents the merging of the simulated MCs and leads to a completely wrong forecast of the further development.
The severe forecast problem of this MC case strongly supports the demand of additional observational data in order to improve operational analyses and to compensate for the general data sparsity in that area.

4 Conclusions

Considering the difficulty of operational analyses and forecasting in the Antarctic, it becomes obvious that numerical modeling of MCs still represents a very challenging task. The studies presented in this work show that mesoscale models are in principle able to capture the development of MCs although some tendency to underestimate the intensity of the developments seems to be present. Comparisons with the successful polar low forecasting for the northern hemisphere lead to the question about the reasons for the differences of the forecast quality. Since the Antarctic near surface characteristics turn out to be one important factor for the MC developments, a good representation of the complex topography of the Antarctic in the model and a sufficient model resolution are important prerequisites. But, taking into consideration the importance of the synoptic forcing, it can be concluded that the quality of the operational analyses is not always sufficient to yield the synoptic forcing with that degree of accuracy as required for a successful MC forecast using a mesoscale limited area model. This underlines the demand to incorporate data sets obtained by remote sensing techniques and AWS in operational Antarctic weather prediction in order to compensate for the general data sparsity in the Antarctic.

Acknowledgments

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References


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Introduction

In the Antarctic context, users have to be aware that the output from the numerical weather prediction (NWP) systems cannot be used in the same way as in mid-latitudes where there is a huge number of verification statistics on model analysis and prognosis performance. Analysis validation and prognosis verification data for the Antarctic are relatively limited although slowly increasing in number. The evidence in the literature is also somewhat variable in conclusions as to the worth of NWP in the Antarctic. For example, the First Regional Observing Study of the Troposphere (FROST) over the Antarctic (Turner et al., 1996, 1999), which examined the quality of Antarctic analyses, found that the models were fairly good over the ocean areas but lacked the mesoscale and small synoptic-scale detail that is often what concerns the forecaster. Adams (1997), however, has reservations about the accuracy of NWP for high southern latitudes. Adams’ (1997) study was based on the model output, for two summer seasons, from the European Centre for Medium-Range Weather Forecasts (ECMWF) model and from the Australian Bureau of Meteorology’s Global Assimilation Prediction System (GASP). Adams (1997) attributes the poor performance to poor initialisation analyses. This attribution has some support from Bromwich and Cullather (1999) who assessed USA National Centers for Environmental Prediction (NCEP) model analyses against FROST analyses and found that there was the suggestion that inaccurate model initial fields (particularly in the vertical temperature profile over continental Antarctica) have a major role in producing the substantial model drift they found in some model fields.

On the other-hand, Cullather et al. (1997) report that “The ECMWF analyses offer a reasonable depiction of the broadscale atmospheric circulation; however, deficiencies in mid-tropospheric temperatures and lower tropospheric winds are evident”. Cullather et al. (1997) also note a marked improvement in ECWMF and NCEP model analyses for the period 1985 to 1994. These authors also showed that the ECMWF analyses were particularly accurate for the period studied over at least one part of the high latitude southern ocean, even in the absence of real-time data for the particular area.

Global model analysis validation

Numerical analyses at 500 hPa

The sparsity of data available for high southern latitudes begs the question: which model, if any, provides accurate analyses, let alone accurate prognoses? It is well known that the height of the Antarctic continent makes reductions to mean sea level pressure problematical, and so the sea level pressure chart is perhaps not the best reference level. The first standard pressure level which does not intersect the Antarctic interior is the 500 hPa level and that will be used as the level discussed here.

While not shown here in detail, where analysis data were available for comparison the mean height differences at 500 hPa between four of the global numerical analysis systems

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were examined for January to August 1999. The models involved were the ECMWF, GASP, NCEP aviation model (here called USAVM) and the United Kingdom Meteorological Office (UKMO) model. It was found, for example, that near the Antarctic coast at about 140° W, the average difference in 500 hPa height contour analysis between the GASP and the ECMWF models for January 1999 gave a peak value of the GASP analysis being 134 m lower than the ECMWF analysis. Whereas for the same approximate location for January 1999 the following mean analysed height differences occurred: GASP was up to about 90 m less than the UKMO analysis system; ECMWF was up to around 50 m higher than the UKMO; and the USAVM analysis was within 20 m of the UKMO model. The locations of areas of model differences varied somewhat among the months examined, but generally speaking, where radiosonde data would have been more frequent (for example, coastal regions of East Antarctica) model analysis differences were less than about 20 m.

While these types of comparisons do not prove which analysis model is the most accurate they do highlight the differences between model systems. This point is relevant when one comes to examine prognosis verifications since a standard technique is for NWP model's prognostic fields to be verified against its own analyses. Bearing in mind that the examples of the differences in analyses shown here are quite typical, one is tempted to assume that, until further detailed validation studies are undertaken using observational data, one is tempted to assume that, based on Cullather et al. (1997), the ECMWF analyses are the most superior.

Site specific performance of the GASP model analyses—some examples from East Antarctica

The following provides some information on how the GASP model analysis scheme represents conditions at three East Antarctic stations: Casey (66.28° S, 110.52° E, elev. 40 m AMSL); Davis (68.6° S, 78.0° E, 16 m AMSL); and Mawson (67° 36' S, 62° 53' E, 10m AMSL) for a snapshot in time. Time series of observed and modelled surface and upper air parameters were prepared for the period 1 March to 14 April 2000. (An example of the surface parameter observations for Mawson is given in Figure 1 and the corresponding time series of the GASP data for the grid point closest (about 8 km) to Mawson is shown in Figure 2). Inferences from the time series for these three stations, about the GASP model's ability to represent the real atmosphere during its analysis cycle are:

- Surface pressure is handled very well by GASP's assimilation scheme: as it should be because surface pressure is directly assimilated into the model.
- Surface temperature is handled reasonably well although occasional lags are noticed in the model data.
- Surface wind direction is not too badly handled although nowhere near as good as pressure and temperature. This is to be expected as wind is not directly assimilated into the GASP model.
- Surface wind speed is poorly handled. Trends are reasonably well represented although some lags are noticeable. However, the magnitude is not well analysed, especially at Mawson where the katabatic is a feature of the local climatology. Again this is to be expected as wind is not directly assimilated into the GASP model.
- Upper air wind and temperature data are better assimilated across all fields than are the surface fields.
- Upper level wind directions are well modelled although sometimes a few degrees different from the observed data.
- Upper level wind speeds are only marginally less in the GASP analyses than observed.
Figure 1  Time series of observed surface data from Mawson for 1 March to 14 April 2000.

Figure 2  Time series of GASP model analysis surface data for Mawson for 1 March to 14 April 2000.
• Upper level moisture is not so well assimilated with GASP seeming to run too moist - especially above 250hPa.
• Even in the surface layers the GASP analyses are not picking the dry events well and carrying too much moisture.

What dry events the GASP does pick tend not to be as dry as reality or as long lived. The model seems to want to increase moisture rapidly.

Concluding remarks

Initialisation of NWP, that is the analysis cycle, has been implicated in some deficiencies of model performance in the Antarctic. Over the ocean areas around the Antarctic continent the performance of the models is slightly poorer than in mid-latitudes because of the lack of in-situ data and the high reliance on satellite sounder data. However, in the interior of the continent the output of the models is of very limited operational use. This probably comes about because of the difficulties in representing the orography of the Antarctic in the models, the fact that satellite sounder data are not used at tropospheric levels, and the small number of automatic weather station observations on the Global Telecommunications System (J. Turner, personal communication). Studies such as Bromwich and Cullather (1999) indicate that problems with NWP over continental Antarctica are increasingly receiving attention.

References


The FROST Project – What did we Learn?

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1. INTRODUCTION

The Antarctic First Regional Observing Study of the Troposphere (FROST) project was organized by the Physics and Chemistry of the Atmosphere group of the Scientific Committee on Antarctic Research and had the goals of studying the meteorology of the Antarctic, determining the strengths and weaknesses of the operational analyses and forecasts over the continent and in the surrounding ocean areas, and assessing the value of new forms of satellite data that are becoming available. FROST was based around three one-month Special Observing Periods (SOPs) – July 1994, 16 October to 15 November 1994, and January 1995 for which comprehensive data sets were established of model fields and in-situ and satellite observations. High quality manual surface and upper air analyses were prepared for selected periods of the SOPs to determine the extent to which non–Global Telecommunications System (GTS) data could improve the interpretation of the synoptic situation. A full description of the FROST project can be found in Turner et al. (1996) and in the Special Issue of Weather and Forecasting on FROST for December 1999. The FROST data can be obtained from http://www.nerc-bas.ac.uk/icd/FROST/.

2. MAIN LESSONS FROM FROST

Some of the main lessons learnt from FROST were:

1. Most of the synoptic reports from the stations are transmitted out of the Antarctic, but there can be problems in receiving the data on parts of the GTS. For example, a total of 7,020 (9,582) surface meteorological reports have been obtained from the staffed stations for the winter (summer) periods, representing about 92% of the possible maximum, based on the station reporting schedules. However, when we compared the roughly comparable amount of data received at Hobart, Australia and Cambridge, UK, we found that a high percentage of the data were different observations, suggesting that data loses were occurring on the GTS outside of the Antarctic. When investigated, it was found that many of these problems were fairly transient, suggesting that frequent monitoring of the Antarctic observations on the GTS would be valuable.

2. Today more observations from automatic weather stations (AWS) are available for the Antarctic than reports from the staffed stations, with the number of AWS observations collected for the two main SOPs being 11,721 (13,515) for winter (summer). It would be very useful if more AWS observations could be put on the GTS if funds were available. The meteorological observations from the AGOs would also be useful in near–realtime.
3. The subjective assessment of the numerical weather prediction (NWP) analyses indicated that no large, synoptic-scale systems were missing from the mean sea level pressure (PMSL) fields, but major discrepancies were found in terms of the depth of the lows, location errors, and failures to resolve the complexities of systems. Generally, the central pressures of the lows were handled better than the locations of the centers. Only four lows out of a total of 161 in the eastern hemisphere during the period 22–28 July had to be relocated more than 500 km. High quality satellite imagery was very important in correcting the locations of the lows and in resolving the structure of multi-centered systems, which were often found to be much more complex than analyzed on the operational charts.

4. Of the four sets of NWP forecasts available to the project (ECMWF, UK Met. Office, Australian GASP and NCEP AVN) the ECMWF forecasts had the smallest errors in objective tests. It should be remembered that the ECMWF NWP system has a relatively late data cut-off time and there is only one forecast produced each day.

5. The Philippot technique for the analysis of the 500 hPa surface over the interior of the continent was of particular value in resolving structure in the circulation over the plateau. The satellite imagery was of less value over the continent since some of the lows here, which were analyzed using automatic weather station data, had no cloud associated with them as a result of the atmosphere being very dry.

6. Few changes were made to the analyzed positions of anticyclones over the Southern Ocean and only minor modifications to ridges were required.

7. The mean PMSL fields for July 1994 produced by the UKMO, ECMWF, NCEP and Australian BOM models were all very similar, but the Australian model stood out as slightly different over the Amundsen Sea because of large differences in the handling on one large low during the early part of the month.

8. When automatic depression identification and tracking software was applied to the NWP analyses from the FROST SOPs it confirmed the Antarctic coastal region as a zone of high cyclone density and of very active cyclogenesis. This is contrary to earlier work that placed the maximum of cyclogenesis close to 40–50° S, but is in agreement with studies based on high resolution satellite imagery.

9. Mesocyclones over the Southern Ocean observed during FROST were investigated using satellite imagery, scatterometer winds, passive microwave data and high resolution (up to 25 km) numerical models. The work showed that this new generation of models was able to resolve much of the structure of these mesoscale systems, suggesting that it may be possible to forecast them soon using the operational models. This would be of great benefit for forecasting in the Antarctic since forecasters are often concerned with mesoscale systems, which at present can only be dealt with using nowcasting techniques.

3. OPERATIONAL ANALYSES IN HIGH SOUTHERN LATITUDES

In support of the FROST, several standard meteorological analysis systems have been reviewed for the Antarctic region (Cullather et al. 1997). In a 10–year period up to the time of the FROST study, the NCEP operational analyses and ECMWF/Tropical Ocean Global Atmosphere (TOGA) archive II were evaluated in comparison to a variety of observations. The quality of the operational analyses increased during the years prior to FROST, particularly for the NCEP analyses during 1985–1990. Overall, the ECMWF analysis agrees better with observations than the NCEP analyses. The topographic representation of Antarctica by standard meteorological analyses has inaccuracies introduced by spectral representation of steep topography and the use of comparatively old orographic representations. On the average, the NCEP analyses show warmer surface temperatures over the high interior plateau of
Antarctica than the more realistic values of the ECMWF analyses during 1985–1994. The analyses may underestimate the intensity of strong synoptic systems in high southern latitudes. Figure 1 shows an example of this at Scott Island AWS during October 1993. Both analyses reasonably capture the minimum pressure on 02 October 1993. The ECMWF analyses, however, overestimates the pressure by about 15 hPa for the minimum on 06 October 1993.

Figure 1. Surface pressure time series for Scott Island AWS (67.37°S, 179.97°W), and corresponding ECMWF and NCEP analysis values, in hectopascals for 01 October 1993–10 October 1993.

During July 1994 (SOP–1), NCEP operational forecasts and analyses are evaluated by Bromwich et al. (1999). Forecasts are produced with the NCEP operational global spectral model. The model has T126 horizontal resolution and 28 sigma levels. The July 1994 SOP is characterized by a series of strong blocking events over the central and eastern Pacific Ocean. The representation of Antarctic topography by the NCEP operational global spectral model leads to ambiguity in evaluating the forecast of surface variables. The dated surface elevation dataset was found to have positive and negative errors of several hundred meters over Queen Maud Land.

The evaluation of the NCEP forecasts revealed that the intensity of the forecasted winter inversion tends to increase after the zero forecast hour. Biases in several near-surface and upper-troposphere fields decrease with forecast time. Atmospheric moisture over the continental interior does not change significantly with forecast hour. A spurious high-latitude wave pattern is found for several variables. One consequence of this is the presence of persistent cloud streets over Antarctica due to proximity of moist and dry bands. An improvement to the horizontal diffusion parameterization implemented in November 1997 has eliminated the problem from more recent versions of the NCEP model. Over the Southern Ocean, forecast error for height and pressure fields increases during blocking conditions. It is uncertain whether this results from bias of the forecast model or the limited observational network over the Southern Ocean.

Comparisons of NCEP analyses with rawinsonde data during SOP–1 indicate that most of the available observational data for high southern latitudes are being incorporated into the analyses. For example, Fig. 2 shows the 500 hPa geopotential height for Campbell Island. The average NCEP height is only 7 gpm less than the observed value. The correlation coefficient between NCEP and the observation is 0.99. The ECMWF analyses are marginally superior in Fig. 2.

An evaluation of the surface energy balance during the FROST study revealed a deficit in downward longwave radiation over Antarctica (Hines et al. 1999). This is a common problem for atmospheric models in the polar regions. During the January 1995 SOP (SOP–3), an update to the NCEP model on 10 January 1995 resulted in a significant change to the surface energy balance and a
positive jump in the surface temperature. The warming partly resulted from a reduction in heat flux into
the snow pack.

Figure 2. Time series of 500 hPa geopotential height (geopotential meters) from rawinsonde, NCEP analyses and ECMWF analyses at Campbell Island (53°S, 169°E) during July 1994.

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GLOBAL ATMOSPHERIC MODEL PERFORMANCE IN THE ANTARCTIC

S. F. Pendlebury⁴, N. D. Adams², T. L. Hart³, and W. Skinner³

Introduction

Accurate numerical weather prediction (NWP) prognoses will allow the forecaster to maximise the chances of correctly predicting the individual weather elements such as wind velocity. Fraedrich and Leslie (1991) suggest that, based on the time taken for errors in the 500 hPa field to double in Antarctic areas of high baroclinicity, predictability time scales might be as short as about one day. On the other hand, Baba (1993) suggests that at least a general trend in the local weather might be predicted well in advance in some circumstances. For example, Pendlebury and Reader (1993) described the forecasting several days in advance by the European Centre for Medium-Range Weather Forecasts (ECMWF) model of a very deep storm that affected Casey station (66.28° S, 110.52° E, elev. 40 m AMSL) giving record wind gusts up to 66.9 m s⁻¹ (130 kt).

NWP model output is available for high southern latitude forecast guidance from a wide variety of global forecast models. The global models referred to in this paper are: the Australian Bureau of Meteorology’s Global Assimilation Prediction System (GASP); the Japanese Meteorological Agency model (JMA); the United Kingdom Meteorological Office model (UKMO); the USA National Centers for Environmental Prediction (NCEP) aviation model (USAVM); and the ECMWF model.

Verification data available for NWP performance in the Antarctic are relatively limited although slowly increasing in number. Adams (1997), for example, has reservations about the accuracy of NWP for high southern latitudes. Leonard et al. (1997) examined the performance of the UKMO model over the Antarctic and found that temperatures over the interior were too cold resulting in the katabatic winds being too strong, although in general found that the model performed satisfactorily stating that "The analysis/forecast model currently has a reasonable representation of the atmospheric circulation".

An overview of uses and performance of NWP in the Antarctic context

Contributions to the draft International Antarctic Weather Forecasting Handbook suggest that uses of NWP in the Antarctic include: determination of the pressure field; assistance with surface wind forecasting; forecasts of the upper wind, temperature, humidity; significant weather prognoses; cloud forecasting; precipitation forecasting; air-frame icing; jet stream turbulence forecasting; and sea wave and swell wave forecasting. Figure 1 is an example of a portion of the forecast data which is typically provided to Antarctic tourist flights which depart Australia over summer.

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⁴ Please Note: In preparing this paper some material has been copied or derived from the draft of "The International Antarctic Weather Forecasting Handbook" which is in preparation (J. Turner and S. Pendlebury, editors) but which has not yet been reviewed. As such this material is still in draft form and the contributors reserve the right to change it. Relevant material from the draft Handbook is included here to draw attention to its probable appearance in the finalised version.
Figure 1  Forecast cross-sectional wind, temperature, geopotential height and MSLP for an Antarctic tourist flight (Boeing 747). These flights typically over-fly abeam northern parts of the Transantarctic Mountains.

Some broad inferences can be made from the draft Handbook contributions on the performance of NWP from global models in Antarctica:

- NWP systems appear to perform well for synoptic-scale systems over high latitude southern oceanic areas, and perhaps over coastal Antarctic areas.
- The models do NOT appear to handle meso-systems well, due to model resolution, although the output can contain some relevant hints on the development of mesoscale lows. It may also be that the lack of data on the meso and small synoptic scales limits the smaller scale systems from being represented adequately.
- The model resolution is too coarse to adequately represent important topographical features even as prominent as the Antarctic Peninsula.
- There are mixed results concerning the prediction of surface wind.
- Forecasts of upper air parameters (particularly wind, temperature, humidity, and turbulence) seem to rely heavily on NWP, particularly due to a lack of upper air observational data (which would, if available, be of use in "nowcasting").
Comparisons of global model performances

Numerical prognoses at 500 hPa

As mentioned by the authors in a companion paper ("Southern Hemisphere operational atmospheric analyses") for this workshop, a standard technique is for a prognostic model to be verified against its own analysis. Moreover, the authors pointed out in this companion paper that until further detailed verification studies are undertaken using observational data one is tempted to assume that, based on Cullather et al. (1997), the ECMWF analyses are the most superior. Based on this assumption it is instructive to examine examples of ECMWF performance. As an example, but not shown here, global charts of the 500 hPa forecast error for the ECMWF prognoses at 24, 48, 72 and 120 hr for January 1999 were examined. At 24 hr the prognosis mean height errors (when compared against the ECMWF analyses) were everywhere less than 20 m. By 120 hr maximum errors over the Antarctic had increased to about 70 m. Examination of similar prognoses for other models suggests that at 24 hr, the GASP model errors were comparable with the ECMWF prognosis at 72 hr; the UKMO model errors at 24 hr were comparable with the ECMWF errors at 48 hr; and the USAVM, at 48 hr had errors which were also comparable with the ECMWF errors at 48 hr.

Bearing in mind the differences in analyses noted by the authors in the companion paper mentioned above, it may be that some of these comparisons are generous. In the case of the GASP model, for example, it was noted that near the Antarctic coast at about 140° W the average difference in 500 hPa height contour analysis between the GASP and the ECMWF models for January 1999 gave a peak value of the GASP analysis being 134 m lower than the ECMWF analysis. If the ECMWF analysis is taken as the "truth" then the GASP prognosis would be in error by a much greater amount than mentioned above.

Bulk model performance statistics for south of 55° S

Figure 2 shows some verification statistics for the ECMWF, GASP, JMA, UKMO, and USAVM, models' ability to predict 500 hPa heights south of 55° S. The results confirm the overall superiority of the ECMWF model.

Concluding remarks

A forecaster should always be aware of the strengths and weaknesses of NWP model output in the Antarctic. Moreover, as models are developed and new parameterisation schemes introduced the nature of the errors can change since the model developers tend to check the results of their changes most carefully in the extra-polar regions. Intrinsically, however, there appears to be no reason as to why NWP should not eventually be very successful in the Antarctic context. Diagnostic numerical simulations (eg: Parish (1984) and Hines et al. 1995) to name only a couple) appear to provide very useful and realistic information on the Antarctic atmosphere. Moreover, as the global models' grid resolutions increase further one might expect that many hitherto poorly represented geographical features will find adequate representation in the models. And one hopes that there will be an increase in the observational data necessary to properly initialise the global model systems.
Figure 2 Some statistics on the performance of some global models at the prediction of 500 hPa heights for the region south of 55° S for the period 1 January to 31 March 2000.

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ANTARCTIC WEATHER FORECASTING WORKSHOP: PLANNING FOR THE NEXT 10 YEARS

WORKING TOWARDS AN OPTIMIZED OPERATIONAL VERSION OF MM5 FOR ANTARCTIC SUPPORT AT AFWA

JERRY W. WEGIEL

ABSTRACT

During the mid- to late-1980's, numerical weather prediction modelers came to the realization that adequate parameterization of deep convection and the planetary boundary layer (PBL) were the two most important components in the improvement of the prediction of mesoscale events. The successful prediction of "convective" weather systems not only hinges upon the convective parameterization, but also upon the magnitude and distribution of the resolvable-scale latent heat release, and the concurrent development of the diurnal cycle in the boundary layer. A key element in the success of any complete precipitation parameterization in a numerical model is "internal consistency" between the individual components of that parameterization. Furthermore, it is essential that interactions between the cumulus parameterization and PBL schemes be optimized in order to attain peak performance of the modeling system.

1. Introduction

The Air Force Weather Agency (AFWA) has been running the MM5 mesoscale modeling system in the production mode since October of 1997. Efforts have been underway to optimize the parameterized physical processes (e.g., large vertical fluxes of heat, moisture and momentum) and their effects on the atmospheric circulation. The magnitude and extent of these effects depend upon geographic location, season, time of day, large-scale environment, and location within convective systems.

Successful prediction of the different types of mesoscale weather systems may hinge upon closure assumptions, physical processes included in the parameterization, detailed terrain forcing, quality of initial conditions and model resolution of the internal structure of the convective systems and the planetary boundary layer (e.g., Ceseski, 1973; Mahrer and Pielke, 1977; Ogura and Chen, 1977; Rosenthal, 1979; Anthes, 1982; Garrett, 1982; Donaud et al., 1983; Perkey and Maddox, 1985). The two most important components in the improvement of the prediction of mesoscale weather events are the cumulus parameterization and PBL schemes.

The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) is supported by several auxiliary programs, which are referred to collectively as the MM5 modeling system. Under contract, updates (new releases) of a modified version of the MM5 are delivered periodically to the AFWA. Currently, Version 3 - Release 2 of the modeling system is in production at the AFWA. Regardless of the release delivered to the AFWA, the numerous physics options available within the modeling system are considered to be some of the most sophisticated schemes available in the world.

The variety of physics options available allows the AFWA to use the MM5 for a broad spectrum of applications including both predictive simulation and four-dimensional data assimilation to monsoons, hurricanes, and cyclones. On the smaller meso-beta and meso-gamma scales (2-200 km), MM5 can be used to resolve meteorological phenomena such as mesoscale convective systems, fronts, land-sea breezes, and mountain-valley circulations. An operational center such as AFWA must determine the most appropriate set of physics options independent of season and location.
2. Background

Due to the vast size of the AFWA’s spatially high-resolution theater grids, the only reasonable approach to configuring MM5 physics options to be theater specific at the AFWA would be to group the theaters into categories based on climatic zones. A climatic zone is defined as a belt of the earth’s surface within which the climate is generally homogeneous in some respect; an elemental region of a simple climatic classification (Glossary of Meteorology, 1959).

The original climate zones were bounded by the Tropics of Cancer and Capricorn and the Arctic and Antarctic Circles: they include the Torrid Zone, two Temperate Zones, and two Frigid Zones. In this sense, the zones are not only divisions of the mathematical climate, but climatic zones which may also be defined by the ‘actual’ climate. Figure 1 is a display of the global MM5 window configurations at AFWA. Thus, based on A. Supan’s definition, we may categorize each of the MM5-theaters into three separate climatic regimes: (1) Polar; (2) Mid-Latitude; and (3) Tropical.

The configurations of the land and water masses of the earth, combined with the current theater configurations demand that the climatic regimes be defined latitudinally.

However, the meteorological phenomena found in these theaters are drastically different. The theater with the most unique and, arguably, difficult modeling challenges is the Antarctic theater (Figure 2).
Optimization of MM5 model physics will receive the most attention in the coming months at AFWA. The model physics for each theater will be determined and fine-tuned. The motivation, of course, is to attain peak performance of the modeling system in order to provide the war fighter with the best possible product.

3. Strategy

To achieve this goal, AFWA has adopted a policy of strategic partnering. This philosophy has replaced the independent, go-it-alone approach. AFWA is committed to leveraging external capabilities for improvement of its in-house numerical weather prediction models. As a result, collaborative partnerships between AFWA and key modeling centers, universities and scientific laboratories have blossomed and exceeded expectation.

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1. INTRODUCTION

Real-time operational forecasts for the Antarctic continent, using a modified version of the Pennsylvania State University / National Center for Atmospheric Research (NCAR) fifth generation mesoscale model (MM5), are generated by the Polar Meteorology Group (PMG) at the Byrd Polar Research Center (beginning in January 2000). A description of the model used, forecast cycle, and a limited verification for January 2000 is presented.

2. DESCRIPTION OF THE POLAR MM5

The community mesoscale model MM5, that is freely available from NCAR, has been modified by the PMG for use in high latitudes, with a particular emphasis on processes over extensive ice sheets, such as Antarctica. This modified version of the model is referred to as the Polar MM5, and is used to generate operational numerical weather predictions for the Antarctic continent.

Dudhia (1993) and Grell et al. (1994) describe the standard version of MM5 in detail. Version 2 of MM5 allows for the use of either hydrostatic or nonhydrostatic dynamics to represent the atmospheric flow. MM5 is formulated using a staggered horizontal grid with a vertical coordinate system that is defined in terms of pressure. The hydrostatic version of the model, that is currently used for the operational forecasting, includes three-dimensional prognostic equations for the horizontal components of the wind, and temperature, and a two-dimensional prognostic equation for $p = p_{\text{surface}} - p_{\text{top}}$, while the nonhydrostatic version of the model includes three-dimensional prognostic equations for the horizontal and vertical components of the wind, perturbation pressure, and temperature. Both versions of the model also predict the mixing ratio of water vapor as well as various cloud species (dependent upon the model physics options selected) at each model grid point.

Parameterizations for horizontal diffusion, cloud microphysics and precipitation processes, turbulence, cumulus convection, and radiative transfer are included in the model, with multiple options available for the representation of many of these processes. Heat transfer through the model substrate is also represented using either a slab model or a multi-layer "soil" model (Dudhia 1996).

The Polar MM5 includes modifications to the cloud microphysics, turbulence, radiative transfer, and "soil" heat transfer parameterizations, as well as the addition of a sea ice surface type.

The Reisner et al. (1998) mixed phase microphysics parameterization is used in the Polar MM5. Excessive cloud cover is found to be a problem over the Antarctic in sensitivity simulations using an unmodified earlier version of MM5 (Hines et al. 1997a, 1997b), similar to results found by Manning and Davis (1997) for high clouds over the continental United States. The implementation of Meyers et al. (1992) ice nuclei concentration equation, as suggested by Manning and Davis (1997), helps to eliminate the cloudy bias in polar simulations with MM5, and is a standard part of the Polar MM5.

Comparison of MM5 simulations of katabatic flows over the Greenland ice sheet with low-level aircraft observations [collected during KABEG'97 and described by Heinemann (1999)] indicate that the use of the Blackadar planetary boundary layer (PBL) (Zhang and Anthes 1982) or the Hong and Pan (1996) PBL (referred to as the MRF PBL in MM5 documentation) parameterizations results in the simulation of an overly deep katabatic layer with a damped diurnal temperature range. Use of either the Burk and Thompson (1989) or the Eta model (Janjic 1994) 1.5 order closure PBL parameterizations produces shallower katabatic flows that match the observed profiles. Based on these results the Eta PBL parameterization is used for the simulations with the Polar MM5.

Radiative transfer in the atmosphere can be simulated in MM5 with the CCM2 radiative transfer parameterization (Hack et al. 1993). In this parameterization the radiative properties of clouds are based on the grid point relative humidity values in the model. From sensitivity simulations it was found that this parameterization generates overly radiatively active clouds that are responsible for excessive downwelling longwave radiative fluxes during the austral winter over the Antarctic ice sheet (Hines et al. 1997a, 1997b). This problem is corrected by modifying the CCM2 radiative transfer parameterization such that the forecast cloud liquid water and ice water mixing ratios, from the Reisner et al. (1998) microphysics parameterization, were used to determine the radiative properties of the clouds at each grid point in the model domain, rather than the grid point relative humidity. The radiative properties for the water and ice phase cloud particles are identical to those used in the CCM3 radiation parameterization described in Kiehl et al. (1996).

The multi-layer parameterization of heat transfer through the model substrate presented by Dudhia (1996) is used in the Polar MM5. Changes to this parameterization include the addition of two additional substrate levels, increasing the substrate depth to 1.91 m (compared to 0.47 m in the unmodified version), and...
modification of the thermal properties of the permanent ice surface type to better match observations. A final modification to the Polar MM5 is the addition of a variable fraction sea ice surface type. This surface type allows a fractional sea ice cover to be specified for each oceanic grid point in the model domain. The sea ice thickness varies from 0.2 m to 0.95 m dependent on the hemisphere and sea ice fraction at the grid point. The surface fluxes for the sea ice grid points are calculated separately for the open water and sea ice portions of the grid point and then averaged before interacting with the overlying atmosphere.

For the operational Antarctic forecasts the Polar MM5 model domain is configured to include the entire Antarctic continent and portions of the adjacent Southern Ocean (Fig. 1). The domain consists of 121x121x28 grid points, with a horizontal grid spacing of 60 km. The lowest model level is located at a nominal height of 12 m AGL. The model terrain is specified using the RADARSAT Antarctic Mapping Project dataset (K. Jezek, personal communication).

Figure 1. Map of the Polar MM5 operational Antarctic weather prediction model domain and terrain elevations (elevation contour interval of 500 m).

3. OPERATIONAL FORECAST CYCLE

The Polar MM5 is initialized once per day, with data valid at 12 UTC, using the output from the National Centers for Environmental Prediction (NCEP) MRF global model. The model output is accessed via the NCEP anonymous ftp site, and is available approximately 4 hours after the MRF initial time of 00 UTC. The Polar MM5 initial and boundary conditions are generated from the gridded MRF output using the standard suite of MM5 pre-processing programs available from NCAR.

Once the MRF model output is processed a 72 h forecast is generated with the Polar MM5. The 72 h simulation requires approximately 18.5 h of CPU time on a PC with a 466 MHz Celeron processor.

The final step in the operational forecast cycle is the generation of surface and constant pressure plots for the entire model domain and meteograms and atmospheric soundings at selected locations around the Antarctic continent. The graphics are posted at http://www-bprc.mps.ohio-state.edu approximately 24 h after the model initial time.

Operational forecasts using the Polar MM5 have been generated at BPRC starting in January 2000, and continue through the present. The Polar MM5 initial and boundary conditions and forecast fields for each forecast cycle are being archived for future analysis and to aid in model improvement.

4. POLAR MM5 VERIFICATION

A limited verification of the Polar MM5 forecasts for January 2000 has begun. The verification has focused on the predicted near surface atmospheric state, and has utilized the automatic weather station (AWS) array maintained by the University of Wisconsin (Stearns et al. 1993). Particular emphasis has been placed on verification near U.S. Antarctic Program stations and field camps.

The Polar MM5 forecasts is found to reproduce the temporal changes in the near surface air temperature, pressure, wind speed, and wind direction at most sites with a reasonable level of skill. Surprisingly the model forecast skill is not found to decrease appreciably during the 72 h forecast period.

Time series plots of the observed and predicted near surface air temperature at the South Pole (Clean Air AWS) and surface pressure and relative humidity at Willie Field are shown in Figures 2, 3, and 4, respectively.

From Fig. 2 it is evident that the Polar MM5 reproduces the observed temporal evolution of the near surface temperature with a reasonable level of skill, although the Polar MM5 predicted temperature is approximately 4°C colder than the AWS observed temperature. This cold bias is also evident in the Polar MM5 simulations at other locations, and is most pronounced for locations on the Ross Ice Shelf.

Figure 2. Time series plot of the AWS observed (thin solid line) and the Polar MM5 predicted (thick solid line) near surface air temperature at the South Pole for 11-31 January 2000. The model time series is a composite of the predictions valid 51 to 72 h after the model initial time.
cold bias may be caused, in part, by an underestimation of the downwelling longwave radiation in the CCM2 radiation parameterization, that has previously been documented.

The Polar MM5 simulations during January 2000 reproduce most of the synoptic variability in the AWS observations of pressure at Willie Field, with the exception of the observed pressure increase on 13 January 2000 (Fig. 3). From the time series plot, a high frequency, irregular oscillation in the modeled surface pressure is apparent. Oscillations of this type are found at other locations in the model domain, and decrease in magnitude with increasing forecast duration. The source of these oscillations is under investigation. It should be noted that simulations with the Polar MM5, using the same model options and domain size, but different initial and boundary conditions do not contain these high frequency oscillations in the pressure field.

The modeled near surface relative humidity is of similar magnitude to the observations at Willie Field during January (Fig. 4). The model does not reproduce the large variability in the observed relative humidity time series. This shortcoming may be a reflection of the limited number of moisture observations available in the Antarctic for incorporation into the operational analyses and forecast models, and highlights a potential problem for boundary layer cloud forecasting in the Antarctic.

Additional analysis of the model output is continuing at BPRC, and efforts to correct known problems in the model physical parameterizations are underway.

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Operational perspective on future improvements

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Once an observation is taken or a forecast is published, the task of weather-support professionals changes from atmospheric study to one of communication. It's no surprise, then, that Mac Weather's vision of the future reaches beyond weather-related advances. Foremost, Antarctic forecasters require more data ... more satellite imagery, more surface observations, more upper-air soundings. Putting these data to good use will require improved visualization capabilities and a safe repository. Of almost equal importance, forecasters require improved mesoscale forecast modeling. Beyond these basic needs, forecasters require continuous, robust, realtime telecommunications across Antarctica and between continents.
Identification of Key Parameters for Aviation Forecasts of Ceiling and Visibility

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1. Introduction

Aviation forecasts of ceiling and visibility are of vital importance to the aviation community, yet generally do not receive as much publicity as other forecast products such as icing and turbulence. Within the United States, ceiling and visibility forecasts are key components of Terminal Area Forecasts (TAFs) generated by individual National Weather Service (NWS) forecast offices for selected airports. Pilots rely heavily on TAFs to determine ceiling and visibility conditions at their destination, and based on these forecasts, whether they will be subject to Visual Flight Rules (VFR), Instrument Flight Rule (IFR) or Low Instrument Flight Rules (LIFR). IFR rules are invoked when the ceiling is between 500 and 1000 feet and/or if visibility is between 1 and 3 miles. LIFR rules are invoked when the ceiling is less than 500 feet and/or if visibility is less than 1 mile. Improvements in ceiling and visibility forecasts directly influence both flight safety and efficiency.

Unfortunately, cloud cover is the most difficult of meteorological variables for numerical models to predict. The Model Output Statistics (MOS) output for predictions of ceiling and visibility is heavily dependent on the most recent station observations rather than the output of the numerical model (Vislocky and Fritch 1997). Because of this factor there has not been the increase in the quality of ceiling and visibility forecasts which have been realized for other forecast variables. For three and six hour forecasts, several studies have shown that local forecasters could not do better and often did worse than persistence (Zurndorfer et al. 1979; German and Hicks 1981; Goldsmith 1993). The situation has not improved in recent years as Dallavalle and Dagostaro (1995) show that persistence forecasts are generally better than those made by the local forecaster for up to a 6 hour time frame and that no improvement in the quality of these forecasts had been made for a number of years. Hence, despite the modernization of the meteorological observation network and continual improvements of numerical weather prediction, ceiling and visibility forecasts remain stuck in the pre-modernization era.

This paper describes a cooperative research project between the University of Kansas and NOAA/NWS forecast office in Pleasant Hill, Missouri which is funded by the University Corporation for Atmospheric Research (UCAR) COMET program. The primary goals of this project are to objectively identify important parameters in
forecasting ceiling and visibility, and to improve the accuracy of ceiling and visibility forecasts. This project consists of three key components:

- ceiling and visibility forecast verification for the past five years;
- identification of meteorological parameters and products used by individual forecasters to make ceiling and visibility forecasts;
- develop objective forecast algorithms using multiple linear regression and fuzzy logic techniques.

While this project is focusing on a single airport (Kansas City International Airport), the methodology and analysis techniques can be applied anywhere and can be readily modified to adapt to the observational and model data available. This includes Antarctic flight operations where accurate ceiling and visibility forecasts are critical to flight safety and efficiency during the limited period when flight operations are conducted.

2. Forecast Verification of Ceiling and Visibility

Assessing current forecast skill for the ceiling and visibility forecasts made for Kansas City International Airport (MCl) is critical to assess the current state of TAF accuracy and as a benchmark for measuring the skill of the new objective TAF forecast system under development. IFR and low ceiling events are currently being examined for the period January 1995 through December 1999. This period represents observations exclusively from the Automated Surface Observing System (ASOS). These events are compared to TAFs for MCI issued by NWS forecasters to determine how often the forecaster improves on a persistence or MOS forecast for IFR or low ceiling conditions at MCI. This task is aided by the national verification statistics currently kept for MCI. This data set includes the Probability of Detection (POD), the False Alarm Rate (FAR), the Threat Score and the Heidke skill score (Wilks, 1995). This work is currently in progress and will not be complete until summer 2000.

3. Identification of Meteorological Parameters

Development of a TAF forecast system is currently underway. The present focus is to develop the TAF forecast system using least squares multiple linear regression techniques which have been previously used in similar studies (Vislocky and Fritch 1997). The variable to be predicted, Y, is modeled as a linear combination of predictors \( X_p \). Thus, Y can be expressed as

\[
Y = a_0 + a_1X_1 + a_2X_2 + \ldots + a_nX_p
\]

The coefficients \( a_n \) are calculated to minimize the squared error between the predicted and observed values of Y. Separate forecast models have been developed for ceiling forecasts and visibility forecasts, and the forecast times are for 1 hour, 3 hours, and 6 hours. We are also exploring a TAF forecast system using non-linear fuzzy logic modeling techniques (Wang et al., 1998).

A list of predictor variables for ceiling forecasts and visibility forecasts have been developed, with the majority of these predictor variables derived from the experience of
the individual forecasters. These predictor variables come from observations, satellite and model data, and were identified by student research assistants working side by side with six different NWS forecasters at the Pleasant Hill Weather Forecast Office. To date, the student research assistants have worked with the NWS forecasters during the fall, winter and spring seasons, and these interactions are planned to continue through summer 2000. The complete predictor variable list for ceiling forecasts is given in tables 1a and 1b. Table 1a includes variables obtained from observations at the time the forecast is generated, and table 1b includes variables predicted for the forecast time by the Eta model or by NGM MOS. A similar parameter list containing 25 parameters has been compiled for visibility forecasts. Most of these parameters are quantified using either GEMPAK or MCIDAS.

4. Objective System for Ceiling and Visibility Forecasts

The process of analyzing past IFR and LIFR conditions is in progress and our goal is to have more than 50 events quantified before serious evaluation of the parameters is conducted. Once we approach this goal, a correlation matrix will identify which (if any) of the parameters are correlated. For each correlated parameter pair, it will be

Table 1a. Predictor Variable List for Ceiling Forecasts From Observations.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameter Name</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ceiling - MCI</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>2</td>
<td>Ceiling Trend</td>
<td>Change in ceiling - GEMPAK</td>
</tr>
<tr>
<td>3</td>
<td>Ceiling Upstream</td>
<td>Upstream observations - GEMPAK</td>
</tr>
<tr>
<td>4</td>
<td>Ceiling in Vicinity</td>
<td>Average of stations in area - GEMPAK</td>
</tr>
<tr>
<td>5</td>
<td>Satellite Difference</td>
<td>Categories 0-5; difference product; MCIDAS</td>
</tr>
<tr>
<td>6</td>
<td>Satellite Difference</td>
<td>Categories 6-10; difference product; MCIDAS</td>
</tr>
<tr>
<td>7</td>
<td>Satellite Difference</td>
<td>Categories 11-15; difference product; MCIDAS</td>
</tr>
<tr>
<td>8</td>
<td>Infrared Satellite</td>
<td>Categories 0-5; brightness; MCIDAS</td>
</tr>
<tr>
<td>9</td>
<td>Infrared Satellite</td>
<td>Categories 6-10; brightness; MCIDAS</td>
</tr>
<tr>
<td>10</td>
<td>Infrared Satellite</td>
<td>Categories 11-15; brightness; MCIDAS</td>
</tr>
<tr>
<td>11</td>
<td>MCI Cloud Cover</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>12</td>
<td>MCI Temperature</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>13</td>
<td>MCI Dewpoint</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>14</td>
<td>MCI Wind Speed</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>15</td>
<td>MCI Wind Dir.</td>
<td>Observed when forecast is made - GEMPAK</td>
</tr>
<tr>
<td>16</td>
<td>Upstream Cloud</td>
<td>Upstream cloud fraction - GEMPAK</td>
</tr>
<tr>
<td>17</td>
<td>Upstream Temp.</td>
<td>Upstream temperature - GEMPAK</td>
</tr>
<tr>
<td>18</td>
<td>Upstream DewPt.</td>
<td>Upstream dew point depression - GEMPAK</td>
</tr>
<tr>
<td>19</td>
<td>Upstream Wind</td>
<td>Upstream wind speed - GEMPAK</td>
</tr>
<tr>
<td>20</td>
<td>24-hr Precip.</td>
<td>MCI 24-hour precipitation - GEMPAK</td>
</tr>
<tr>
<td>21</td>
<td>Time of Day</td>
<td>Time (UTC) when forecast is made.</td>
</tr>
</tbody>
</table>
Table 1b. Predictor Variable List for Ceiling Forecasts From Model Output.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameter Name</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>950 mb R.H.</td>
<td>Eta model 950 mb relative humidity- GEMPAK</td>
</tr>
<tr>
<td>23</td>
<td>850 mb R.H.</td>
<td>Eta model 850 mb relative humidity- GEMPAK</td>
</tr>
<tr>
<td>24</td>
<td>700 mb R.H.</td>
<td>Eta model 700 mb relative humidity- GEMPAK</td>
</tr>
<tr>
<td>25</td>
<td>MOS Ceiling</td>
<td>NGM MOS ceiling at MCI- GEMPAK</td>
</tr>
<tr>
<td>26</td>
<td>LCL</td>
<td>Eta Model Lifted Condensation Level- GEMPAK</td>
</tr>
<tr>
<td>27</td>
<td>Pressure Advection</td>
<td>Eta Model pressure advection (300K) - GEMPAK</td>
</tr>
<tr>
<td>28</td>
<td>Omega</td>
<td>Eta Model Omega (700 mb) - GEMPAK</td>
</tr>
<tr>
<td>29</td>
<td>Q-Vector Div.</td>
<td>Eta Model Q-Vector Div. (850-500mb)- GEMPAK</td>
</tr>
</tbody>
</table>

Possible to drop one of the parameters from the TAF forecast model. The next step is to calculate the coefficients in the multiple linear regression model and eliminate those parameters with small (absolute value) coefficients. The resulting parameter set will include only critical predictor variables, and regression coefficients will again be calculated by the multiple linear regression algorithm. The result will be the optimized TAF forecast system, and will require that each of the critical predictor variables be input at the time the forecast is made. The TAF forecast system will generate ceiling and visibility forecasts for 1, 3, and 6 hours. We intend to test this forecast system against persistence climatology as is typical for verification of ceiling and visibility forecasts, and to compare the model forecast skill to previous levels of forecaster skill described in section 2.

5. References


Possibilities for Seasonal Climate Prediction in the Ross Sea Sector of the Antarctic

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1. Introduction

Operational numerical analyses produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) have been used to calculate the moisture flux convergence (MFC) into the West Antarctic sector bounded by 120°W and 180° meridians and by the 75°S and 90°S parallels (Cullather et al. 1996; Bromwich et al. 2000). MFC equals precipitation minus evaporation/sublimation (P-E) as a consequence of the atmospheric moisture budget. As shown by Fig. 1 that is updated through March 1999, there is a strong in-phase relation between MFC into this sector and the Southern Oscillation Index (SOI) from the early 1980s to 1990 (note that only qualitative conditions are resolved prior to 1985 because of ECMWF WMO analysis shortcomings). The relation then abruptly switches to a strong anti-phase relationship from 1990 to the end of the time series. This relationship is robust as the continually expanding time series demonstrates and is supported by a moderate amount of surface-based observations (Bromwich et al. 2000; Bromwich and Rogers 2000). Analysis of P-E obtained from ECMWF analyses for Thurston Island area (east of 105°W) by Marshall (2000) shows that the above bimodal relationship with the SOI is not stable over time for that area; this means that the SOI modulation of P-E is primarily manifested to the west of 105°W. Here we consider whether the strong SOI signal in the area of the Ross Sea-Ross Ice Shelf and Marie Byrd Land can applied to discern aspects of the weather conditions for the operational season of the U.S. Antarctic Program. We focus on the extremes of the SOI for which the forcing is strong. In addition we consider annual means to filter out short-term variability and emphasize the dominant circulation changes.

2. Circulation Anomalies Associated with Extremes of the SOI

We use the reanalyses produced by the National Centers for Environmental Prediction (NCEP) in conjunction with the National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996) to describe the annual 500-hPa anomalies for the strong El Niño events (SOI < 0) of 1997/1998 and 1982/1983 and the strong La Niña event (SOI > 0) of 1998/1999. The anomalies for the years centered on the SOI extremes are relative to the average for 1979-1999.

Figure 1 shows that 1997/1998 El Niño event and the 1998/1999 La Niña event were comparatively wet and dry in the West Antarctic sector. Both of these occur in current anti-correlated phase of MFC with the SOI. By contrast the strong El Niño event of 1982/1983 is relatively dry and occurs in the positively correlated phase between MFC and the SOI. Cullather et al. (1996) note that the SOI modulation of MFC is a
consequence of changes to the mean circulation, and thus should be reflected in the mean geopotential height fields. The equivalent barotropic nature of the Antarctic atmosphere means that similar behavior should be present at many levels, for example at sea level and at the 500-hPa level.

Figures 2-4 present the annual 500-hPa anomalies for the dry 1982/1983 El Niño event, the wet 1997/1998 El Niño event, and the dry 1998/1999 La Niña event. Figures 2 and 3 show that away from Antarctica the height anomalies are similar for the two El Niño events (consistent with van Loon and Shea 1987), but are quite different over the West Antarctic sector. In 1997/1998 the anomalous circulation steers moisture from the north into the sector to support the enhanced precipitation. By contrast, in 1982/1983 this circulation is absent and the area is overlain by a weak high, consistent with the drier conditions for this El Niño event.

Figure 4 reveals that the La Niña circulation away from Antarctica is opposite to that for the previous year's El Niño event in many respects. For example, there is a band of positive height anomalies stretching from New Zealand to South America in Fig. 4 but a band of negative anomalies extending from south of New Zealand to South America in Fig. 3. The blocking ridge over the Bellingshausen Sea in Fig. 3 is replaced by negative height anomalies in Fig. 4. Figure 4 shows that easterly and southerly flow covers the West Antarctic sector and brings drier conditions in relation to those in Fig. 3.

3. Discussion

The strong SOI modulation of MFC into the West Antarctic sector is accompanied by coherent changes in the mean atmospheric circulation. The MFC modulations are likely to be accompanied by similar changes in cloud amount and perhaps fog frequency, both of importance for operational activities. Because the SOI is predictable to some extent up to a year in advance, it is proposed to use the strong SOI modulation of the MFC as a predictor of the average conditions to be expected during the Antarctic field season in the Ross Sea sector.

Clearly much research is needed to establish the validity and reliability of the proposed approach. Ice core records can be retrieved that will provide annual time series of the MFC variations for decades into the past. These can be used to establish the duration and variability of the circulation phases. These records can also be used to stratify the 45-year McMurdo Station meteorological record according to the circulation phase and to the sign of the SOI and thus explore which variables are strongly and persistently modulated by the SOI.

Acknowledgments. This research was supported by National Science Foundation grant OPP-9725730.

References


Figure 1. Annual running mean of P-E (left scale) from monthly MFC values for the West Antarctic sector calculated from ECMWF WMO and TOGA data (updated through March 1999) along with the SOI (right scale).

Figure 2. Annual 500 hPa geopotential height anomaly field in geopotential meters for July through June of dry 1982/1983 El Nino conditions.
Figure 3. Annual 500 hPa geopotential height anomaly field in geopotential meters for July through June of 1997/1998 wet El Nino conditions.

Figure 4. Annual 500 hPa geopotential height anomaly field in geopotential meters for June through May of 1998/1999 dry La Nina conditions
Predictability of Antarctic Dipole

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In searching the roles of polar ocean and sea ice in global climate, we previously found a few typical teleconnection patterns which link sea ice variations in the Antarctic and the tropical, mid-latitude climate, as well as link variations between different basins in high latitudes (Yuan and Martinson, 2000). The typical patterns include (1) an ENSO-like pattern in the tropics with strong correlation in the Indian Ocean and North America, (2) a teleconnection pattern between the eastern Pacific region of the Antarctic and western/central tropical Pacific, (3) an Antarctic dipole across the Drake passage, and (4) meridional banding structures in the central Pacific and Atlantic expending from polar regions to the tropics. Those teleconnection patterns stand above noise level based on a field significance test using quasi-periodic colored noise. They are most likely to be physically meaningful according to the significance test and multiplicity theory. In addition, we found that the sea ice edge (SIE) in the central/eastern Pacific and Atlantic regions of the Antarctic are most responsive to the extra-polar climate variations. Moreover, the sea ice edge in these two regions usually has an out-phase relationship: so called "Antarctic Dipolar". The first EOF mode of SIE, which contains 37% of total variance, well displays this phenomenon (Figure 1). To further isolate the relationship between the Antarctic Dipole and extra-polar climate, we conduct an EOF analysis on NCEP/NCAR reanalysis surface air temperature anomaly in the Pacific and Atlantic from 20°N to 90°S. The leading mode eigenvector (Figure 2) shows a strong ENSO pattern with a maximum center in the central tropical Pacific. Associated with this ENSO pattern in the tropics is a maximum center of the same phase near 60°S in the South Pacific and a maximum center of opposite phase in the Weddell Gyre. The robustness of the Antarctic dipole and its links with the tropical climate inspire us to search for the predictability of this phenomenon.

Unlike the ENSO phenomenon whose mechanism is relatively well understood, the mechanisms for the Antarctic Dipole and its link with extra-polar climate are not yet well understood. We rely on last two decades satellite observation and reanalysis data products to investigate the phenomenon statistically. The Figure 2 suggests that the Antarctic Dipole pattern is associated with interannual variation in the central tropical Pacific. Although the two largest ENSO events during the last two decades (in 1982-83 and 1997-98) displayed the largest sea surface temperature anomaly in the eastern tropical Pacific near the coast of central America. The other ENSO events and La Nina events all showed large sea surface temperature anomalies in the central tropical Pacific. Linear correlations between SIE east of the Ross Sea (one of climate sensitive regions in the Antarctic) and El Nino indices including Nino1-2, Nino3, Nino3.4 and Nino4 also suggest a better relationship with Nino3.4 (near the central Pacific) than with Nino3 (in the central/eastern Pacific) and Nino1-2 (in the eastern Pacific). Therefore, a linear prediction model is built using the variables representing climate variation in the central tropical Pacific, such as Nino3.4 and the leading mode (Figure 2) principal component of the surface air temperature (called temperature mode 1 here after), to forecast the SIE variations in the Antarctic.

The SIE east of the Ross Sea not only responded well to the extra-polar climate variation but also exhibits a peak energy in the Antarctic Dipole oscillation (Figure 1). A cross correlation between the SIE in this area and temperature mode 1 indicates that the best relationship occurs with temperature leading four months. Figure 3 (A) shows the
temperature mode 1 shifted backward four months and SIE near 132°W as function of time. The correlation coefficient between the two time series reaches 0.6 at 99% of confidence level taking account of auto-correlation in the both series. The maximum ice anomaly corresponds well to all four temperature mode 1 maxima representing the cold condition in the central tropical Pacific. The ice responded well to the two warm events in early 1980s and between 1992 and 1995, but failed to respond to the other two warm events. The linear regression between these two time series as well as 95% confidence levels for the regression line and for all points are given in figure 3 (C). The regression line can explain 36% of total variance between the two variables. The rms error is about 1 degree of latitude. To isolate the covariations that have large contribution to the linear correlation, we calculated instantaneous correlation shown in Figure 3(B). The instantaneous correlation is defined by

\[ C_i = 100 \times \frac{SIE' \times Tml'}{\sigma_s \times \sigma_t \times r} \]

where SIE' is SIE anomaly, Tml' is temperature mode 1 anomaly, \( \sigma_s \) is standard deviation of SIE', \( \sigma_t \) is standard deviation of Tml', and \( r \) is the correlation coefficient between the two series. The large instantaneous correlations occur in the extreme events when SIE responded well to the temperature. This suggests that the extreme condition in the tropics (especially the cold condition) likely trigger the large variation in the ice field in the polar region. When we select data points with instantaneous correlation larger than 1%, the rms error is reduced to 0.8 degree of latitude (Figure 3 (D)). The correlation between those points reaches 0.93, indicating that the linear regression can explain 86% of total variance among selected points. The autocorrelation of the SIE drops to 0.4 at four-month time lag. Therefore, we can predict extreme ice condition reasonably well using temperature data four months ahead. In the same way, we can predict sea ice extreme condition using Nino3.4 instead of temperature mode 1 with a ten-month leading time. Once we predict the sea ice extreme condition in the Pacific region of the Antarctic and we will know that sea ice in the Weddell Gyre is in the opposite extreme.

We conclude that our simple linear regression model can predict sea ice extreme condition from the central Pacific to Weddell Gyre regions of the Antarctic reasonably well, especially in the La Nina condition. The ability to predict the extreme condition of sea ice extent not only benefits to marine operation near ice marginal zone, but also provides additional information for region weather forecast. During austral winter, a quasi-stationary wavenumber three pattern prevails in the Southern Ocean atmospheric circulation. The sea ice edge also has three maximum extents in the Indian Ocean, east of the Ross Sea and in the Weddell Gyre. Utilizing the satellite observed sea surface wind data, we examine the relationship between the wave pattern in monthly mean atmospheric and sea ice extent distribution. The southerly branches of the wavenumber three pattern coincided with the three sea ice extent maxima in the two La Nina years (1996 and 1999). Such coincidence did not exist from 1992 to 1995 when there is a warm phase in the tropical Pacific. The sea ice extent maximum in the Indian Ocean and east of the Ross Sea were stronger in 1996 and 1999 than in the other years, which suggests that atmospheric circulation influences the ice distribution. In a recent study based on surface vector wind data in 1996 (Yuan et al., 1999), we found that the sea ice distribution could have a positive feedback to the atmospheric circulation, and the coupled process could influence the severe storm distribution in the open ocean north of the ice pack. Moreover, Rind et al., in a recent modeling study show if the meridional temperature gradient is increased in the Southern Pacific the sea ice will be reduced in the Pacific basin and increased in the Atlantic basin. In the mean time, there are more high latitude
cyclogenesis in the South Atlantic than in the Southern Pacific. Although we cannot predict seasonal storm statistics based on our current understanding of the air-sea-ice system in the Antarctic region, it is undoubted that sea ice distribution plays an important role in the regional weather system. Such prediction is not impossible in the future when we have a better understanding the mechanism of the link between the tropics and polar region and the mechanism of cyclogenesis associated with the changing of sea ice distribution.

References

Figure 1. The leading mode eigenvector of sea ice edge anomaly (1978-1998). It contains 37% of the total variance.

Figure 2. The leading mode eigenvector of surface air temperature anomaly (1975 to 1999). It accounts for 18% of total variance.

Figure 3. (A) Leading mode principal component of surface air temperature anomaly (leading 4-month) and sea ice edge anomaly near 132W (dashed line) as functions of sea ice time; (B) Instantaneous correlation coefficients (see text for the definition of instantaneous correlation); (C) A scatter plot of sea ice edge anomaly and temperature leading mode principal component in A, and their linear regression. The 95% confidence levels for the regression line and for individual point are marked; and (D) Same as in C except for the points with fractional correlation above 1%.
The Delayed Decline of Baroclinic Activity During the Spring Transition over Antarctica

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Extended Abstract

1 Introduction
A feature unique to Antarctica is the disappearance of the tropopause in winter and its reappearance in the spring as first noted by Court (1942). Related to this feature, a recent paper by (Neff, 1999) described delays in the transition from winter to spring over the South Pole and other long-term trends in the tropospheric circulation. Of particular note, the effect of the stratospheric ozone depletion of recent decades has been to delay the springtime formation of the tropopause by about a month with a number of dynamical consequences for tropospheric weather phenomena.

Two aspects of results obtained in the interior of the continent may be of particular relevance to weather phenomena in coastal areas. The first aspect arises from the effect of baroclinic activity over the continent that may control the genesis of cold air surges from the interior to the coast. In particular, as meridional gradients in temperature increase at the spring equinox, baroclinic activity increases over the continent. This activity gradually diminishes until the breakup of the polar vortex in late spring. Thus, a delay in the decline of baroclinic activity due to the later breakup of the polar stratospheric vortex may cause winter-type phenomena to persist later into the spring. The second aspect is related to the transport of moisture from ocean, beyond the boundary of the sea ice, to the interior. In particular, with the formation of a strong tropopause, the Rossby radius of deformation contracts, presumably leading to downsizing of synoptic scale eddies that can transport moisture into the continent. Because this contraction first occurs when the sea ice is at its maximum extent, moisture transport to the interior is reduced until such a time as the sea ice retreats towards the coast. As shown by Neff (1999), this hypothesis is consistent with a spring minimum in cloudiness at the South Pole that now shares the same delay as the initial time of tropopause formation.

2 Behavior of the Surface Wind and Temperature During Synoptic Events
(Neff, 1978) first noted the control of cold downslope flows by synoptic time scale events in the free troposphere over the interior of Antarctica together with the fact that winds aloft were bimodal in direction and tended to align with terrain contours, suggesting that the geostrophic pressure gradient field tended to orient itself upslope or downslope. Such a result implied that the large-scale pressure gradient either aided or opposed that arising from the effect of the sloped surface inversion. Furthermore it was noted that deeper, cold-air downslope surface flows occurred with winds aloft from the southeast (135°E) whereas warming events with along-slope surface winds occurred with winds aloft from the northwest (45°W).

In the study of Neff (1999), the fact that warm and cold events occurred with surface winds appearing in orthogonal directions as shown in Figure 1, led to the use of a covariance method to quantify both intra-seasonal and well as interannual variability in downslope cold-air surges.

![Figure 1. Directional distribution of hourly winds during warm and cold events using hourly wind speed and direction and temperature data available from NOAA Climate Monitoring and Diagnostic Laboratory for the period April-September 1996. Frequencies of occurrence of cold and warm events using hourly wind azimuth values are shown for temperature fluctuations in excess of 7.5°C. (From Neff, 1999)](image)

Quantification of these events followed from the use of the cumulative covariance function:

\[ C_{uv}(N) = \sum_{i=1}^{N} u^i T^i \]
where \( u' \) is the perturbation in the downslope wind component and \( T' \) is the associated temperature perturbation. The resulting "flux" was derived in finite difference form as

\[
F_s(N) = \frac{C_s(N + \Delta N) - C_s(N)}{\Delta N}
\]

Within each season, the resulting covariance function was smoothed with a 15 day tapered filter and then differentiated. This downslope component of the flux is referred to as "baroclinic" because the upper-level winds from the southeast that are normally associated with enhanced downslope cold-air surges, show strong speed shear indicating more strongly baroclinic conditions aloft.

3 Recent trends and interannual variability associated with the El Niño-La Niña couplet of 1997-1999

Figure 2 shows the trends and interannual variability in time of tropopause formation through this last winter-to-spring transition.

![Figure 2. Times of initial spring increases in stability in the layer from 150-100 hPa (solid circles) and the final summer tropopause formation in the layer from 300 to 200 hPa (diamonds), without yearly filtering. The timing of the breakup of the polar vortex (diamonds with dashed line) is derived from Total Ozone Mapping Spectrometer (TOMS) data for every year except 1995 when TIROS operational vertical sounder (TOVS) data were used. (After Neff, 1999)](image)

Examination of Figure 2 shows that while the polar vortex broke up relatively early in the spring during the 1997-1998 El Niño, its demise was much delayed in the subsequent and following year, after La Niña had developed. An obvious question is whether there were consequent changes in the behavior of the downslope eddy flux of cold air. This is analyzed in Figure 3, which shows the cumulative covariance function (smoothed) and its slope, the "baroclinic flux" for each of the last three years. In both 1997 and 1999 the flux increases at the fall and spring equinoxes were consistent with the normal semiannual oscillation (SAO) behavior noted by Neff (1999). Curiously, the year 1998 (during the transition to a strong La Niña) appears as a distinct anomaly, with weak baroclinic activity similar to that occurring in the late 1970s and the early 1980s that has been related previously to a weakening of the SAO. That such behavior may be related to the expansion and contraction of the polar vortex in concert with variations in the SAO has also been noted by (Burnett and McNicoll, 1999).

![Figure 3. The baroclinic cumulative covariance functions (dashed lines) and the resulting flux values (solid lines) for 1997, 1998, and 1999. The periods of April and October following the fall and spring equinoxes are outlined by the boxes.](image)
Figure 4 shows temperature anomaly fields at 400 hPa south of 60°S for October for each of the three years shown in Figure 3. In 1997, Figure 3 showed increased baroclinic activity in September-October consistent with the colder temperatures over the interior and warmer conditions over the Ross Sea and West Antarctica regions. In 1998, Figure 4 shows reversed meridional gradients consistent with the lack of activity shown in Figure 3. Finally in 1999, the increased baroclinic activity at the South Pole appears to reflect the increased gradients associated with warming over the Weddell Sea region. Considering Figures 3 and 4, it appears that baroclinic activity over the South Pole does reflect larger scale processes on the periphery of Antarctica. What is unknown from the current research and availability of data is the relationship between baroclinic events and subsequent outflows of cold air to the coastal areas of Antarctica.

An indication of such a connection lies in the case studies of katabatic surges across the Ross Ice Shelf in June and July 1988 reported by (Carrasco and Bromwich, 1993). In particular, in July, winds at 300 hPa had swung through southeast and then back to south-southwest over the South Pole as shown in Figure 5. In this case cooling at the surface in the interior preceded the subsequent outflows reported for the ice shelf.

Figure 5. Wind direction at 300 hPa and surface temperatures at the South Pole for the period July 8 through July 16, 1988 corresponding to the katabatic outflows reported by (Carrasco, 1993 #146). Surge events on July 11th and 12th are indicated by the arrows.

4 Behavior of the Surface Inversion

Given the possibility that 1) the surface inversion over the interior of the continent plays a central role in supplying cold air that exits over the continental
coastal areas in response to synoptic scale events, and 2) the spring cessation of baroclinic transports is now delayed, we examined long-term trends in the surface inversion behavior (Figure 6). Because of the strong interannual variability demonstrated in each of the three seasons it is not entirely clear whether the trends toward increasing inversion strength have been maintained over the entire record or as December might suggest, began in earnest after 1980.

5 Discussion and recommendations

The results described here in combination with results already reported in Neff (1999) suggest that long-term changes have occurred in the tropospheric circulation over Antarctica. It also appears quite plausible that these changes should affect coastal weather. This argues that the coupling of phenomena over the interior to those of the coastal areas and ice shelves should be addressed in future field programs. To support such research, it seems advisable to provide a more extensive array of automatic weather stations (AWS) along the potential drainage channels from the high plateau together with continuous upper air observations from existing manned stations. The location of surface sites would be aided by analysis of both past AWS data and well as satellite data such as in (Carrasco and Bromwich, 1993). Given the strong interannual variability observed, it would also be advisable to maintain such an observing network over a substantial period of time.

References


SEASONAL MODELLING OF THE ANTARCTIC REGION USING ANTARCSYM

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1. INTRODUCTION

The study of climate in the Antarctic is unique not only in the extreme temperatures, but also the large seasonal variation in sea ice extent, the high glacial plateau, and ubiquitous ice clouds. Regional modeling on longer timescales in the Antarctic is relatively new (e.g., Walsh and McGregor 1996). In general, regional model simulations have showed lower errors than comparable global simulations (Walsh and McGregor 1996; Hines et al. 1997; Bailey and Lynch 2000a,b). However significant errors in simulations of the Antarctic region remain, and have been attributed primarily to atmospheric moisture processes and sea ice.

Hines et al. (1997) found that simulations by a mesoscale model exhibited greater skill over land when moisture processes were not included. Bailey and Lynch (2000b) also found that simplified moisture schemes are not sufficient, and that a more sophisticated approach is required. With a range of new observations now available, recent improvements in explicit moisture physics to account for better parameterization of mixed and ice phases (Girard and Curry 2000, D.H. Bromwich pers. comm.) hold great promise for more accurate simulation of Antarctic clouds and water vapor.

Simmonds and Budd (1991) found that open water in the sea ice in global model simulations had a marked influence on the polar atmospheric circulation. Heinemann (1997) and Gallée (1997) found that, in mesoscale simulation, the presence of open water had a strong impact on the katabatic wind regime. Bailey and Lynch (2000a) found that the simulation of sea ice in particularly sensitive to oceanic heat fluxes, and that ice changes have impacts on the atmospheric circulation on seasonal and longer timescales.

This presentation presents simulations using a coupled regional model, the Antarctic Climate System Model (AntARCSym, Bailey and Lynch 2000a). The period of interest for this paper is 1988-89, during which time a deep ocean polynya in the Cosmonaut Sea region near 45°E showed several strong events. The eventual goal of the AntARCSym development is a fine resolution, regional scale simulation of this polynya.

2. DATA

Antarctic station and upper air data for 1988-89, including data for all of the U.S. Automatic Weather Station (AWS) systems, were obtained. Only the surface pressure and temperature were used from the stations. Stearns and Weidner (1993) found that the range of the response of the relative humidity sensors decreased with air temperature. Large gaps were found in the wind record for the period of interest, which may be due to the accumulation of frost on the aerovanes. Hence, relative humidity and winds were deemed unreliable for this study. Additional station and upper air data were obtained from the Australian Bureau of Meteorology and the National Institute of Polar Research (NIPR). Energy balance data for Neumayer, Syowa, and South Pole stations were obtained from the British Antarctic Survey. Additionally, the cloud climatology of Hahn et al. (1995) has been used to compare the total cloud fraction from the model. This cloud climatology was derived from 10 years (1986-91) of surface observations, and incorporated the effect of moonlight. The monthly means for 1988-89 from the International Satellite Cloud Climatology Project (ISCCP) version D2 product (Rossow et al. 1996) are included for reference and were found to differ from the Hahn climatology as did the C2 product (Hahn et al. 1995). European Centre for Medium-Range Weather Forecasting (ECMWF) operational analyses and ice concentration from satellite passive microwave (SSMI) analysis were also used.

3. MODEL AND EXPERIMENT DESCRIPTION

The AntARCSym is a Southern Hemisphere version of the extensively used Arctic Region Climate System Model (ARCSym, Lynch et al. 1999). ARCSym is a hydrostatic, primitive equation model with a terrain following vertical coordinate, and incorporates the NCAR land surface exchange and vegetation model LSM and a dynamic/thermodynamic sea-ice model. The oceanic component of ARCSym presently includes a high resolution one-dimensional mixed layer ocean model (Kantha and Clayson 1994) based on a second order turbulence closure scheme which explicitly simulates the whole vertical water column, and a three dimensional ocean circulation model (Heinrichs 1996). The AntARCSym version includes special land surface types for the Antarctic continent. In addition, the ocean circulation component has been more rigorously tested in this region.

The model simulations were performed for an Antarctic domain at 100 km resolution for the period January 1998 to March 1989 and a Cosmonaut Sea domain at 20 km resolution for January and July (Fig. 1). The low resolution experiments used a simple implicit atmospheric moisture scheme, whereas the high resolution experiments used an explicit moisture scheme with ice phase microphysics. The model was initialized and driven at the boundaries using ECMWF analyses. Initial ice concentration was provided from SSM/I analysis. The Antarctic domain was used for simulations of the atmosphere-sea ice system and the sea ice-ocean system. High resolution simulations used the atmosphere-sea ice configuration.
4. RESULTS

The AntARCSyM atmosphere-sea ice simulations exhibit reasonable skill at 100 and 20 km resolutions. The simulated circulation and upper level temperatures are well represented. In the winter, the sea ice extent (Fig. 1b) agrees fairly well with the observed (SSM/I) extent (Fig. 1a). The model simulation produces higher concentrations of sea ice in the Ross and Weddell Seas, but it should be noted that the SSM/I-derived sea ice concentration can be underestimated by up to 5%. By the end of the summer (not shown) the sea ice has melted away very rapidly in the model simulations and the ice extent is not as great as the SSM/I-derived field.

The ice extent in the atmosphere-ice model is reproduced most accurately when variable oceanic heat fluxes are used. This variability would be captured better in a dynamical ocean model, initial results of which are shown in Fig. 1c. Here the ice-ocean simulation captures more of the dynamical aspects of the sea ice. The ice extent does not cover as large an area as the SSM/I product. It is thought that this is due to unresolved issues associated with ocean initialization and spin up, but the true reasons will be revealed from further analysis.

Figure 1. Winter mean (JJA 1998) sea ice concentration for (a) SSM/I; (b) atmosphere-ice model and (c) ice-ocean model. Also shown is the Cosmonaut sea domain.

Figure 2. Scatter plots of model and ECMWF analyses vs. station surface air temperature: (a) JJA; (b) DJF.
The low level air temperature from the 100 km resolution atmosphere-ice simulation, however, shows a systematic warm bias when compared to both ECMWF operational analyses and station data (Fig. 2). In particular, the coldest temperatures are overestimated by as much as 5 to 15 K. This is attributable to elevation differences, poor resolution of the boundary layer inversion, and biases in clouds and longwave radiation (Bailey and Lynch 2000b).

In contrast, the high resolution simulation with more sophisticated moisture physics shows no systematic temperature bias. Compared to the analyses, an RMS difference of 1.4 K is found. The differences are small and arise in part from the spatial interpolation. Analysis using surface data (Fig. 3) and radiosonde launches (not shown) yield RMS errors from 1 to 5 K, with correlations ranging from 63% to 90%. The upper air agreement is better at all stations than the surface for both model and analyses.

5. CONCLUSIONS

In small domains, limited area models are strongly constrained by boundary forcing and produce simulations which are consistent with this forcing. Large domains and coupled modelling approaches present a greater challenge as the simulation can evolve largely independently of the forcing. In this work we have shown that using current modelling approaches, the ECMWF operational analyses are adequate to provide forcing for smaller domains and shorter simulations. Simulations on seasonal timescales, however, will require both better treatment of atmospheric moisture processes and a realistically evolving sea ice, which in turn requires accurate under-ice heat fluxes.

6. REFERENCES


Girard, E. and J.A. Curry, 2000: Simulation of arctic low-level clouds observed during the FIRE Arctic Cloud Experiment using a new bulk microphysics scheme. J. Geophys. Res. (in review.)


Figure 3. Mean July surface air temperature (K) comparison at (a) Syowa, (b) Molodezhnaya, and (c) Mawson.
ENSO TELECONNECTIONS WITH ANTARCTICA

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Introduction

The interannual variations of atmospheric circulation in the Southern Hemisphere (SH) extratropics frequently exceed the interseasonal mean variations (Trenberth, 1979). These low-frequency variations provide the boundary conditions within which higher frequency "weather" takes place (e.g., Bryson, 1997). Globally, the most important coupled ocean-atmosphere anomaly pattern is the El Nino Southern Oscillation (ENSO) of the tropical Pacific. The two extreme phases of the ENSO (i.e., the "warm event", or El Nino, and "cold event", or La Nina) have associated long-distance anomalies, or teleconnections, of atmospheric circulation and climate (e.g., precipitation, temperature, winds, cyclonic activity), sea surface temperatures: SSTs, and sea ice conditions (i.e., ice extent and concentration), with the higher southern latitudes. These are most evident in the Pacific sector, and also West Antarctica, where they interact with, and may be modulated by, teleconnection patterns that are of dominantly extratropical origin. The extratropical teleconnections to ENSO occur via preferred modes of the Rossby barotropic waves that are both zonally symmetric, and zonally asymmetric (i.e., wavenumbers 1 to about 4). They include the following: (1) the Pacific-South America (PSA) pattern of a standing wavenumber 3 anomaly extending from the subtropical South Pacific into the Amundsen Sea and southwest South Atlantic; (2) the Antarctic Circumpolar Wave (ACW), or a dominantly 2-wave pattern of coupled atmosphere-ocean-ice anomalies that migrates eastwards within the Antarctic Circumpolar Current: ACC; (3) an eccentricity in zonal wavenumber 1 that occurs preferentially between the Australia and South America sectors, and is depicted by a "Trans-Polar" circulation index (TPI); and (4) the "Antarctic Oscillation": AAO (Gong and Wang, 1999), or zonal alternation of atmospheric mass between Antarctica and middle latitudes.

The ENSO Teleconnection to the Southern High Latitudes

An ENSO teleconnection over the SH extratropics, especially the South Pacific sector, has been identified in the following quantities:

1. The spatial fields of sea level pressure: SLP, tropospheric height, streamfunction, and surface winds;
2. Station climate variables of precipitation (i.e, rainfall, snow accumulation), temperature and winds, at the southern ocean islands including New Zealand, and also over Antarctica. In particular, the sign of the composite anomalies of Antarctic surface...
pressure and temperature reverses between the 12-month period prior to and following the minimum in the Southern Oscillation Index: SOI—i.e., around an El Nino event (Smith and Stearns, 1993). During the major warm event of 1982-83, very low temperatures over Antarctica and a deeper circumpolar trough were expressed as stronger katabatic winds near the coastline (Savage et al., 1988);

3. The meridional and also zonal transports of heat, momentum and moisture;

4. Transient eddy activity, primarily related to the cyclones on synoptic and also subsynoptic scales (i.e., frontal cyclones and "cold-air" mesocyclones);

5. The location and intensity (i.e., frequency of occurrence) of the satellite-observed South Pacific Cloud Band (SPCB) that manifests the South Pacific atmospheric Convergence Zone (SPCZ);

6. The Antarctic sea ice extent and concentration in key regions; notably, the Ross, Amundsen-Bellingshausen, and Weddell seas, and also the southern Indian Ocean; and

7. The anomaly patterns of southern ocean SST, sea-air temperature difference, and the coupled SST-SLP variations.

Evolution of the ENSO Teleconnection over Southern High Latitudes

Teleconnections to the ENSO warm event in the southern extratropics become evident in circulation anomalies up to two winter seasons (i.e., 6 and 18 months, respectively) preceding the extreme in the SOI that typically occurs in southern summer (van Loon, 1984; van Loon and Shea, 1985). In particular, the annual cycle of the wave in the Tasman Sea is enhanced (weaker) for the winter season 6 months ahead of: yr0 (the winter 18 months preceding: yr1), the negative extreme in the SOI. Accordingly, large anomalies of wintertime SLP and cyclonic activity occur in the New Zealand area that precede by about 2 seasons, those occurring in the Indonesian "pole" of the Walker Circulation (Trenberth and Shea, 1987; Karoly, 1989). There is enhanced blocking in the southwest Pacific, with associated "troughing" downstream. Thus, these tropical-extratropical circulation interactions may also involve Antarctica via the advection of cold air and vorticity downstream of the enhanced ridge in the Ross Sea sector.

Over the eastern and south-east Pacific, there are distinct responses to the tropical anomalies of coupled SST and atmospheric circulation occurring during an El Nino event. These comprise the Pacific-South America (PSA) teleconnection pattern (Mo and Ghil, 1987; Karoly, 1989). There is an eastward shift, and reduced frequency of occurrence of, the SPCB in southern summer yr0 of a warm event. The greater Hadley Cell overturning that occurs in a warm event enhances the intensity of the subtropical jet stream (STJ), but the intensity of the polar front jetstream (PFJ) is reduced along with the central pressure of the time-averaged low pressure in the Amundsen Sea: ASL. The latter promotes colder than normal conditions in winter along the western side of the Antarctic Peninsula (Marshall and King, 1998). Further downstream, the Weddell Sea mean low (WSL) is intensified, which enhances cold air advection east of the Antarctic Peninsula. Accordingly, the sea ice conditions in the southwest South Atlantic tend to
be more severe (i.e., ice extends to lower latitudes), in the summers of ENSO warm events, contrasted with the summer of the year before, although the ice-water concentration is reduced within the pack due to ice divergence (Carleton, 1988). The abovementioned patterns tend to reverse during the cold event, or La Nina. That is, there is a westward migration and greater frequency of occurrence of the SPCB; a weaker STJ and stronger PFJ; a deeper ASL—giving warmer conditions to the west coast of the Antarctic Peninsula—and a weaker WSL. The last means that the ice edge in the southwest Atlantic is further south, yet with a higher ice-water concentration due to convergence of the pack, under conditions of more frequent northerly airflow.

**Interactions of the ENSO With Other Southern Hemisphere Teleconnections**

While being largely independent modes of atmospheric low frequency variability over the southern middle and high latitudes, the AAO, ACW and TPI interact with the tropical ENSO at key times and in key regions. In particular, the following features suggestive of inter-teleconnection associations have been identified:

1. An out-of-phase association between the pressure/height and zonal westerly wind anomalies over lower-middle and high latitudes, and also the trade winds over the Pacific sector, suggesting links with the AAO and TPI. In an El Nino (La Nina) the westerlies south (north) of about 45°S are weak (strong) and the trades are weak (strong), in the Pacific sector (e.g., Carleton, 1989). Also, the recent trend of increasingly positive polarity of the AAO (i.e., cooling over Antarctica and strengthening westerlies in subantarctic latitudes) has occurred concurrently with warmer SSTs in the central and eastern tropical Pacific and a greater frequency of El Nino events (Thompson and Wallace, 2000);

2. The time scale of the ACW is broadly similar to that of the ENSO. Moreover, the ACW may transmit the ENSO signal from the Pacific basin into the South Atlantic and southern Indian Oceans as a “slow oceanic teleconnection” (Peterson and White, 1998);

3. At least for the period of the 1970s and early 1980s, negative (positive) extremes of the SOI tended to follow negative (positive) winter values of the TPI and greater (lesser) sea ice extent in the Australia (South America) sectors (Carleton, 1989).

**Concluding Remarks**

Our understanding of ENSO teleconnections with the Antarctic and sub-antarctic has improved in recent years, prompted by intensive observing programs such as the Antarctic First Regional Observing Study of the Troposphere (FROST), and the “long-term” (40 year) re-analysis products now available. However, the picture is by no means complete. In particular, the following issues remain to be fully resolved: (1) the role of the Madden-Julian Oscillation in transmitting the tropical anomalies into the eastern subtropical Pacific; the inter-associations of the observed recent changes in phase of the dominant inter-seasonal mode of variation, or semi-
annual oscillation, with the ENSO; and the association between the SOI and various derived quantities of the extratropical atmospheric circulation in the South Pacific (e.g., moisture convergence).

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Ground-Based Remote Sensing in the Polar Regions

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Extended Abstract

1 Introduction

Over the past several decades there have been significant developments in remote sensing applied to research in Antarctica ranging from the deployment of acoustic and radar ground-based profiling systems to airborne lidars mapping the horizontal distribution of aerosols, ice crystals and clouds. In this brief review, we describe some of the past applications and the advances in technology that may create opportunities for new observations that will benefit both the research endeavor as well as weather-dependant field operations in Antarctica.

2 Sodar Methods

Acoustic sounding systems (sodars) were first used in the Antarctic interior beginning in 1975 (Neff, 1980) with subsequent, more widespread use in coastal areas (Argentini et al., 1992) (Argentini et al., 1996) (Liu and Bromwich, 1993). In many of these applications, sodars proved most useful for measuring winds below 500 m, for estimating the depth of the boundary layer, and for documenting (using time-height cross sections of reflectivity) the character of the boundary layer, including the presence of convection as well as intermittent turbulence and layering in the boundary layer (Neff, 1996). Because the use of sodars depends on the scattering of sound waves from small-scale thermal inhomogeneities, this method has been of greatest value in studying winds associated with the low-level temperature inversion.

3 Radar Methods

More recently, a UHF radar wind profiler operating at 915-MHz was tried for the first time in the interior of continent (Neff, 1994; Neff, 1996; Gottas, 1998). In contrast to sodars, radars depend on the scattering of radio waves from small-scale humidity variations as well as hydrometeors. Unfortunately, the dryness of the interior of the continent provides one of the more challenging environments for the use of radar technology. The results of the 1993 field program (Gottas, 1998) showed that profilers operating at 915-MHz worked best during periods of precipitation (snow grains and ice crystals) and poorly during clear sky conditions where the radar operated at the limits of its sensitivity for technology available in the early 1990s. Figure 1 shows the five-beam radar configuration used in 1993. Inside each enclosure is a flat plate antenna composed of micropatch radiators. The enclosure serves as a clutter screen for the antenna. With extensive blowing snow at the South Pole it also created extensive drifting around the array. Although beam-switching electronics were becoming available at the time of the experiment that would have allowed a smaller footprint with a single 2-m by 2-m antenna array, it was decided to maintain separate antennas in case the switches proved unreliable at low temperatures. The figure shows two of the four acoustic sources (black objects) used for RASS temperature retrievals, located between orthogonal radar antenna pairs.

Because of the low-signal-to-noise ratios found on the high plateau (due to low humidity), the sensitivity of the radar was more easily compromised by radio interference and clutter as shown in Figure 2. However, since 1993, a number of advances have been made in wind profiler technology. First, signal processing methods using wavelet methods on raw wind profiler time series allow the removal of ground clutter and interference (Jordan et al., 1997). Second, a wide-dynamic range receiver has been designed and tested for operation on remote buoys that allow

Figure 1. Five-axis 915-MHz radar wind profiler with four RASS acoustic sources operating at the South Pole during the winter of 1993.
removal of clutter from the buoy superstructure as well as the sea (Jordan, personal communication). The effect of these innovations has been the deployment of simpler wind profiling radars in much more challenging environments (Figure 3). In the case of remote buoys, the wind profiler must operate with limited power in a highly cluttered environment. The relevance to Antarctic applications lies in the reduced aerodynamic profile, reducing drifting of snow, and the ability to extract signals in a noisy background environment.

4 Combined Acoustic and Radar Methods (RASS)

Evaluation at the South Pole of the potential of combined radar/acoustic methods for profiling of the virtual temperature at 915 MHz revealed several fundamental limitations arising primarily from the nearly laminar flow that often occurs just above the surface inversion (100 to 200 m) at the South Pole. Radio acoustic sounding system (RASS) techniques depend on using sound propagating vertically to modify the density of air (dependent on temperature and humidity) at a wavelength close to that of the radar. The radio signal then scatters from these artificial inhomogeneities. The resulting Doppler shift represents the speed of sound from which virtual temperature is calculated.

In normal situations, there is sufficient turbulence in the atmosphere to spread the radio waves scattered from the surfaces of vertically propagating acoustic waves over a large region on the surface. However, in the nearly laminar flow characteristic of very stable atmospheres, the scattered energy can be focused in small spots that are not coincident with the receiving antenna, thus severely limiting RASS performance.

![Small radar wind profiler (white object to the right of the superstructure base) on a 10-m discus buoy. (Photo by J. Jordan)](image)

Figure 3. Small radar wind profiler (white object to the right of the superstructure base) on a 10-m discus buoy. (Photo by J. Jordan)

![Spectral density vs. Doppler velocity](image)

Figure 2. Velocity and temporal characteristics of the contaminated signals that most frequently occur in the South Pole Doppler power spectra. Spectral density is in decibel (dB) units (10*log10 (spectral density in units of W s m^-1)). Spectra are shown for a single range cell over a period of almost two days. Note the intermittency in atmospheric echoes at this fixed range gate over the period. (From Gottas, 1998).
The Potential for 449 MHz Profilers

The study by Gottas (1998) also assessed the potential performance of profilers operating at the lower frequency (and greater wavelength) of 449 MHz. One measure of the ability of the atmosphere to scatter signals is the refractive index structure parameter $C_n^2$ which measures the magnitude of small scale refractive index variations to which the radar is sensitive. For the South Pole, Gottas concluded that nominal clear-air values of $C_n^2$ were in the range $10^{16} - 10^{17}$ m$^{-3/2}$. Examining the performance curves in Figure 4 shows that the 915-MHz profiler range should be limited to a few hundred meters in these conditions whereas the 449-MHz profiler should produce usable echoes to at least 2 km with a low-power transmitter.

Such a profiler was built and tested at Barrow, Alaska in anticipation of deployment on the Arctic sea ice. Using a 700-watt transmitter it routinely obtained winds to 2 km and intermittently, to 4 km, during the Boreal winter and spring, consistent with the general expectation from Figure 4. Its ability to obtain temperature profiles depended on wind speed and direction. Under higher wind speeds its range was limited to 500 m whereas under light wind speeds its range often exceeded 1.5 km. Its RASS performance did not appear to suffer the same limitations as the 915-MHz system at the South Pole, perhaps because of the larger antenna (5 m by 5 m, Figure 5) and/or different atmospheric conditions. Since these early tests, the power transmitted by the 449 MHz radar system has improved by a factor of ten. In addition, signal processing techniques, applicable at both frequencies, have improved the detectability of signals at low signal levels in a cluttered environment.

In addition to the clear-air use of radars described above, one should note the increased sensitivity of the radar systems, particularly at higher frequencies, to precipitation via Rayleigh scattering (scattering from objects much smaller than the radar wavelength). For the most part, reliable wind data were obtained at the South Pole with a 915-MHz profiler system only during periods of precipitation. As noted by Gottas (1998), however, because of trade-offs in power and antenna aperture size, a lower-frequency 449-MHz radar system would perform more effectively in clear air while maintaining the same sensitivity to precipitation.

A final observation on the use of lower frequency radar systems relates to their minimum range. As the transmitted frequency is lowered and the power increased, the minimum range is increased. For example, data reported from a VHF system deployed in 1998 at Dumont d’Urville shows a minimum range of about 600 m (Pettre et al., 1998). The 449-MHz profiler described above is limited to a minimum range of about 400 m. Thus, attempts to increase the vertical range of radar systems will necessitate using other methods, such as Doppler sodars to observe the lowest region from ~25 m to ~500 m.

![Figure 4](image)

**Figure 4.** Minimum detectable signal levels as a function of radar frequency and system settings in terms of $C_n^2$, a measure of atmospheric turbulence. (From Gottas, 1998)

![Figure 5](image)

**Figure 5.** Quarter-size 449 MHz radar wind profiler developed originally for deployment in the Arctic. The flat surface (open mesh) is the ground plane whereas the orthogonal rods contain the transmitting elements.
6 Conclusions and recommendations

We have primarily described the use of radar wind profilers in this abstract because of their widespread operational deployment elsewhere in the world. Preliminary tests of UHF profilers in Antarctica established some of the minimum performance characteristics of profilers including lower-frequency systems. Expectations based on these analyses as well as the limited tests of a VHF system at Dumont d’Urville on the coast of Antarctica suggest that wind profilers might well address the need for continuous wind observations below 4 to 5 km for operational and research applications, particularly in coastal areas where the air should have a higher moisture content than on the high plateau.

In the future, other remote sensing methods might well be considered for the dry interior including devices such as molecular backscatter lidars now being designed for space-based measurement of winds in the upper atmosphere. Similarly, in situations where RASS does not perform well, new scanning radiometers (Westwater et al., 1999) may provide the means to profile the strong temperature inversions over the interior. Similarly, studies of cloud water and phase may be aided by recent advances in short-wavelength radars and lidars (Intrieri et al., 2000; Shupe et al., 2000).

References


As satellite meteorology celebrates its 40th anniversary, the Polar Regions have benefited from those years of observing from polar orbiting platforms. Many applications of raw data remotely sensed from space have been developed. In particular, the following applications important for the Antarctic are:

- Multi-spectral imagery and animations for forecasting/nowcasting
- Atmospheric sounding – temperature, moisture (ATOVS and GPS) and wind (cloud drift and scatterometer) retrievals
- Detection of clouds, fog, ice, and sea surface temperature
- Numerical model verification via Antarctic composite images
- Environmental monitoring: katabatic winds, polynyas, icebergs
- Precipitation estimation

Although this is not an all-encompassing list of modern day satellite capabilities, these essential abilities are reviewed. Some concluding thoughts are presented, along with discussion of future possibilities.
Advanced Satellite Products: The SIO Arctic and Antarctic Research Center

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Since 1989, the mission of the Arctic and Antarctic Research Center (AARC) at the Scripps Institution of Oceanography (SIO) has been to provide satellite remote sensing data and services to all interested researchers working in the polar regions. The AARC is one of three centers providing such services under the auspices of the NSF Office of Polar Programs. The AARC's major focus is on the polar oceanographic community. The major focus of the University of Wisconsin's Antarctic Meteorology Research Center (AMRC) is the atmospheric science community, while the National Snow and Ice Data Center (NSIDC) tailors its satellite remote sensing services to the terrestrial and glaciological communities.

The AARC receives and archives digital telemetry from the NSF-supported satellite tracking facilities at Palmer and McMurdo stations in the Antarctic, and from the U.S. Coast Guard icebreakers when these ships are operating at high latitudes. These tracking facilities provide the AARC with data from both the NOAA and Defense Meteorological Satellite Program (DMSP) polar orbiters. The AARC can provide interested researchers with a variety of data processing services, ranging from simple copies of the telemetry to specialized image processing in support of a particular research project. The AARC's data holdings, spanning more than ten years, are archived on DLT media and are browseable over the world wide web (http://arcane.ucsd.edu). This presentation focuses on three new satellite data applications currently in use or under development at the AARC: (1) the Special Sensor Microwave Imager (SSMI) 85.5 GHz sea-ice mapping support provided to research vessels, (2) Antarctic cloud detection research for improving climate model simulations, and (3) remote sensing of Antarctic snow surface optical properties.

For several years, the AARC has provided near-real time sea-ice mapping support for research vessels operating in Antarctic waters. Most research vessels do not have the capability to track and decrypt the DMSP polar orbiter telemetry containing the SSM/I data, but the AARC has been able to offer sea-ice imagery via satellite communications links, to help masters and chief scientists avoid areas of heaviest ice concentration, or to steer toward preferred ice features. The standard SSM/I sea-ice algorithms (such as the NASA Team Algorithm) utilize the 19 and 37 GHz SSM/I channels, and therefore offer too coarse a spatial resolution for reliable ice navigation. However, using an algorithm originally proposed by Prof. Tom Grenfell (University of Washington), we are able to correct for atmospheric extinction in the 85.5 GHz vertically and horizontally polarized SSM/I channels, and provide sea-ice mapping support with a spatial resolution of 12.5 km. This resolution enables accurate ice edge positioning and polynya location. We
have validated the performance of the 85.5 GHz algorithm with data from the 1994 Arctic Ocean Section, and research is ongoing in collaboration with Dr. Caren Garrity (Microwave Group - Ottawa River) to further improve the accuracy of our sea-ice mapping services.

Two additional remote sensing projects at the AARC are part of an NSF-supported collaborative project, involving SIO (Prof. Richard Somerville and Dr. Dan Lubin), the Byrd Polar Research Center (Dr. David Bromwich), and the University of Wisconsin (Dr. Von Walden), to evaluate and improve global climate model (GCM) simulation of Antarctic climate. One of the recurring uncertainties with GCM simulation of polar climates involves cloud amount, and we are analyzing a large volume of the AARC’s Advanced Very High Resolution Radiometer (AVHRR) data to develop a climatology of cloud amount suitable for validating GCM simulations. Once common technique for polar cloud detection involves the use of AVHRR channel 3 (3.7 microns) to search for the near-infrared reflectance signatures of clouds. At 3.7 microns, the thermal infrared and solar backscatter components of the signal are roughly the same order of magnitude. A snow or ice surface reflects very little in the 3.7 micron window, while a liquid water or ice cloud exhibits a considerable backscattered solar radiance in this wavelength range. Hence a cloud will usually appear in 3.7 micron imagery as an area of elevated effective brightness temperature (typically tens of degrees). However, we find that the brightness temperature threshold for cloud detection (expressed as a difference between the brightness temperatures in channels 3 and 4) must be chosen with care, and should not necessarily be set to an arbitrary value as is frequently done in global satellite cloud climatology programs. We are currently investigating how the near-infrared signature of Antarctic cloud cover varies with latitude, season, and cloud top height.

In principle, the three AVHRR thermal infrared channels can be used to retrieve cloud optical properties (optical depth and effective radius) for use in improving GCM simulations. In our effort to apply AVHRR data to this problem, however, we first noticed an issue with the interpretation of clear-sky imagery over the Antarctic Plateau. In clear-sky scenes during summer (as identified by South Pole Weather Office observations), the channel 3 brightness temperature typically appears 10-20 K warmer than either of the middle-infrared channels, while the brightness temperatures from the middle-infrared channels agree very well with surface air temperature measurements. In the Antarctic winter, all three AVHRR thermal infrared channels agree to within a few Kelvin, except over the coldest scenes where the channel 3 detector sensitivity is inadequate. The summertime discrepancy over clear-sky scenes must be understood before attempting retrieval of cloud optical properties. Suspecting that the channel 3 solar backscatter component of the Antarctic snow surface is not negligible, we constructed a discrete-ordinates radiative transfer model in which a simulated pristine Antarctic snow pack is couple to a model atmosphere based on South Pole rawinsonde data. This model shows that at 3.7 microns, the snow surface albedo is indeed a few percent, which is sufficient to explain the brightness temperature discrepancies. At 3.7 microns, as at shorter wavelengths, the Antarctic snowpack exhibits a pronounced bidirectional reflectance distribution function (BRDF). In addition, the 3.7-micron
backscattered radiance is sensitive to snow grain size, for snow grain effective radius smaller than 100 microns. This may offer the potential for using AVHRR data to differentiate between old and new snow on the Antarctic Plateau.
The lack of data over the oceans and remote areas of the Earth greatly contributes to the uncertainties of global weather analysis, which in turn, limit the skill of weather prediction models. The problem is particularly severe over the Southern Hemisphere, which is covered mostly by oceans. As an example, we show in Fig. 1 the rms differences in 500-mb geopotential height between the ECMWF (European Centre for Medium Range Weather Forecasting) and the NCEP (National Centers for Environmental Prediction) global analyses during the period of January 6, 1997 through February 27, 1997. For the Northern Hemisphere (Fig. 1a), the major differences occur over the Pacific Ocean, the Atlantic Ocean, and the Arctic regions. The maximum rms difference is 27 m near the North Pole. The differences over the continents (i.e., North America, Asia, and Europe), where there are significant amounts of upper air observations, are much smaller. For the Southern Hemisphere, the differences are much more widespread. The maximum difference between the two global analyses reaches a value of 50 m over the Southern Oceans, and 60 m near Antarctica. Clearly, more observations (particularly, remote sensing observations) are needed if we are to improve the quality of global analysis.

A potential data source over the Southern Hemisphere is the radio occultation soundings. The radio occultation technique was developed in the 1960s by scientists at Stanford University and the Jet Propulsion Laboratory (JPL) for remote sensing of the planetary atmosphere. The application of the radio occultation technique to sound the Earth's atmosphere was proposed in the 1970s, but did not receive serious consideration until the establishment of the Global Positioning System (GPS) by the Department of Defense. In 1993, UCAR, together with JPL and U. of Arizona, established a GPS/MET (GPS/Meteorology) program (Ware et al. 1996) to demonstrate active limb sounding of the Earth's atmosphere using the radio signals provided by GPS. An experimental satellite carrying an advanced GPS receiver was launched into low Earth orbit on April 3, 1995 to observe occulted

Fig. 1. RMS differences between ECMWF and NCEP global analyses during the period of Jan. 6 through Feb. 27, 1997 for (a) Northern Hemisphere, and (b) Southern Hemisphere.
GPS satellite signals. Analysis of GPS/MET radio occultation soundings indicated that the GPS/MET soundings are of high vertical resolution (200 m – 500 m in the troposphere) and high accuracy (~1 K in temperature from surface to 40 km). Moreover, accurate water vapor profiles can be retrieved with the use of ancillary temperature data. With the success of GPS/MET, the GPS radio occultation sounding technique is now widely recognized as a potential candidate for a new, accurate global observing system in support of weather prediction, climate change research, and space weather (Anthes et al. 2000).

COSMIC -- Constellation Observing System for Meteorology, Ionosphere and Climate is a collaborative science project between the United States and Taiwan. The goal is to launch a constellation of six small satellites into three orbital planes in late 2003. The primary science payload is the latest version of the GPS flight receiver developed by the JPL. Two secondary payloads are a Tiny Ionospheric Photometer (TIP), developed by the Naval Research Laboratory (NRL) and a Tri-Band Beacon (TBB) transmitter, jointly developed by NRL and Applied Research Laboratory at the University of Texas. COSMIC will produce approximately 3,000 radio occultation soundings per day, uniformly distributed around the globe. The TIP and TBB will provide ionospheric measurements that are highly complementary to the GPS occultation soundings. COSMIC is a research and operational demonstration program designed to provide atmospheric and ionospheric data in near real time. Figure 2 shows the typical distribution of COSMIC soundings in 24 hours (solid dots). The current radiosonde stations over the Southern Hemisphere are marked with open circles. The COSMIC data will be provided openly to research and operational communities, at the minimum cost of communication and reproduction. In this presentation, I will discuss the preliminary design of the COSMIC system and its potential applications to weather analysis and prediction over the Antarctica and Southern Oceans.

References:


![Occultation Locations for COSMIC, 6 S/C, 3 Planes, 24 Hrs](image)

**Fig. 2.** Typical daily COSMIC soundings are shown in solid dots, location of radiosonde sites in open circles.
ABSTRACT

Advanced Aviation Forecasting Techniques
Applicable to Antarctic Support

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During the past decade scientists and engineers at NCAR's Research Applications Program (RAP) have developed several advanced techniques for detecting or forecasting parameters important to aviation operations (icing, turbulence, thunderstorms, and microburst wind shear). These phenomena have traditionally been very difficult to not only predict but to detect accurately. The patchiness of such phenomena spatially, and their short life spans explain most of this difficulty. Inadequate data, or attempts to use a single data source to detect them, explains the rest of the difficulty. Numerical models have progressed significantly over this period but are still far from being able to detect or predict these phenomena with high probabilities of detection and low false alarm rates.

The new techniques developed at NCAR\RAP came about as a result of three factors. First, 20 years of focused research on the atmosphere at the meso-scale began to pay dividends. Although the spatial and temporal nature of turbulence is still largely unknown, the other phenomena referenced are much better understood today as a result of this research. Once a scientific basis is developed for a phenomenon, it then becomes possible to engineer sensors for better detection, to build a climatological database, to build algorithms that can focus on a short-lived phenomenon, to better understand extreme values of the phenomenon, to build models that can attempt to predict the phenomenon and to think about how to engineer forecast systems to forecast it.

The second important factor relates to the development and deployment of advanced sensor systems and the research that these sensors made possible. Such systems include radar, satellite, airborne, wind profiling, and GPS-based sensors. Each has contributed significantly to our understanding of aviation hazards and has provided the raw material for detecting and forecasting them.

The final element, fuzzy logic, requires a bit more discussion because its role in advanced forecast algorithms is less obvious. Fuzzy logic is not just another version of artificial intelligence; rather, it is a fundamental new form of mathematics that provides us with a more precise tool than Boolean logic to better understand the physical world. This "calculus of compatibility" is not encumbered with the need to classify data, the awkwardness of cross-correlated data in statistical applications, and ambiguities that often arise in algorithms using Boolean-based processes. This tool was first applied by NCAR to develop an improved method for detecting and characterizing low-level wind shear. In the mid-1990's, scientists at NCAR showed how well this mathematical logic worked as the basis for pattern recognition algorithms applied to wind profiling sensors.
Since then, our work has embraced fuzzy logic as the mathematical basis for 90% of our algorithm development associated with advanced forecast systems.

A generalized design for a nowcasting (0-4 hours) system is shown in the diagram below. We refer to this design as an intelligent weather system or IWS. It uses fuzzy logic throughout, in the quality control processes, in the real-time data algorithms, in the model post-processing algorithms and especially as an integrator of all of the major streams of intelligence associated with the diagnosis or prognosis of one of the aviation hazards. It uses any kind of model input, but high-resolution (<20 km) model data is preferred. Output from several models may be used. The sensors are selected based on availability and relevance to the end product. In the Antarctic satellite, ground-based conventional sensors, GPS (space-based, but also ground-based if feasible), radar near primary landing sites and wind profilers appear to hold the best hope of feeding such a nowcasting system.

Although not shown, the design for a forecasting IWS is similar. It has less emphasis on real-time data and much more emphasis on model data. The point is that such a system goes beyond numerical modeling. It squeezes information from the best of all model data available but also includes other data – selective climatology, local forecast rules and local land-use effects below the resolution of the model, to name a few.

We now consider some specific applications of the IWS approach.
**Enroute Icing** — Detection and more recently, prediction algorithms have been under development for several years and represent the most mature of the advanced techniques. These systems, referred to as the Integrated Icing Detection Algorithm (IIDA) and the Integrated Icing Forecasting Algorithm (IIFA) use model data, ground based observations for inferring conditions aloft, satellite data and radar data if available. IIDA has been tested and validated extensively over the continental U.S. and is now ready to be applied to more data-sparse domains. The fuzzy logic-based algorithm makes it ideal for detecting a weak signal in a noisy or data-sparse area.

**Enroute Turbulence** — The integrated turbulence forecasting algorithm (ITFA) relies heavily on model data and airborne reports, but also can incorporate satellite data where few turbulence reports exist. Forecasts are generated out to nine hours.

**Ceiling/Visibility** — Algorithms are now being developed for detection and prediction of ceiling and visibility using the same IWS techniques. This work is being done for the FAA, NASA and the U.S. Navy. The development will gradually expand to global applications of the algorithm, including data sparse areas like the polar regions. This work should have significant applications to Antarctic re-supply flights, particularly at the primary and backup landing sites.

**Wind** — To date the IWS techniques have not been applied to wind forecasts. The reason for this is that most of the algorithm development has been for the continental U.S. where model wind forecasts are generally good enough for flight planning. Antarctic re-supply missions are another matter and would benefit significantly from the IWS approach by incorporating the best of model data available with real-time satellite wind data to fine tune the wind forecasts.

**Oceanic Nowcasting Demonstration** — Another development effort at NCAR\RAP is relevant to the Antarctic flight forecasting problem. Techniques are being developed for long-haul flights from the west coast of the U.S. to New Zealand and Australia. Although initial efforts are focused on turbulence generated from thunderstorms generally along the equatorial portions of the flight, the initiative will eventually lead to extensive use of satellite data for automatically detecting hazardous conditions along long flight legs over the ocean.

In summary, the IWS approach to the development of advanced aviation algorithms appears to have significant potential for applications in the Antarctic. Algorithms based on fuzzy logic are ideally suited for data-sparse areas and allow efficient melding of numerical model and real-time data.
RIE – A POSSIBLE EXPERIMENT FOR ADVANCING ANTARCTIC WEATHER PREDICTION

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1. INTRODUCTION

   Based on previous experience with mesoscale modeling in the Antarctic (Hines et al. 1995; Walsh and McGregor 1996; Hines et al. 1997a, 1997b; VanLipzig et al. 1999; Bailey and Lynch 2000a, 2000b), as well as from recent experience with operational numerical weather prediction in the Antarctic (Cassano et al. 2000), it is known that forecast skill is limited by both data availability and the accuracy with which numerical models represent physical processes in the atmosphere of the high southern latitudes. Given these two problems it is proposed that an extensive field campaign be conducted in the Ross Island region to improve our ability to simulate the mesoscale circulation and precipitation features prevalent in this region. A preliminary name for this field campaign is RIME; the Ross Island Meteorology Experiment.

   A description of RIME, and tentative timetables for the implementation of this program are presented below.

2. OVERVIEW OF RIME

   The primary goal of RIME is to improve the skill of numerical weather prediction of the mesoscale circulation and precipitation features prevalent in the Ross Island region. These features are poorly resolved in global models, and thus pose a difficult forecast problem that directly impacts U.S. Antarctic Program logistics and flight operations.

   Improvement in numerical model skill will be sought through both improved representation of physical processes in the models and enhanced utilization of unique data sources for model initialization (such as GPS/MET and other remotely sensed data).

   It is envisioned that a suite of mesoscale models will be run in an operational mode for the duration of RIME. Validation of the model forecasts, as well as intercomparison between the models, will be conducted to highlight processes that are poorly represented by the models and that are in need of improvement. In addition, numerical experiments in which non-traditional atmospheric observations are incorporated into the models will be conducted to determine which measurements provide the greatest improvement in forecast skill.

   As part of this study, a suite of observing tools will be deployed in the vicinity of Ross Island to provide a comprehensive picture of the three-dimensional structure of the lower atmosphere over the northwestern Ross Ice Shelf. It is envisaged that the observational platforms will include an enhanced array of automatic weather stations surrounding the Ross Island region, satellite measurements, portable SODAR and RASS systems, instrumented micrometeorological towers with flux measurement capabilities, and an instrumented airborne platform.

   These measurements will provide ground truth for the numerical simulations conducted during RIME. It is envisaged that a synergistic observational and modeling approach will be followed. Observations of moist atmospheric processes and boundary layer cloud and fog formation will be used to improve the representation of these processes in mesoscale models. Planetary boundary layer model parameterizations will be thoroughly tested using detailed surface energy budget measurements at multiple sites. It is imperative that the fundamental surface boundary processes are simulated with precision, and refinement of stable boundary layer parameterizations will be sought.

   Although the study will focus on mesoscale features, application to larger-scale events is a logical by-product. Resulting parameterizations would be useful in coupled ocean-ice-atmosphere global models necessary for simulations of climate change.

   It is expected that RIME will have important operational and logistical consequences. Improved mesoscale forecasts in support of U.S. operations in the Ross Sea region will be one tangible outcome of this study. A two-phase approach is proposed.


   Currently there exist a wide variety of numerical models used to simulate Antarctic meteorological processes. In addition, many of the models have options for inclusion of multiple parameterization schemes. Although the availability of mesoscale models is unprecedented, applicability and validation of simulations over the high southern latitudes are limited. Many of the parameterization schemes have been designed with mid-latitude applications in mind. The first task of Phase I of RIME will be an intercomparison and evaluation of ongoing modeling efforts. This research activity will take place during primarily the first year of RIME (1 June 2002 - 31 May 2003). The Ross Island area represents an ideal site to validate numerical simulations since it hosts the most complete observing network over the entire Antarctic continent. Simulations will focus on several case studies of significant weather events over the western Ross Sea. A series of sensitivity studies of model parameterization schemes will be performed initially. For example, a series of MM5 simulations will be conducted in which the planetary

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boundary layer parameterization is changed. Similar experiments will be conducted for surface layer representations, precipitation schemes, radiative transfer schemes, etc. During the first two years, emphasis will be placed on sensitivity experiments with some limited validation checks. Commencing with data from field seasons in 2003-04 and 2005-06, increasing emphasis will be placed on model validation and detailed assessment of planetary and surface boundary layer parameterization schemes.

A tangible delivery as part of Phase I will be an ensemble of real-time model simulations. It is planned that this will commence 1 June 2002 and continue for the duration of RIME. The forecast output will be available on the web in a convenient user-specified format. Thus, this initial phase opens new logistical possibilities.


Two field studies will be conducted as part of RIME. The first field study will commence early in the field season of 2003-04. It is envisaged that two remote camps will be established, one near Cape Crozier and a second just east of Minna Bluff, with a third camp at Willie Field (Fig. 1). The sites of the field camps have been selected to sample both the marine and continental environments. In addition, both remote camps are accessible via helicopter from McMurdo. Aside from an AWS, each site will possess surface-based sounding capabilities via RASS and SODAR or conventional balloon launches. In addition, a 10-m micrometeorological tower could be deployed at each site. Measurement of terms comprising the surface energy budget will be made, including direct turbulent flux measurements of momentum, heat and moisture, as well as longwave and shortwave radiative fluxes. Such measurements will be required for the validation and refinement of surface boundary layer parameterizations in mesoscale models. It is proposed that the field camps be established as early as possible during the summer field season and remain operational until as late in February as possible. The AWS will remain at each site throughout the winter period and for the duration of RIME.

It is also proposed that an airborne campaign be mounted. This will give the capability to examine the three-dimensional structure of the low-level environment over a broad area near Ross Island, and is required for model validation. Previous field work, both in the Antarctic as well as in mid-latitudes, has clearly demonstrated the need for an airborne platform to enable the broadscale structure of the ambient environment to be depicted. Two options are being examined. The first involves developing a PC-based data acquisition system for use onboard the Twin Otter platform, that is widely used in the Antarctic. This low cost option will simply provide a means to measure state variables currently obtained in the cockpit without the need for mounting additional instrumentation on the airframe. A second option is to utilize a portable instrumentation package similar to the HELIPOD, a new helicopter-borne in situ measurement system (Muschinski and Wode 1998). Such a package is suspended below a helicopter and can sense state variables and turbulence quantities. The airborne campaign will focus on select case study days. Additional launches of radiosondes at the remote field camps will complement the airborne data collection.

It is proposed that an analysis year follow the first field season, to allow for modification of the measurement strategy and improvements in the model parameterizations and model simulations. After the second field season, it is anticipated there will be two years of analysis required to complete the project.

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Assimilation of GPS Radio Occultation Data for Numerical Weather Prediction

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Abstract

With the availability of approximately 3,000 radio occultation soundings per day within three hours of observation, COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) has the potential to contribute significantly to global and regional weather analysis and prediction. However, the basic radio occultation measurements (phase delays) are very different from traditional meteorological measurements (i.e., temperature, water vapor), and to effectively assimilate them into weather prediction models is a challenging task. Over the past five years, considerable progress has been made in the development of an effective strategy for the assimilation of GPS radio occultation data. In this paper, we discuss the various strategies for data assimilation, review results from recent data assimilation research, and provide suggestions for future research.

Results from recent studies have led to the conclusion that the best strategy to assimilate GPS radio occultation data is a mixture of bending angles below 10 km and refractivity above 10 km using a variational approach (Zou et al. 1999, Zou et al. 2000). The assimilation of GPS radio occultation data is likely to have a significant positive impact on global and regional weather prediction through improved definition of water vapor, temperature and wind fields. Although refractivity and bending angles are not directly related to the winds, the assimilation of GPS data leads to improvements in the wind analysis through internal model dynamic adjustments (Kuo et al. 1997).

In order to make optimal use of GPS radio occultation data in weather analysis and prediction, considerable research is needed in: (1) better characterization of GPS measurement errors, particularly in the lower troposphere, (2) improving the computational efficiency and optimizing the strategy of bending angle and refractivity assimilation, and (3) performing a set of observing system simulation experiments with realistic simulation of GPS radio occultation data. These research tasks should be conducted prior to the launch of the COSMIC satellites, so that we can fully realize the potential of COSMIC data in global and regional weather prediction.

References

Multiscale Weather Forecasting with Unstructured Grids

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The Operational Multiscale Environment model with Grid Adaptivity (OMEGA), a high resolution, high fidelity, operational weather forecasting system (Bacon, et al., 2000) has been developed for the past 8 years to advance the state-of-the-art in numerical weather prediction and hazardous dispersion. OMEGA, a non-hydrostatic multiscale forecast model has since been used to forecast extreme or severe meteorological events from global scale to local scale as well as point and large area dispersion phenomena. Figure 1 shows the grid structure used by OMEGA to simulate multiscale weather. This single grid, based on an unstructured triangular mesh, provides for a variable grid resolution ranging from 25 to 150 km that resolves the important land/water boundaries and topographic features without interior nest boundaries.

While OMEGA was originally designed for hazardous dispersion forecasting, its flexible grid structure has proven to be extremely useful in modeling may complicated meteorological situations including those forced by topographic and or coastal circulations (c.f. Figure 2), and even hurricanes. The latter provides an excellent example of the application of unstructured grids to meteorological forecasting (c.f. Figure 3).

OMEGA was recently applied to hurricane forecasting with surprising results. The forecasted track error for all of

Figure 1. The OMEGA model can provide high resolution where it is necessary, thus optimizing the use of computer resources. This grid consists of 31 layers, with 11240 cells per layer and a horizontal resolution ranging from 25 km to 150 km. The inset shows how the triangular grid better resolves the coastline and hence improves the simulation of coastal circulations.

Figure 2. The unstructured grid of OMEGA allows the model to better resolve coastal and terrain structures without using an arbitrary North-South / East-West grid alignment.
the simulations performed for Hurricane Floyd were significantly below that of the operational weather forecast models used at the National Hurricane Center (c.f. Table 1). The same result was repeated for a study of Hurricane Dennis.

SAIC is now looking at the application of OMEGA to multiscale weather forecasting issues that span the range from meso-γ scale to meso-α scale and even global scale. Figure 4 demonstrates this with a simulation in which the grid structure was varied from 20 km in the Washington, DC vicinity to roughly 300 km over the oceans. This figure shows the grid, the elevation model based on this grid, and the temperature and moisture distribution.

Figure 5 shows a global OMEGA grid. Starting from an icosohedron (a 20 sided solid), the OMEGA grid generator refines this grid iteratively 5 generations in approximately 2 seconds to generate a near uniform global grid at roughly 250 km resolution. At that point, the underlying terrain data is queried to generate a grid adapting to the underlying topography and land/water boundaries.

The importance of this model to weather forecasting in Antarctica is that there are no grid singularities anywhere in the model domain. The beautiful aspect of a triangular grid structure is that the grid resolution can vary smoothly from one part of the grid to another without internal boundaries. The numerical scheme views each triangular grid cell as identical elements with three lateral faces, a top, and a bottom face. We believe that this will be a distinct advantage in forecasting for Antarctica.

Table 1: Track Error (km) for the four initial sensitivity simulations.

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<td>47</td>
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<td>94</td>
<td>58</td>
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</tbody>
</table>

Figure 3. Dynamic adaptation puts high resolution only where required leading to higher efficiency. Seen are the Hurricane Floyd grid and wind speed (grey) (a) initially, (b) at 24 hours, and (c) at 48 hours. The white dots show the observed storm track; the black line the forecasted track.
Figure 4. The OMEGA modeling system supports global simulations with locally high resolution using (a) a single triangular mesh grid. This permits (b) the accurate representation of the elevation and coastline (or other surface property). This grid consists of 20 layers, with roughly 25000 cells per layer and a horizontal resolution ranging from 20 km to 300 km. Shown are the (c) the global temperature distribution and (d) the global moisture distribution.
Figure 5. The triangular OMEGA grid, by its very nature, does not possess singularities at the poles - or anywhere else. Starting from an icosohedron (top left), the OMEGA grid generator uses quadrature for 5 iterations (top right and bottom left) to produce a nearly uniform triangular grid at roughly 250 km resolution. It then queries the underlying datasets to refine the grid along coastlines and in complex terrain. The result is a singularity free grid.