1. Introduction

Weather forecasting in and around Antarctica is notoriously difficult. This arises in part because of the failure of current models to include the important orographic and coastal features of the continent and problems with basic surface and boundary layer physics and cloud processes. The uncertainty in model forecasts presents logistical problems for the United States Antarctic Program (USAP), including cancelled and aborted flight operations. It has also contributed to an increased risk for USAP personnel both in deployment phase and in the ability to mount rapid recovery operations in an emergency.

The Ross Island Meteorology Experiment is proposed to improve our basic understanding of the meteorology of the Ross Sea region. The Ross Sea area is considered to be a representative region for studies of physical processes and of moisture, momentum, and energy fluxes, hence the knowledge gained on RIME will improve our modeling for the entire continent of Antarctica.

A model is the instantiation of our understanding of the physical processes of the system the model purports to represent. To the extent that a model agrees with observations, it represents a confirmation of the physical understanding and the techniques used to simulate the physical processes encapsulated in the model. To the extent that a model disagrees with observations, it represents evidence that either the physical understanding is lacking or the techniques used to simulate the physical processes are inappropriate or both. In the case of Antarctica, it is easy to document that the techniques used to date are not sufficient to the task; it is also quite evident that our physical understanding is incomplete.

The weather of Antarctica is dominated by three processes: (1) the polar high and the baroclinic waves that circumnavigate the continent leading to incursions into the continental landmass; (2) terrain forcing as the synoptic circulation interacts with the steep terrain and coastal and ice boundaries; and (3) katabatic processes that arise from strong radiative cooling of the surface and the downslope acceleration of the flow. These processes then couple with the moisture and surface features leading to rapid degradation in ceiling and visibility and high wind situations that preclude air operations. This has a severe impact on the science mission of the USAP due to the cancellation of flight operations, or worse the aborting of an operation in process.

Weather forecasting, however, involves a system of systems, each of which must be considered in order to improve forecast skill. The system of systems includes: (1) data acquisition; (2) data ingest, quality control, and assimilation; (3) physical modeling; (4) visualization; and (5) results dissemination. Only via a balanced approach will it be possible to improve forecasting for operations in Antarctica.

Several groups are proposing new observation systems (ATOVS, COSMIC) that will add much needed data to the system, but this new data must be ingested, quality controlled, and assimilated into the forecasting systems. RIME has the potential not only to add to our understanding of the basic physical processes but to also provide ground truth to verify some of the remotely sensed data that is soon to be collected.

Finally, RIME could serve as a testbed for testing new operational forecasting concepts. This could include a distributed modeling concept in which local computing resources are used to provide operational numerical weather prediction and / or high bandwidth communications channels could be used to provide a reach-back capability to enable remote resources to provide support.

This paper discusses the physical modeling aspects of RIME (surface properties, air-surface fluxes, multiscale dynamics, thermodynamics, and microphysics), on the required datasets for model
development and evaluation, and on the potential operational concepts that could be explored during the course of the experiment.

2. Antarctic Meteorology

Circulations such as baroclinic waves and gravity waves can lead to flow instabilities (e.g. Kelvin-Helmholtz instabilities) due to the associated wind shear. These instabilities occur over scales of tens to tens of thousands of meters increasing the turbulence intensity levels leading to increased gusts that are important for air operations. Furthermore, wind shear and/or buoyancy play an important role in generation of atmospheric boundary layer turbulence. At night, the formation of a nocturnal surface inversion due to longwave radiation cooling decouples the nocturnal boundary layer from the remainder of the well-mixed daytime planetary boundary layer. The resulting changes in the wind direction and speed may result in moisture at different levels being advected at different speeds (speed shear) or directions (directional shear). In the morning, the unstable daytime boundary layer begins to grow, the shear-distorted moisture mixes vertically potentially leading to ceiling and/or visibility problems.

Perhaps one of the most important mesoscale circulations generated from the interaction of the Antarctic surface with the atmosphere is the terrain forced (Schwerdtfeger, 1975) and katabatic (Parish, 1981) winds. Due to the diurnal heating and cooling of mountain slopes, thermal circulations often develop along these slopes. During the day, solar radiation warms the mountain slopes or valley walls, which in turn warm the air in contact with them. Due to convective mixing, air gets heated up to several hundred meters above the sloping surface. This heated air, being less dense than the air at the same elevation above valley floor, rises as an upslope wind. During the night, mountain slopes cool more quickly by outgoing radiation than the valley floor. The air in contact with the slopes and up to a depth of several tens of meters cools through conduction and turbulent mixing. This cooler dense air flows down the slope. These winds are sensitive to the local and regional topographic slope and diurnally varying temperature. They are observed in many mountainous regions of the world, particularly in Alaska, Greenland, Antarctica, Alps, Himalayas, and Rockies. Wind speeds of more than 90 m/s in Antarctica and 50 m/s in the mountain regions of Europe have been observed in some of these flows.

Intrinsic in the formation of katabatic flow is the exchange of heat and moisture between the surface and the lower layers of the atmosphere. This exchange is governed by the surface properties, which for the Antarctic involves a dynamic snow/ice condition. Fresh fallen snow has a low density, high ventilation factor, significant forward scattering component and hence different albedo and heat transfer coefficients than snow that has been compressed and glazed or completely melted to form an ice sheet. Blue ice has entirely different properties. Atmospheric radiation transport is an important factor in the melting of the snow surface and hence in the aging of the snow. Once the energy and moisture is in the lowest layer of the atmosphere, the boundary layer circulations and microphysics become important processes in determining the vertical energy and moisture distribution. A better understanding of the energy and moisture exchange will lead to better simulation of the katabatic circulation and also to the low level moisture which is important for visibility and ceiling prediction. Another factor important for visibility is blowing snow.

The discussion above shows how the atmospheric energy is distributed over a variety of flow modes, including thermally and internally generated global and local circulations and their eddies in an inherently multi-scale environment. The weather in Antarctica is significantly affected by this wide range of flow scales through variations in the mean transport wind, differential advection of moisture due to vertical and horizontal wind shear, and vertical mixing. When these complex flow modes and winds associated with them are generated, they can lead to ceiling and/or visibility restrictions on air operations. Therefore, these space-time flow scales and their interaction with each other and the moisture should be represented accurately in any study of Antarctic weather.

3. Numerical Weather Prediction for Antarctica

The earliest numerical simulations of Antarctic meteorology were conducted at the University of Wyoming (Parish, 1981) and research has since been conducted into terrain forcing (Parish, 1983) and katabatic winds (Waight, 1987; Gallée and Schayes, 1992). While these simulations were informative, the ability to forecast using these techniques was limited due to the resolution of the models. To study these processes numerically, it is essential that five conditions be met: (1) horizontal resolution sufficient to resolve the
important variations in surface properties including elevation, land/water fraction, ice/snow coverage, and albedo; (2) vertical resolution sufficient to resolve the near surface stability and moisture profiles; (3) surface properties at a resolution sufficient to drive the relevant physics; (4) a physical formulation that is consistent and contains all of the relevant physics; and (5) a numerical method that is appropriate for the solution of the equation set that encapsulates the physical formulation. The current state-of-the-art does not satisfy any of these criteria.

To demonstrate the resolution requirement for Antarctica visually, it is only necessary to consider the topography of the continent. Figure 1 shows the recent RADARSAT data obtained by the Canadian Space Agency and analyzed by The Ohio State University (Liu et al., 1999). Clearly visible are the steep elevation changes along much of the coastline as well as the long gradual sloping regions from the continental plateau towards the coastal regions. This terrain data, especially the local variation in slope, is critical to accurate forecasting of the weather.

Most weather forecasting systems put the bulk of their resources in the middle troposphere. This is a natural result of the fact that the mid-latitude weather is most variable in terms of the precipitation, of which the governing cloud microphysical processes typically occur in the middle troposphere. In Antarctica (and in the Arctic), the lack of a liquid phase means that most of the important microphysical processes occur in the planetary boundary layer (PBL). This is the reason for the statement above that vertical resolution is required, and also the explanation for why most operational forecast systems are not designed for this problem.

The surface of Antarctica is not homogeneous; the physical properties of snow and ice of various ages are different in ways important to understanding the surface heating and the flux of moisture, momentum, and heat to the atmosphere. This is one of the fundamental areas of RIME – measuring these critical fluxes and documenting the variability.

The measurements conducted by RIME may represent the best hope for completing a physical understanding of the processes that drive Antarctic meteorology and hence allowing us to create an accurate model for simulation and forecasting of the atmospheric environment of the region. Because of the wind range of scales of motion, it is important that simulations and forecasts at many scales be performed. Flow simulations ranging from local katabatic wind systems to large scale cyclones should be studied. This will help explore the interaction of baroclinic systems with the topography of Antarctica and the resulting terrain forced circulation. It will also examine the development of katabatic flow in the near-coastal regions.

4. OMEGA

A number of numerical weather prediction models have potential application to Antarctic forecasting and should be considered as part of the modeling component of RIME. COAMPS, ETA, and MM5 are all used operationally and could be extended to this region. MM5 has already been extended with the development of the Polar MM5 version (Cassano et al., 2001). COAMPS, ETA, and MM5, however, all use a conventional nested grid methodology with essentially the same equation set and hence proof of concept with one of the models is a strong indication that similar modifications to the others will yield similar improvement in skill.

Over the past eight years, the Center for Atmospheric Physics (CAP) of SAIC has developed the Operational Multiscale Environment model with Grid Adapivity (OMEGA), a high resolution, high fidelity, operational weather forecasting system (Bacon et al., 2000). OMEGA, a non-hydrostatic multiscale forecast system developed originally for atmospheric dispersion issues, has been used to forecast extreme or severe meteorological events from global scale to local scale as well as point and large area dispersion phenomena.

While the bulk of the applications of OMEGA to date have been at the mesoscale and below, its
unstructured grid provides a powerful advantage in problems that involve a spectrum of scales from global to local. (Figure 2 shows a global OMEGA grid that was constructed to test the concept of multiscale forecasting for Washington, DC.) This is important for Antarctica where the circumpolar circulation and its interaction with the complex terrain of the continent are important contributors to the weather.

A fairly complete description of OMEGA can be found in Bacon et al. (2000). OMEGA is a complete, operational, atmospheric simulation system. It includes the OMEGA model, static world-wide surface datasets required to define the necessary surface properties (elevation, land/water fraction, albedo, vegetation, etc.), data preprocessors to assimilate meteorological data, automated routines to download data from various operational data centers, as well as post-processors to analyze and visualize the simulation results. The kernel of the system is the OMEGA model – a three-dimensional, time-dependent, non-hydrostatic model of the atmosphere. It is built upon an unstructured triangular grid, which can adapt to a variety of static user-defined fields as well as dynamically during the simulation to the evolving weather. The triangular unstructured grid makes it possible to represent the underlying terrain with great accuracy. The dynamic adaptation increases the spatial resolution only where it is needed, (such as in the region of weather systems or steep terrain), automatically during runtime, thus optimizing the use of the computational resources.

The variable resolution and adaptive nature of the OMEGA grid structure give it a unique advantage in simulating the Antarctic atmospheric circulations. For example, the OMEGA grid can adapt to the terrain and/or initial sea ice concentration, thus resolving the large-scale dynamics as well as the local scale circulations associated with fine scale representation of the terrain features. This means that OMEGA can simultaneously resolve the meso-α scale (O(100 km)), meso-β scale (O(10 km)), and meso-γ scale (O(1 km)) forcing that drives the local scale wind field without the need to place high resolution everywhere and without human interaction.

OMEGA includes an embedded Atmospheric Dispersion Model. This capability is useful in the Antarctic in terms of monitoring the potential path of an effluent plume and hence to the study of a number of air quality issues in Antarctica. The meteorological and dispersion capabilities of OMEGA have been the subjects of several model evaluation and verification studies, the most recent of which was evaluation against data from the ETEX experiment (Boybeyi et al., 2001).

5. Benefits of Static and Dynamic Adaptation

The unique capabilities of OMEGA have shown the benefits of static and dynamic adaptation. Figure 3 shows a static grid that was constructed for a regional simulation of the Antarctic Peninsula. This grid had horizontal resolution ranging from 30 to 75 km. The OMEGA simulation clearly showed flow blocking caused by the geography of the peninsula.

Figure 4 shows how dynamic adaptation can maintain resolution in those regions required by physical processes. This simulation of a severe tornadic outbreak in 1979 used a dynamic adaptation criteria of low-level moisture concentration. The grid was able to maintain high resolution automatically in those regions where the physical processes produced severe convection and tornados.

6. Conclusions

RIME is intended to advance our understanding of the meteorology of Antarctica and its potential impact on the weather and climate of the rest of the world. As such, the knowledge gathered in RIME must be transferred to models to allow us to extend our knowledge and to test it under varying assumptions. This is justification enough to have multiple modeling efforts participating in order to form a critical mass.
OMEGA represents a unique atmospheric modeling and forecasting system. The adaptive grid permits the easy gridding of the complex terrain of Antarctica and the dynamic adaptation should allow us to explore the interaction of weather systems with the complex topography of the Antarctic coast – including the area surrounding the Ross Sea.

Finally, OMEGA in its global mode, may prove useful in understanding the global impact of Antarctic weather.

References


