Antarctic Satellite Meteorology: Applications for Weather Forecasting

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(Manuscript received 6 April 2001, in final form 5 October 2001)

ABSTRACT

For over 30 years, weather forecasting for the Antarctic continent and adjacent Southern Ocean has relied on weather satellites. Significant advancements in forecasting skill have come via the weather satellite. The advent of the high-resolution picture transmission (HRPT) system in the 1980s and 1990s allowed real-time weather forecasting to become a reality. Small-scale features such as mesocyclones and polar lows could be tracked and larger-scale features such as katabatic winds could be detected using the infrared channel. Currently, HRPT is received at most of the manned Antarctic stations. In the late 1990s the University of Wisconsin composites, which combined all available polar and geostationary satellite imagery, allowed a near-real-time hemispheric view of the Southern Ocean and Antarctic continent. The newest generation of satellites carries improved vertical sounders, special sensors for microwave imaging, and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor.

In spite of the advances in sensors, shortcomings still impede the forecaster. Gaps in satellite data coverage hinder operations at certain times of the day. The development and implementation of software to derive products and visualize information quickly has lagged. The lack of high-performance communications links at many of the manned stations reduces the amount of information that is available to the forecasters.

Future applications of weather satellite data for Antarctic forecasting include better retrievals of temperature and moisture and more derived products for fog, cloud detection, and cloud drift winds. Upgrades in technology at Antarctic stations would allow regional numerical prediction models to be run on station and use all the current and future satellite data that may be available.

1. Introduction

The Antarctic continent is a most inhospitable place to perform research. The extremes of temperature and weather conditions make survival dependent on accurate weather forecasts. Transportation to and from the continent is also very dependent on weather conditions. Accurate real-time forecasts of wind and visibility conditions such as fog or blowing snow are critical for aviation. Ship operations need accurate forecasts not only for mesoscale features such as polar lows with their accompanying high winds, but also for fog and sea ice extent. Transportation around the continent for research and operational purposes needs similar forecasting support.

Early weather information was restricted to mainly the manned stations in coastal areas. Most of the southern oceans and the interior of the continents were without observational data. The advent of weather satellites opened up these data-void areas. The synoptic patterns as well as mesoscale features such as polar lows could be viewed in real time. Later satellite temperature retrievals provided information over both the oceans and the interior of the continent, and the additional information on the structure of the atmosphere helped the weather forecasters determine safe conditions for both aviation and land-based traverses. Additional channels, such as infrared, allowed research work on the circulation around the continent to continue through the darkness of winter. Finally, continued improvements in sensors and retrieval techniques are providing better quality data for use in local/regional numerical weather prediction models.

This review recounts the significant historical events related to the early use of weather satellites in Antarctica, especially with regard to the forecast problem. Current applications and some problems with weather data usage, such as cloud identification and data gap issues, are documented for a sample of current Antarctic weather forecasting operations. Proposed new satellite sensors are discussed as well as potential future applications of weather satellite data for derived products such as cloud identification or cloud drift winds.

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2. Historical uses of satellites in Antarctic meteorological activities

A history of the use of satellite remote sensing for the polar region, and especially the Antarctic, is given by Massom (1990), Rao et al. (1990), and King and Turner (1997). Table 1 provides information on the time of operation and instruments for past and current United States satellites, and Table 2 provides the same information about non-U.S. satellites. Below is a sample of the many efforts in the Antarctic in the evolution of science research and operational weather forecasting.

a. Early use of satellite imagery

Applications of satellite imagery during the early days of the polar-orbiting weather satellites [Television Infrared Observing Satellite (TIROS) and Nimbus] were few for the Antarctic. The high altitude and coarse resolution made it difficult to resolve many surface features. With the advent of the first Environmental Science Services Administration satellite (ESSA-1), equipment and procedures had progressed enough to allow processing of operational products from the digitized video data. Bristor et al. (1966) described the procedures necessary to produce operational pictures. One example produced by Bristor et al. was a full-resolution polar stereographic mosaic of a section of the Southern Hemisphere from the South Pole to the equator along 10°E.

While these products could be made available, they needed much larger storage memory areas than computers had at that time.

A solution to the memory problem was to process the hemisphere in sections and then assemble the entire picture. This allowed a daily cloud photograph to be produced, but some sections of the picture could be almost 24 h older than other sections. Nevertheless, it was now possible to view cloud systems over sections of the earth such as the Southern Hemisphere south of 40°S, which had never before been seen on a large scale. Kermann and Frame (1966), Keith and O’Neal (1967), and Godin...
b. Science and operational use of satellite data and imagery

Early uses of satellite imagery established a climatology of weather events, and later generations of satellites brought more opportunities and information to the research and operational communities.

1) The advent of high-resolution picture transmission (HRPT), mosaic projects, and aviation forecasting

The United States Antarctic Program (USAP) offers an example of how technology and science began to evolve for Antarctic meteorology programs. On 12 January 1980, the USAP installed an HRPT system to receive the National Oceanic and Atmospheric Administration satellite NOAA-6 and TIROS-N series of satellites (Wiesnet et al. 1980). This system was upgraded in October 1987 (Office of Polar Programs 1988; Van Woert et al. 1992), and several times in the 1990s for reception of Defense Meteorology Satellite Program (DMSP) Real Time Data (RTD) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellites. With the installation of an HRPT and RTD receiver at McMurdo to replace the simpler automatic picture transmission (APT) reception system, scientists were able to utilize the output for a variety of applications. The new system
Fig. 2. Example of mesoscale vortex (located near arrow) that does not appear in the sea level pressure analysis. (a) Composite imagery from 0900 UTC 3 Apr 1997 showing a mesoscale vortex (arrow) to the left of the Antarctic Peninsula. (b) NCEP MRF sea level pressure 12-h forecast from 0000 UTC valid at 1200 UTC 3 Apr 1997.

is primarily used for operational weather forecasting, especially in support of aviation operations (Wiesnet et al. 1980; Foster 1982). Foster (1982) notes that with very little weather data available through direct observations, weather satellites have been able to fill that void. In addition, one of the first research uses was the development of an Antarctic mosaic for a joint NOAA and United States Geological Survey (USGS) program funded by the National Science Foundation (NSF) (Wiesnet et al. 1980). That mosaic provided useful information for all scientists interested in Antarctica, from geographers to oceanographers. This would be the beginning of a series of mosaics using polar-orbiting weather satellite imagery, with each new generation a dramatic improvement over the previous one. HRPT data are received at most of the manned stations including Palmer, McMurdo, Rothera, Terra Nova Bay, Dumont D’Urville, Commander Ferraz, Syowa, Halley, and Casey. Tapes of raw HRPT data are held by several data centers including the British Antarctic Survey (BAS), Arctic and Antarctic Research Center (AARC), Scripps Institution of Oceanography (SIO), the Australian Bureau of Meteorology (ABOM), and the Antarctic Meteorological Research Center (AMRC) (Turner et al. 1996).

2) Polar Low and Katabatic Wind Studies

With the availability of science quality polar-orbiting imagery, mesoscale features could be investigated. Two features, mesoscale vortices and polar lows, with their small size but intense winds, were especially troublesome not only for aviation but also oceanographic vessels and research projects. Mesoscale vortices were difficult phenomena to forecast using standard meteorological tools such as numerical model output because...
of their small size and the lack of observational data in the Southern Oceans. Satellite imagery allowed investigators to pinpoint favored regions of development as well as synoptic conditions that enhanced the possibility of their occurrence. These mesoscale features were investigated regionally in the area around the Antarctic Peninsula (Heinemann 1990; Turner and Thomas 1994) as well as the Ross Sea (Bromwich 1991) and the Southern Ocean in general (Carleton and Carpenter 1990). Polar lows, similar-sized features but occurring under different synoptic conditions, were also examined (Carleton 1985; Fitch and Carleton 1992).

Another feature that can affect operations at various manned stations including the Italian base at Terra Nova Bay, the French base at Dumont D’Urville, and the United States base at McMurdo is the katabatic wind. Satellite infrared imagery (Fig. 1) allowed detection of the characteristic thermal signature of the adiabatically warmed air (e.g., D’Aguanno 1986; Bromwich 1989a,b; Bromwich et al. 1992; Carrasco and Bromwich 1993; Breckenridge et al. 1993). The warm river of air stretches from the Siple Coast to the Ross Sea with additions to the stream from the glaciers in the Transantarctic Mountains. Frequent incidents of katabatic winds across the Ross Ice Shelf can form or maintain polynyas in the Ross Sea near the ice edge. The Australian bases at Casey, Mawson, and Davis and the Chinese base at Zhongshan also report difficulties with katabatic winds (Turner et al. 2000).

3) WISCONSIN COMPOSITES

In late 1992, with support from NSF, the University of Wisconsin began to routinely generate composite satellite images over the Southern Ocean and Antarctic continent (Stearns et al. 1999). These composites combined the available geostationary and polar-orbiting satellite imagery, which were remapped into a polar stereographic projection. This display has been valuable for research and forecasting operations and has not been equaled in the Northern Hemisphere to date. This product is useful to researchers for the depiction of the at-
mospheric circulation from a hemispheric view. It is even more popular with forecasters who are able to determine longwave patterns and monitor regions upstream and beyond the area covered by typical APT, HRPT, RTD, and other polar-orbiting satellites local/regional view.

c. Project FROST

In 1994 and 1995, the First Regional Observing Study of the Troposphere (FROST) project, organized by the Physics and Chemistry of the Atmosphere Group of the Scientific Committee on Antarctic Research (SCAR), took place. The main objective was to focus on "the meteorology of the Antarctic, determine the strengths and weaknesses of operational analyses and forecasts over the continent and in the surrounding ocean areas, and to assess the value of new forms of satellite data that are becoming available" (Turner et al. 1996). In a study of Southern Hemisphere analyses during this time (Turner et al. 1999), reanalyzed surface charts were created using data from satellite sources, especially TIROS Operational Vertical Sounder (TOVS) for temperature and water vapor profiles; Wisconsin composite images; DMSP [Operational Linescan System (OLS) and Special Sensor Microwave Imager (SSM/I)] for monitoring sea ice, water vapor, and ocean surface winds; NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery for monitoring clouds; and even satellite temperature (SATEM) data posted on the Global Telecommunications System (GTS). The satellite data were important and in some cases critical in improving most of the analyses (Turner et al. 1999). For example, Fig. 2a shows the composite infrared image for 0900 UTC 3 August 1997. The arrow in the figure points to a mesocyclone approaching the Drake Passage. Such mesocyclones tend to be short lived (24 h or less) but very intense. A ship passing through such a feature could encounter 60-kt winds. The National Centers for Environmental Prediction (NCEP) Medium-Range Forecast model (MRF) sea level pressure forecast closest to the satellite imagery time (Fig. 2b) shows only a very weak trough approaching the area. Hutchinson et al. (1999) note that high-resolution satellite imagery (NOAA or DMSP) provides details on the locations of frontal systems over the Southern Ocean and the structure of mesocyclones found off the coast of Antarctica. Additionally, they noted that although TOVS data were found to be of best quality over the open, ice-free ocean, it was still of value even if the TOVS data were flagged as suspect. TOVS data over the continent were of poor quality but still useful and worthy of additional study. TOVS data have been found to be not nearly as good as radiosonde reports around the coast of the Antarctic; however, it has been valuable in depicting information at midlevels in the atmosphere (Adams et al. 1999).

d. International forecasting studies

In 1998, the First International Symposium on Operational Weather Forecasting in the Antarctic was held in Hobart, Australia. Forecasters from most of the countries that have interests in the Antarctic were in attendance (Turner et al. 2000). From this start a collaborative effort was launched that resulted in a detailed forecasting manual for most stations in the Antarctic. The International Antarctic Weather Forecasting Handbook (Turner and Pendlebury 2000) is a comprehensive examination of the climatology and topography of each station along with specific guidelines for forecasting. In a substantial section on satellite data, each of the AVHRR channels on the NOAA satellites is discussed along with ways to use them singly or in combination as forecasting tools. Scatterometer instruments on several satellites are examined along with data quality and availability and suggestions for how to use the wind information they provide in delineating fronts and low pressure systems. Passive microwave instruments such as SSM/I have many derived products including cloud liquid water and total precipitable water. The process of deriving vertical profiles of temperature and water vapor [TOVS and Advanced TOVS (ATOVS)] is explained in detail. The problems encountered when processing retrievals near and over Antarctica are discussed. Several studies are cited that have developed techniques to compensate for the peculiar properties in the atmosphere over Antarctica. The handbook also provides an interesting look at the challenges of forecasting in very complex terrain, and the tools that forecasters need to provide these forecasts.

e. New generation of satellite sensors

The latest set of satellites launched contains improved sensor capabilities. NOAA-16 carries the ATOVS while the DMSP satellite uses the Special Sensor for Microwave Imaging and Sounding (SSMIS). The National Aeronautics and Space Administration (NASA) has launched its Earth Observing System (EOS) Terra satellite, and the EOS Aqua, which was launched in May 2002. Both Terra and Aqua transmit data at X band (18 GHz) with much higher data rates than NOAA or DMSP satellites and both carry the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor with 36 channels and increased spatial resolution (Bernstein 2000). MODIS offers the multispectral capability to retrieve a large number of atmospheric properties that are useful for forecasting and numerical modeling simulations (Bromwich and Cassano 2000). Aqua and the Japanese Advanced Earth Observation Satellite (ADEOS-2) will carry the Advanced Microwave Scanning Radiometer (AMSR) that greatly improves upon the capabilities of SSM/I for detecting cloud liquid water and precipitation rate over the ocean. The data rates for these new satellites are 15 times greater than current NOAA and
DMSP satellites and only a small fraction of the data can be sent via the Internet because of the vast amount of data and limited Internet bandwidth capability in the Antarctic (Bromwich and Cassano 2000). New systems are being developed and deployed to receive and process data for Terra, Aqua, ADEOS-2, and the imaging radar satellites [European Remote Sensing satellite (ERS-2), RADARSAT]. This increased sensor capability provides more information for the forecaster, but in order to make the information available on a near-real-time basis, new tracking facilities will be required in Antarctica.

3. Current applications of satellite imagery in operational Antarctic meteorology

In order to ascertain the current accessibility and usage of satellite imagery in Antarctic weather forecasting, questionnaires were sent to countries with manned stations in the Antarctic. Some countries did not respond, and contacts for other countries were not available at the time of publication. Information from the First International Symposium on Operational Weather Forecasting in Antarctica (Turner et al. 2000) was used for some of the countries that were not directly contacted.

a. United Kingdom—Antarctic Peninsula and Ronne Ice Shelf

The British Antarctic Survey has forecasting responsibility for the BAS stations at Rothera and Halley as well as Bird and Signy Islands and field camps during the summer season. In addition, two ships operated by the BAS also require forecasts. HRPT receivers, for mostly NOAA AVHRR data, are located at the manned stations and on the ships. The NOAA satellite imagery in the near-infrared (NIR) is used for identifying low water clouds and fog. Forecasts for water clouds and fog are especially critical for aviation because these conditions can lead to severe icing (Wattam and Turner 1995). The infrared (IR) channels are used to produce sea surface temperature maps for marine biologists and for cloud classification research (T. Lachlan-Cope 2001, personal communication).

The lack of observations near and to the west of the Antarctic Peninsula make the satellite imagery invaluable in detecting mesoscale lows. These features are very common around the Antarctic Peninsula, the Ronne Ice Shelf, and near Halley (Wattam 2000). Also lows on the western side of the Peninsula are often blocked by the terrain, and a new low will form on the eastern side and affect Halley.

Difficulties in using satellite imagery mainly arise from the necessity of training new forecasters in the use and interpretation of satellite data. The imagery has been used to validate numerical model analyses so access to passive microwave sounder and imager data from the DMSP would be an additional aid to forecasting.

b. United States—Ross Sea and Ross Ice Shelf, Siple Coast

The USAP forecasters at McMurdo have the responsibility for forecasts for the Southern Hemisphere south of 60°S. This includes aviation forecasts for flights to McMurdo and the South Pole as well as to field camps and other research activities. In addition, they assist with ship operation forecasts for the area between 150°E and 120°W. The USAP forecasters utilize satellite data from the full suite of operational polar-orbiting satellites from the United States—the NOAA series (currently NOAA-12, -14, -15, and -16), the DMSP series (currently DMSP F-13, -14, -15, and -16), and the SeaWiFS—via two HRPT/RTD-type ground stations. Forecasters also receive data from the Russian METEOR satellites via APT. On the NOAA satellites, the visible through IR channels are the most useful, with the visible channels used for cloud identification and for cloud thickness, the NIR channel for fog forecasting, and the IR channel for cloud-height representation and fog identification. No specific enhancement or derived products are created or used. However, the weather forecasters do use other data, including Wisconsin composites, U.S. Air Force Weather Information Network (AFWIN), and U.S. Navy data via the World Wide Web (A. Cayette 2001, personal communication). Automatic weather station (AWS) data, limited radiosonde data, and other surface observations are used to verify satellite observations.

The biggest problem forecasters face is the lack of polar-orbiting satellite data coverage during the operational afternoon. The new NOAA-16 as well as the Geostationary Meteorological Satellite (GMS-5, Japan) have been of some help with this problem (A. Cayette 2001, personal communication). The SeaWiFS satellite images are now available for part of the time when the other polar-orbiting satellites are not in position to see the McMurdo area. While SeaWiFS offers new operational and scientific capabilities, the development of software to derive products and visualize information quickly has lagged (Bromwich and Cassano 2000).

c. Italy—Ross Sea and East Antarctica

The Italian Air Force has responsibility for weather forecasting for Victoria Land, Adelie Land, King George V Land, and the Ross Sea. The Italians provide aviation services for the French to Dome C and Dumont D’Urville on the Adelie Coast (Turner et al. 2000). The Italian station at Terra Nova Bay has an HRPT/RTD facility that receives NOAA and DMSP satellite data. NOAA AVHRR and DMSP OLS data are used extensively both at Terra Nova Bay and at the ENEA Research Center in the Rome Remote Forecasting Office in Italy (A. Pellegrini 2001, personal communication). Other satellite products are acquired via the Internet. Forecasts must be provided for both helicopters and Twin Otters, which have very different requirements for
safe flying weather. NOAA AVHRR visible and IR channels are used for cloud detection and cloud structure. The NIR channel enhances the contrast between the cloud edge and the surface background that helps to distinguish fog patches. This channel also is useful in detecting blowing or drifting snow along the Antarctic escarpment where Twin Otter and helicopter fuel dumps are located. Katabatic winds can be detected by the thermal gradient in the IR imagery and by the sunglint variation in polynya areas in the visible imagery. Sea ice concentration maps and estimates of ocean winds are produced from the SSM/I data and verified with the NOAA AVHRR and DMSP OLS visible channels. AWS observations, radiosonde profiles, and pilot reports are also used for verification of satellite imagery.

Present satellite imagery does not provide all the detail desired by the forecasters. Multispectral techniques applied to MODIS imagery would assist with cloud detection and analysis. In addition, the Terra and Aqua satellites with their advanced microwave imagers will provide much more information for the forecasters. The lack of a high-performance communications link between Terra Nova Bay and Rome reduces the amount of data that can be processed off station and sent to the forecasters. In order to use the new satellites, much of the data processing would have to be done in Antarctica, but at present the computer resources are quite limited with respect to the huge amount of data to be generated.

d. Australia—East Antarctica

The Australian National Meteorological and Oceanographic Centre is responsible for forecasting for the Southern Hemisphere; however, the Antarctic Meteorological Centre at Casey and the Antarctica and Regional Forecasting Centre at Hobart, Tasmania, are responsible for forecasting from 40° to 170°E on the Antarctic Continent. The Australian Antarctic Program utilizes meteorological satellite data from the NOAA series, GMS-5, Meteosat-5 (Europe), and the METEOR series (if available) for forecasting operations. Generally, visible and IR window imagery are used for weather and sea ice forecasting (S. Pendlebury 2001, personal communication). Shortwave IR is used for detecting supercooled clouds. GMS water vapor imagery also provides important information for weather forecasting. The Australians do not derive any products at this time; however, they are in the process of developing an automated sea ice analysis. Cloud drift winds and ice drift vectors along with improved sea ice analysis would help improve forecasts. In the future, they would like to be able to get the DMSP series of satellites, if funding were available. Difficulties with the use of satellite imagery include being limited to channels affected by clouds when trying to detect sea ice. Also, the temporal and spatial resolution of the polar-orbiting data limits the availability of imagery for sea ice forecasts and some weather forecasting activities. TOVS data are used with GMS cloud drift winds north of 60°S for initializations of numerical modeling efforts (using multivariate statistical interpolation). The accuracy of the TOVS data is assessed against radiosondes with other observational data being used occasionally.

e. Russia—East Antarctica and polar plateau

Forecasters are responsible for regional forecasting for the Russian stations and surrounding areas and seasonal forecasting of atmospheric conditions for the Southern Hemisphere. Russian forecasters use satellite imagery of cloudiness and ice cover for forecasting for their Antarctic stations and sea transport operation service. Satellite data are received at all of the Russian Antarctic stations (Bellinghausen, Mirny, Novolazarevkaya, and Vostok) via APT. Satellites received include NOAA-12, -14, and -15; METEOR 3 and 5; and the RESURS series. The satellite imagery is used to define the ice edge and the spatial position of synoptic and mesoscale eddies as well as their trajectories (V. Lagun 2001, personal communication). Derived products include morphological properties of cloudiness and sea ice fields. The NOAA series are used for establishing background prevailing climatological conditions up to seasonal in length. Surface observations of cloud cover and ice edge position are used to assess the accuracy and quality of the satellite imagery. Limitations on the use of satellite imagery are the viewed area at the Russian coastal stations and the speed and volume of information transfer from Antarctica to the Arctic and Antarctic Research Institute (AARI) in Saint Petersburg. A necessary improvement for the forecasters would be to have operational access to the Internet so they can access satellite information available at various sites and to have access to remote sensing measurements such as surface temperature and surface wind vectors from scatterometers.

f. Brazil—Antarctic Peninsula and West Antarctica/ocean islands

On King George Island, South Shetlands, the Commander Ferraz Brazilian station is responsible for regional and local forecasts and employs satellite data from a variety of sources. On station, they receive HRPT and APT for the NOAA series of satellites but also utilize the Russian METEOR series and the RESURS series of satellites via APT reception. The APT and HRPT imagery are used for weather forecasting with the APT used more commonly. Other sources of satellite data include Geostationary Operational Environmental Satellite (GOES) images via radio-facsimile and from a nearby Chilean Navy station at Valparaiso. In addition, they utilize the recently installed Internet to view the Wisconsin composites and GOES data from the Argentinian Air Force.
The visible channel is the most valuable channel in forecasting operations at Commander Ferraz station. Visible channels provide much more information on the type of clouds, cloud coverage, and cloud structure than the thermal channels. Unfortunately they are limited to the summer months and to daylight hours only. Obviously, this only applies to forecasting in the Antarctic Peninsula region with vast ocean surfaces surrounding small islands. The black ocean background is great for clouds in the visible channels (A. Setzer 2001, personal communication). The only enhancements placed on data operationally are contrast stretching in the visible and IR to help identify important weather patterns. With regional and local forecast responsibilities, this station would like to see the availability of satellite-derived maps of winds, water vapor, and temperature. In the future, they plan to continue to receive satellite data from satellites that offer the data in a low-resolution mode (such as APT). Since satellite imagery is the most useful forecasting tool, difficulties ensue when satellites such as NOAA-16 (APT) are not available for afternoon forecasting. While satellite data may be used in the initialization of numerical models, in the Antarctic Peninsula region model forecasts are not relied upon because many of the mesoscale features are missed.

4. Potential future applications of satellite data and imagery for Antarctic forecasting

This section presents some meteorological satellite areas that would significantly contribute to improving Antarctic forecasting.

a. Molniya orbits

In May of 1991, a conference, sponsored by the Alabama Space Grant consortium, was held regarding the potential use of meteorological and oceanographic satellites in a Molniya orbit. The Molniya orbit (Fig. 3) was originally developed and used by the Soviet Union for communications satellites, starting in 1965 (Kidder and Vonder Haar 1991). This orbit offers the potential to be nearly geostationary in the high latitudes for several hours at a time (Fig. 4) (Kidder and Vonder Haar 1990). There are challenges that would have to be addressed with this orbit including accurate attitude control and the need for more than one satellite for 24-h observing. Currently, the polar-orbiting series of DMSP, NOAA, and Feng Yun (FY-1, China) are all sun-synchronous, which leaves portions of the Antarctic continent and Southern Ocean without data during a portion of the day. Few non-sun-synchronous satellites are available (the older Russian METEOR polar-orbiting series) to fill such a gap in continuous satellite coverage. A series of ideally three Molniya satellites would be able to not only provide continuous high-resolution imaging and sounding of the Antarctic but would also help to solve the communications problems that have plagued
South Pole station and other inland stations. While the challenges to implementing a series of satellites in Molniya orbits are both scientific and monetary, the potential for improved satellite imaging and sounding of the polar atmosphere would be of great value in Antarctic forecasting.

b. Retrieval data

One of the conclusions from Project FROST was that the satellite imagery was quite valuable, but an improved means of deriving objective data from the imagery is needed (Turner et al. 1999). Current remote sensors such as NOAA AVHRR can provide information about atmospheric properties such as cloud opacity and effective particle size. The capability of TOVS, ATOVS, COSMIC (see section 3e below), and the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite increases the amount of derived retrievals of moisture and temperature that can be made available to the forecaster as well as for the assimilation scheme for synoptic and mesoscale numerical modeling efforts. (See Table 3 for estimated launch dates and instruments). Algorithms for these retrievals must be developed for the Antarctic since most retrieval algorithms are usually used for midlatitude or tropical areas. In addition, substantial validation by special fieldwork will be necessary to have confidence in the derived products (Bromwich and Cassano 2000).

c. Derived product imagery

Based on the current use of satellite data in the Antarctic by operational forecasters, there is a lack of derived products targeted at depicting atmospheric features such as fog and cloud plumes. One possible advancement would be to have items such as a fog product, or cloud detection/cloud plume identification product, made available to forecasters for use at appropriate times. [Fett (1990) discusses some cousin phenomena for the Arctic]. Modern weather services in the mid-latitudes currently enjoy these luxury items (such as GOES-derived product images) that would be of critical value during forecasting situations in the Antarctic. Currently, derived parameters from scatterometers and passive microwave instruments cannot be created on station in the Antarctic, but the information can be computed within a few hours of collection with the geophysical parameters being assimilated into numerical analysis schemes or sent to the Antarctic stations (Turner et al. 2000). With the new satellite sensors, the ability to derive products on station becomes increasingly necessary to take advantage of improved capabilities.

d. Satellite-derived winds

As noted from the lessons learned during the Project FROST study, cloud drift winds for the high southern latitudes would be valuable (Turner et al. 1999). Currently, the winds are either derived from sequences of NOAA AVHRR images (if at all) or more commonly from stretched imagery from the geostationary satellites. Scatterometers on ERS-1, ERS-2, and ADEOS also provide wind measurements that can help with analyses over the southern Pacific Ocean and are especially useful for ships. The NASA Quick Scatterometer (QuikSCAT) satellite is also used to observe ocean surface winds (Turner and Pendlebury 2000). As with other derived products, the ability to have satellite-derived winds available for actual use as well as input for numerical modeling efforts is important. Work begun by J. Key (2001, personal communication) and others hopes to show the ability to derive quality winds from MODIS on the Terra and Aqua satellites. Figure 5 shows an example of these derived winds over the Ross Ice Shelf. Each wind image is derived from a sequence of three MODIS images with each pair of images 100 min apart (a total of 200 min per wind image). The winds are

<table>
<thead>
<tr>
<th>Estimated launch date</th>
<th>Satellite (orbit), country</th>
<th>Relevant Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>METEOR 3M-1 (polar), Russia</td>
<td>SAGE III, HRPT, MSR, TOMS</td>
</tr>
<tr>
<td>2001</td>
<td>INSAT-3 (geostationary), India</td>
<td>Vis/IR</td>
</tr>
<tr>
<td>2002</td>
<td>NOAA-M (polar), United States</td>
<td>AVHRR, HIRS, AMSU, ATOVS</td>
</tr>
<tr>
<td>2002</td>
<td>MSG-1 (geostationary), Europe</td>
<td>Vis/IR</td>
</tr>
<tr>
<td>2002</td>
<td>ADEOS-II (polar), Japan</td>
<td>Vis/IR</td>
</tr>
<tr>
<td>2003</td>
<td>GOMS (geostationary), Russia</td>
<td>VISSR</td>
</tr>
<tr>
<td>2003</td>
<td>METOP-1 (polar), Europe</td>
<td>IASI, AVHRR, HIRS, AMSU, MHS</td>
</tr>
<tr>
<td>2004 (2008)</td>
<td>NOAA-N, -N’ (polar), United States</td>
<td>Updated instrument base</td>
</tr>
<tr>
<td>2004–08</td>
<td>FY-3A, -B (polar), China</td>
<td>Test sounders</td>
</tr>
<tr>
<td>2005</td>
<td>NPP (polar), United States</td>
<td>VIIRS, CrIS, ATMS, AIRS</td>
</tr>
<tr>
<td>2005</td>
<td>COSMIC (geostationary), United States</td>
<td>GPS/MET</td>
</tr>
<tr>
<td>2009</td>
<td>NPOESS (polar), United States</td>
<td>VIIRS, CrIS, ATMS, ASCAT</td>
</tr>
</tbody>
</table>

* MSR, Multi-channel Scanning Radiometer. SAGE III, Stratospheric Aerosol and Gas Experiment.
determined by tracking cloud features from one image (time) to the next. Vectors are collected into three levels (all the levels are combined in Fig. 5). In the process, the ability to derive synoptic-scale winds from the Wisconsin composites will become a reality. To date, cloud drift winds are used on a limited basis with few Antarctic programs taking advantage of the derived winds that are available or choosing not to use them because of limitations to their southern extension over the Southern Ocean and Antarctic continent.

e. New technology

New meteorological satellite technologies are rapidly emerging. Japan will launch the ADEOS-2 satellite, which will carry the Advanced Microwave Scanning Radiometer (AMSR) for water cycle information, the Global Imager (GLI) for high-precision ocean and cloud observations, and the Sea Winds sensor (SeaWinds) in support of global climatic change studies and monitoring of the ozone hole. The European community will launch a polar-orbiting environmental satellite (METOP) in 2003. The primary task of METOP is to measure the temperature and humidity of the atmosphere and a secondary task is imagery of clouds and weather systems as well as information on ocean system winds. METOP will carry an updated AVHRR for better imagery of clouds and several instruments for improved temperature and humidity profiles [High Resolution Infrared Sounding Unit (HIRS), Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS), and Infrared Atmospheric Sounding Interferometer (IASI)]. In the spring of 2005, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) program will begin with improved GPS/MET-style retrievals of temperature and moisture. The improved information from all of the proposed new sensors for temperature and moisture and the additional and enhanced data for clouds and ocean winds will be invaluable to the forecaster. The large number of soundings available over Antarctica will greatly increase the coverage of observations (Anthes et al. 2000), and assimilation of the soundings into numerical weather prediction models will improve forecasts for Antarctica (Kuo and Ha 2000; Kuo 2000). Additionally, other planned sounders such as the aforementioned AIRS, Ad-
vanced Baseline Sounder (ABS), Advance Baseline Imager (ABI), and Geostationary Imaging Fourier Transform Spectrometer (GIFTS) will offer up to thousands of spectral channels for improved imaging and retrievals of temperature and moisture in the atmosphere (Gurka and Dittberner 2001; Smith et al. 2001).

In the second half of the decade, the National Polar Orbiting Environmental Satellite System (NPOESS) becomes operational with the launch around 2005 of the NPOESS Preparatory Platform (NPP). NPP plans to carry several upgraded sensors including the Visible/Infrared Radiometer Suite (VIIRS), which combines the AVHRR and OLS technologies to provide more channels of information with better resolution; the Cross-track Infrared Sounder (CrIS) for temperature and moisture profiles using 1000 channels with 1-K resolution; and the Advanced Technology Microwave Sounder (ATMS) with improved AMSU technology. All of this new technology and rapid growth needs to be extended to the Antarctic. There is enormous potential that these new developments will be of great value both directly and indirectly to the Antarctic weather forecaster. Steps need to be taken now to ensure that access to the data and associated derived products from these new platforms will be available for improving numerical weather predictions for the Antarctic.

5. Summary and conclusions

The Antarctic has greatly benefited from the advent of modern meteorological satellites. Operational satellite imagery began with daily polar-orbiting-only mosaics (Bristol et al. 1966; Wiesnet et al. 1980). Later satellites with better-resolution imagery provided enough information for use in operational forecasting. More recently geostationary and polar-orbiting mosaics have been combined to make near-real-time Southern Hemisphere (south of 40°S) composites (Stearns et al. 1999). Most of the currently manned Antarctic stations receive HRPT data for use in their forecasting activities.

The arrival of science quality satellite imagery and the information from temperature and water vapor profiles allowed forecasters and researchers to begin to examine smaller-scale features such as mesoscale vortices, fog, and katabatic winds, which are difficult to forecast. Intensive studies such as FROST and meetings such as the First International Symposium on Operational Weather Forecasting in the Antarctic have led to better documentation on the use and effectiveness of weather satellites for predicting the onset of some of these smaller-scale features.

In addition to meteorological forecasting problems, forecasting operations face other logistical problems. Any decrease in coverage or availability of satellite imagery greatly impacts operations. A lack of computer resources and/or high performance communications links continues to limit the amount of information available to the forecasters. Temperature, moisture retrievals, and cloud drift winds are very useful for forecasting, but these products are usually derived at other locations off the Antarctic continent, making it difficult for forecasters to receive them in a timely fashion. With the launch of new satellites and improved sensors along with higher transmissions rates, stations responsible for regional forecasts will need to upgrade their receiving stations and/or equipment. It will also be necessary, in the not too distant future, to enable forecasters to run local or regional numerical prediction models employing satellite data on station.

Acknowledgments. This work was supported by the NSF Office of Polar Programs, Ocean and Climate Program Grant OPP-9908842. Thanks are also extended to David H. Bromwich of The Ohio State University for organizing this special section of the Monthly Weather Review. Finally, thanks to everyone who helped with information on the present uses of meteorological satellite data and imagery in the Antarctic, especially Steve Pendlebury, Alberto Setzer, Tom Lachlan-Cope, John Turner, Art Cayette, Andrea Pelligini, P. F. Coppola, and Victor Lagun.

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