NOTES AND CORRESPONDENCE

On the Reanalysis of Southern Hemisphere Charts for the FROST Project

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ABSTRACT

An overview is presented of the analysis procedures and problems encountered in the FROST reanalysis of weather charts poleward of latitude 50°S carried out in Hobart by the Australian Bureau of Meteorology, with advice from the Institute of Antarctic and Southern Ocean Studies. A summary of findings as a result of the FROST exercise is given and some topics for research projects in the future are identified.

1. Introduction

The Working Group on Physics and Chemistry of the Atmosphere (PACA) of the Scientific Committee on Antarctic Research (SCAR) initiated the concept of the Antarctic First Regional Observing Study of the Troposphere (FROST; see Turner et al. 1996). The Hobart office of the Australian Bureau of Meteorology, the Institute of Antarctic and Southern Ocean Studies and the Antarctic Cooperative Research Centre at the University of Tasmania, the British Antarctic Survey (BAS), and the Byrd Polar Research Center at The Ohio State University combined to implement the FROST plan. FROST was designed to assess the quality of numerical weather analyses and prognoses over the Antarctic continent, its surrounding ice shelves, and the seasonal sea ice zone. A goal of FROST was to produce high-quality surface and upper-air analyses, using as the starting point analyses or initial conditions in operational global weather prediction models run by the U.K. Meteorological Office (UKMO) or the Australian Bureau of Meteorology's Global Assimilation and Prediction (GASP) system. The plan was to produce revised analyses in the light of data and satellite imagery not available in real time (Hutchinson 1996). Different procedures were adopted for the reanalysis over the Southern Ocean, East Antarctica, and West Antarctica. A schematic diagram of the FROST analysis technique is given as Fig. 1. This paper discusses the effectiveness of the analysis techniques employed and presents some preliminary findings.

a. Scientific background

The first significant attempt to define an objective diagnostic analysis technique from Southern Hemisphere satellite imagery was made by Martin (1968), and Zillman (1969) comprehensively demonstrated the application of his technique. Troup and Streten (1972) developed a classification scheme for cloud vortices southward of latitude 20°S using visual imagery from polar orbiting satellites. In this application of cloud signature techniques to the analysis of extratropical cyclones over the Southern Ocean, models for various

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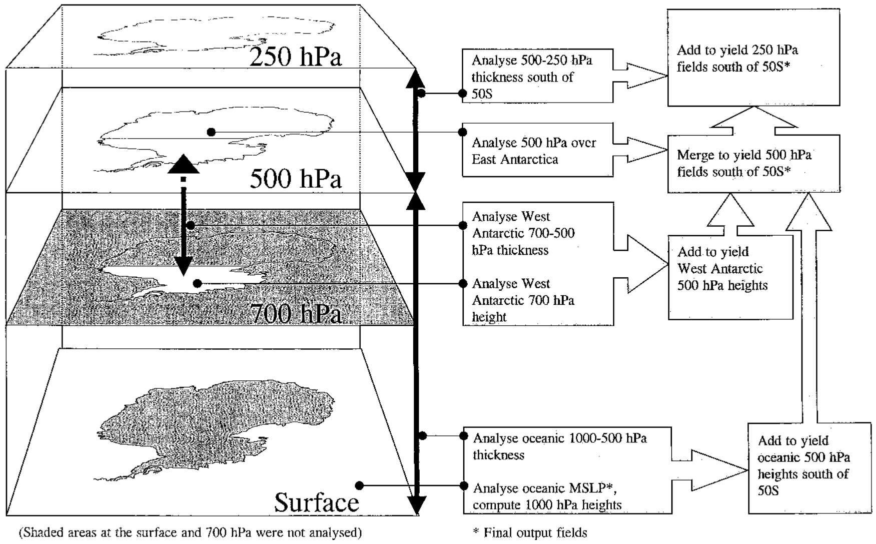

FIG. 1. Schematic of FROST analysis routine.

vortex types were expressed in terms of anomaly patterns of mean sea level pressure (MSLP), and 500- and 300-hPa geopotential height. Such models found application in the analysis technique used in data-void areas of the FROST domain. Evans et al. (1994) proposed a satellite-based classification scheme to differentiate between various types of rapid maritime cyclogenesis in the western North Atlantic region. This scheme was derived from signatures in visible and infrared satellite imagery. The technique for layer thickness analyses from satellite imagery reported by Guymer (1978) gives a method whereby objective analysis of 1000–500-hPa layer thickness can be performed in the absence of high confidence measurements from upper-air temperature and pressure soundings.

b. Forecasting

Adams (1997) examined model prediction performance over the Southern Ocean and coastal region around East Antarctica. A comparison of skill scores for the European Centre for Medium-Range Weather Forecasts (ECMWF) MSLP prognosis and the Antarctic Meteorological Analysis at Casey station in Antarctica over the summers of 1993/94 and 1994/95 showed that forecasters were able to produce minor improvements in forecast skill over numerical guidance. However, a preliminary study of numerical model skill for the period June 1994–January 1996, although highlighting steady improvement in model performance, found the outputs of global numerical weather prediction models to exhibit low forecasting skill over the East Antarctic sector and adjacent Southern Ocean. A major source of error appears to stem from the base analyses used by the models.

2. The FROST special observing periods

FROST data were collected for three special observing periods (SOPs): SOP-1 in July 1994, SOP-2 from 16 October to 15 November 1994, and SOP-3 in January 1995. To ensure that as complete a set of observations as possible was compiled, two nodes of the Global Telecommunications System (GTS)—at Bracknell, United Kingdom, and Melbourne, Australia—were used to collect data during SOP-1, SOP-2, and SOP-3. As discussed in Turner et al. (1996), both locations received about the same number of surface synoptic observations (SYNOPs), but many of these were received at one site only. When the data from both locations were merged, the new dataset contained about 30% more observations than were received at either location. This merged set was then further supplemented by non-GTS observations received from contacts in the agencies responsible for operating the national meteorological observing programs in the Antarctic.

The three 1-month periods of special observations provide a valuable database in themselves. All data gathered in real time via the GTS and subsequently by other means for the FROST SOPs, for example, the Defense Meteorological Satellite Program (DMSP) imagery, have been archived as part of the FROST dataset and are readily available to research scientists.

3. The FROST reanalysis method

Although there were three SOPs in FROST, the reanalysis of weather charts has been confined to SOP-1 and -3. SOP-2 data were collated for those researchers looking into aspects of the meteorology of the ozone hole breakup or who may have a particular interest in the meteorology of the transition between winter and summer. FROST reanalysis meteorologists faced a heavy workload in coping with full reanalysis of weather charts from SOP-1 and -3, and reanalysis was therefore split into three components.

- ''FROST SOP-1 analyses'' refer to the initial reanalysis of all of the information that could be assembled for SOP-1 at the time. Satellite imagery—the University of Wisconsin, Madison mosaics (Stearns et al. 1995)—was used either from screen display or in printed form.
- Subsequent to the FROST workshop of 16–17 March 1995, MSL charts for the period 22–28 July 1994 were again reanalyzed with intensive application of DMSP satellite imagery. These are referred to as ''FROST SOP-1 special week analyses.''
- In reanalysis of SOP-3 data it was decided to examine a reduced period (19–25 January 1995).

a. *Southern Ocean: MSL pressure analyses*

Over the ocean areas, the MSLP charts were redrawn for each day of SOP-1 for 0000, 0600, 1200, and 1800 UTC, over the ocean area south of latitude 50°S, including the Ross and Ronne Ice Shelves. These postanalyses were based on the computer-drawn UKMO real-time analyses and consideration of the operational charts from the Australian National Meteorological Centre (NMC). The UKMO analyses include plots of 500-km-wide swaths of scatterometer wind vectors. Data used in the reanalysis consisted of standard SYNOPs, ship observations, drifting buoy data, and automatic weather station (AWS) observations. In SOP-3 the MSLP analyses were constructed for 0000 and 1200 UTC, while taking account of data plotted for the intervening hours.

Where there was concurrence between the two analysis centers then changes were only made to the analyzed field if late data revealed necessary modification. If there was a conflict of opinion, or if it became evident that neither analysis was correct in a particular sector of the FROST area, a decision on the correct version of the analysis in that sector was made as objectively as possible.

There are usually no surface measurements (as was the case in SOP-1) of atmospheric parameters over the Pacific Ocean south of latitude 40°S, between the longitudes of New Zealand and South America. On the Antarctic coast there is a data void between Siple Island near 125°W and the Antarctic Peninsular. Two drifting buoys deployed by Australia moved east of the date line prior to mid-October 1994. Four other drifting buoys were deployed by the United States in a network of about 500-km spacing over the Southern Ocean, well east of New Zealand longitudes, prior to the commencement of SOP-2. Accordingly a well-spaced array of six drifting buoys was available during SOP-2 between 175°E and 120°W and from 48° to 58°S.

The array of drifters had moved so that by the end of SOP-3 all six were still operating and were still providing a good operational network, being located between 175° and 100°W and from 46° to 57°S. These data are important because West Antarctica and the southeast Pacific sector of the Southern Ocean are possibly the most important region for seeking evidence of a link between the Antarctic atmosphere and the phase of the El Niño–Southern Oscillation (Van Loon and Shea 1987; Smith and Stearns 1993; Cullather et al. 1996).

Any data in the merged FROST dataset not received and plotted in real time were sent after the relevant SOP, in tabular or graphical form, from BAS to the Australian Bureau of Meteorology in Hobart, for incorporation in the FROST analyses.

The reanalyzed surface charts included frontal positions based on satellite data, as well as the available surface data. The satellite imagery available for the whole month of July 1994 included polar stereographic composite images covering the area south of 40°S produced every 3 h by the University of Wisconsin—Madison (Stearns et al. 1995), together with imagery from the geostationary satellites GMS and Meteosat, as well as GOES-West, which was of value at more northerly latitudes.

The great importance of satellite imagery became clear in the production of the surface fields; hence, efforts were made to acquire very high-resolution imagery to further refine the analyses over the ocean. Because of the effort required to process and utilize the high-resolution imagery, one week of FROST analyses, covering the period 22–28 July 1994, were drawn for a second time. The analyses were further refined over the Eastern Hemisphere only (Greenwich meridian through east to 180°). Additional data used included visible and infrared DMSP imagery, which have a horizontal resolution of 2.7 km, along with extra AWS data over West Antarctica (C. R. Stearns 1995, personal communication). Also 12-km resolution quick-look compressed Advanced Very High Resolution Radiometer (AVHRR) images received via the Casey High Resolution Picture Transmission (HRPT) antenna were available. Due to an archival malfunction at Casey, and incompatibility of the McMurdo archive format with Australian Bureau of Meteorology workstations, AVHRR 1-km resolution imagery from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites was not available to the FROST analysts for SOP-1.

MSLP analyses for 0000 and 12 UTC digitized to a 1.25° × 1.25° latitude–longitude array were used to derive 1000-hPa geopotential heights (mostly negative over the Southern Ocean) using the hypsometric formula:

$$Z = K(273 + T^*)(\ln\mathrm{MSLP} - \ln 1000), \qquad (1)$$

where Z is the depth of the layer between the MSLP and 1000 hPa, K is the hypsometric constant, and T^* is the mean virtual temperature of the layer. The mean virtual temperature (T^*) of the atmospheric layer between MSL and 1000 hPa (fictitious over most of the area south of latitude 50°S) was assumed to be represented by the monthly zonal mean surface air temperature (1972–91) obtained from the Australian NMC analysis set, which is regarded as accurate for the Southern Ocean (Trenberth 1979; Pook 1992).

b. Southern Ocean: 1000–500-hPa layer thickness

The overall ''shape'' of the computer-drawn Australian GASP model and UKMO model (when available) 1000–500-hPa thickness analyses, including the Ross and Ronne Ice Shelves and West Antarctica, were first considered. FROST 1000–500-hPa fields were constructed for the same areas as those for MSLP, using TIROS Operational Vertical Sounder (TOVS) data obtained from the GTS in satellite-coded messages (SATEMs), and the very sparse network of radiosonde upper air-soundings. TOVS data were plotted on a 1:20 million polar stereographic projection at 6-hourly intervals—0000, 0600, 1200, and 1800 UTC. Finally FROST analyses for 0000 and 1200 UTC were completed taking account of all data.

MSL pressure and 1000–500-hPa layer thickness analyses were checked for spatial and temporal consistency before digitizing. The 500-hPa height fields were computed from the summation of 1000-hPa geopotential heights and 1000–500-hPa thickness values.

c. West Antarctica: Analysis of 700-hPa geopotential height

There were no occupied stations within West Antarctica during any of the special observing periods, so no upper-air sounding data (wind and temperature measurements) were available. Phillpot extended his earlier work on the derivation of 500-hPa heights above East Antarctica (Phillpot 1991) to estimate the geopotential height above sea level of the 700-hPa pressure surface at the location of Byrd station (Phillpot 1997). The 700-hPa level is above the ice sheet surface that constitutes West Antarctica, and it provides a satisfactory constant pressure surface on which to build layer thickness values obtained from SATEMs.

Using Byrd (1530 gpm) upper-air soundings made during the International Geophysical Year (IGY) in 1957–58, a linear regression equation was formulated (Phillpot 1997) from which 700-hPa height can be satisfactorily estimated using surface pressure and air temperature data and the height above sea level; this approach was applied to observations from the Byrd AWS (80°S, 120°W). This approach is similar to the method (Phillpot 1991) derived for estimating 500-hPa height from high-elevation AWS sites in East Antarctica. This technique cannot be applied to stations near MSL. However, tests with radiosonde observations at Little America, a coastal station near the edge of the Ross Ice Shelf using IGY data, suggest that acceptable estimates of the 700-hPa height can only be made from surface observations at elevations of 1000 m or more. AWSs were installed at sites Harry and Theresa (both at approximately 1500 m above sea level) during November 1994, providing data for SOP-3 analyses, along with that from the Uranus Glacier site. Although other stations were installed, they were not used because of elevation problems; they were either too low in elevation for application of the Phillpot technique or there were inconsistencies between reported surface pressures and stated elevations (Cowled 1997).

d. West Antarctica: 700–500-hPa layer thickness fields

These analyses were constructed from the TOVS data obtained from SATEMs distributed on the GTS and plotted on FROST charts at 6-hourly intervals. Using the 0000 and 1200 UTC 700–500-hPa thickness analyses and the 700-hPa height analyses, the 500-hPa contour fields were then produced manually, avoiding unnecessary digitization.

e. East Antarctica: Analysis of 500-hPa geopotential height fields

The main reanalysis effort over East Antarctica was directed toward producing improved 500-hPa height fields, because this pressure surface is everywhere above the topography of the Antarctic continent, and 500-hPa heights estimated from surface data (Phillpot 1991) can be used over the high interior to supplement the coastal radiosonde observations. A series of twice-daily 500-hPa contour fields was constructed over East Antarctica for the first and third SOPs (July 1994 and January 1995).

Analyses for SOP-1 were drawn independently of the output from operational runs of global models using the high-elevation AWS pressure and temperature method to supplement measurements of geopotential height from the upper-atmospheric network of sounding stations along the coast of East Antarctica. This proved to be a most time-consuming exercise because of delayed data receipt, and uncertainties such as those associated with faulty pressure sensors on some AWSs. The first station to be installed by the United States in a network of Automatic Geophysical Observatories (AGOs) was AGO4, at about latitude 82°S, longitude 97°E with an elevation of 3565 m. The availability of non-real-time data from AGO4 provided some compensation for the absence of operational upper-air temperature soundings from Vostok (78°S, 107°E; 3488 m above sea level), which ceased in 1992. The new Japanese station Dome Fuji (near 77°S, 40°E, and at 3810 m above sea level) about 1000 km inland from Syowa was established in December 1994 for three years, and was another useful part of the basic synoptic weather network reporting on the GTS, during SOP3.

In the reanalysis of SOP-3 data, Phillpot used the radiosonde-determined geopotential heights of the 500-hPa pressure surface to verify the GASP analyses in the coastal zone instead of doing a completely independent application of his technique over East Antarctica as was the case in SOP-1. He determined spot values by the regression method, from some 14 AWS- and AGO-observed values of surface pressure and temperature, to modify, as necessary, the operational 500-hPa height fields produced by the Australian GASP model.

f. Area south of latitude 50°S: 500-hPa contour fields

The analyses for the whole area south of 50°S were first formed by merging the West and East Antarctic continental fields; these were digitized and merged with the oceanic 500-hPa fields (themselves formed by integrating the oceanic 1000-hPa contour field and the 1000–500-hPa thickness fields).

g. Area south of latitude 50°S: 500–250-hPa layer thickness fields

These analyses were constructed for the entire area south of latitude 50°S using the TOVS data contained in SATEMs, plotted on standard FROST charts at 6-hourly intervals, to produce 0000 and 1200 UTC FROST analyses. Quality control was performed through checking of vertical consistency of analyses and through ensuring temporal continuity of troughs and ridges from one analysis to the next. Attempts were also made to calibrate remotely sensed data with the very sparse data from the network of balloon-borne radiosonde stations.

h. Area south of latitude 50°S: 250-hPa height fields

The 250-hPa geopotential height contour analyses were formed by the addition of the 500-hPa height analyses and the 500–250-hPa layer thickness fields.

i. The final FROST products

The revised fields are currently being digitized in a 1.25° × 1.25° latitude–longitude array of data and will be made available in gridded binary (GRIB) code format. A table of the analyses that have been produced in machine-readable form is given in Table 1.

The output fields are designed to describe the troposphere over the whole domain poleward of latitude 50°S. MSLP fields and 1000–500-hPa atmospheric layer thickness fields are not physically real over the Antarctic continent (because of the high-altitude ice sheet). The summation of the intermediate fields (oceanic 1000-hPa geopotential height and 1000–500-hPa layer thickness analyses) gives an oceanic 500-hPa field, providing a physical representation of the lower troposphere at high latitudes over the Southern Ocean. To produce the final output of 500-hPa contour fields over the whole domain south of latitude 50°S, a linear weighting function, within 5° of latitude of a numerically defined coastal boundary, was used to merge the continental 500-hPa fields with the oceanic 500-hPa field.

TABLE 1. FROST analyses—digitized fields poleward of latitude 50°S.

Intermediate fields	Final output fields
Oceanic 1000-hPa heights	Oceanic MSLP
Oceanic 1000–500-hPa thickness	500-hPa heights
Antarctic continental 500-hPa heights	250-hPa heights
500–250-hPa thickness	

4. Discussion of issues arising during the analysis

Analysis of FROST SOP-1 charts commenced in earnest in Hobart in September 1994 with one full-time analyst. A second person joined the FROST project in February 1995. There were systematic errors discovered in vertical profiles of wind velocity reported in real time by several upper-air sounding stations. These caused inordinate delays. An intermittently faulty algorithm for calculating wind shears (when winds decreased with height and were directionally within 90°), in the computer of the Regional Operational System in Hobart was discovered.

During SOP-1 radiosonde data were obtained from 19 stations within, and just outside, the FROST area of interest. Of those 19 stations only 10 provided twice-daily measurements. Over vast areas of the Southern Ocean information from satellite-borne instruments was the only source of mid- and upper-level atmospheric data for the FROST reanalysis project. Thus NOAA/National Environmental Satellite, Data and Information Service (NESDIS) TOVS data were a fundamental component in the construction of the analyses for the 500- and 250-hPa levels.

During SOP-1 radiosonde measurements from 19 Antarctic and sub-Antarctic stations (see Fig. 2) were compared with over 39 000 TOVS thickness estimates for 1000–500-, 700–500-, and 500–250-hPa layers. Each TOVS thickness value is labeled either *high confidence* (flagged as 9 in the SATEM code), *low confidence* (flagged as 1 in the code), or as *confidence unspecified* (coded as 0). The low-confidence data appeared relatively infrequently. Comparison was made between radiosonde-measured atmospheric thickness data and TOVS-derived thickness data within close distance and time proximity (500 km and 2 h). Approximately 2800 TOVS estimates of 500–250-hPa thickness satisfied these distance and time criteria. The number of data from lower thickness layers was reduced over elevated ice sheets of East and West Antarctica.

TOVS thickness data for the 1000–500-hPa layer

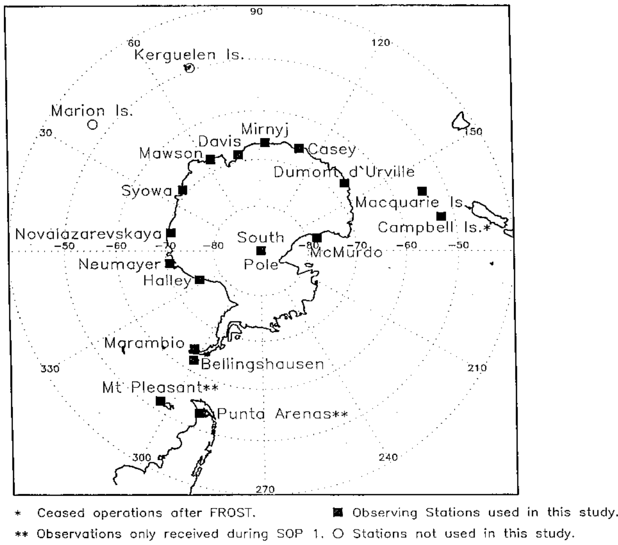

FIG. 2. WMO network of upper-air sounding stations.

over the Southern Ocean and the Guymer (1978) technique were integral parts of the production of the 500-hPa geopotential height contour analyses over the Southern Ocean, an area that would otherwise be almost devoid of data. Apart from stations on the Antarctic continent, a maximum of only four staffed stations routinely launched balloon-borne upper-air radiosondes south of latitude 50°S during FROST. They were Macquarie Island, Campbell Island (800 km northeast of Macquarie Island), Punta Arenas (southern tip of Chile), and Mount Pleasant (Falkland Islands and 1000 km from Punta Arenas); see Fig. 2. The upper-air sounding station on Campbell Island was closed by the New Zealand Meteorological Service after SOP-1 in October 1994 (after determining that the data had insufficient impact on the accuracy of predictions obtained as output from global models). Bellingshausen and Marambio (separated by 300 km on the Antarctic Peninsula and approximately 1500 km from Punta Arenas) were also representative of the nearby Southern Ocean.

Over the Southern Ocean TOVS gave a denser and higher confidence data array than over the continent. The 1000–500-hPa layer information was found to be reasonably coherent. Great reliance was placed on this because of the very sparse network of upper-air temperature soundings available to represent the Southern Ocean south of latitude 50°S. Without TOVS data there would be vast expanses of the atmosphere above the Southern Ocean completely devoid of any upper-air data.

a. Southern Ocean

An attempt was made to check the discovered data available for each of the levels analyzed. This led to the manual plotting of AWS data, mainly at or near MSL not available during the data collection phase. For the oceanic thickness analyses (1000–500 and 500–250 hPa), each observation had to be checked manually for plotting errors, and missing data entered where possible (mostly for the BAS Antarctic station Halley, Mount Pleasant Airport on East Falkland Island, and Punta Arenas in Chile).

1) MSL PRESSURE FIELDS

These analyses were based on the UKMO analyses, with an attempt made to improve the result from additional satellite information. For the initial analysis, low-resolution (10 km) mosaics of satellite images from the University of Wisconsin—Madison were used to locate circulation centers and other features of the 1000–500-hPa layer thickness, using Guymer's (1978) technique. Conceptual models of the relationship between the MSL airflow and the 1000–500-hPa thickness pattern were then employed to position cold fronts, the axes of troughs and ridges lines and centers of low and high pressure systems. Drifting buoy data also assisted in the analysis of the MSL charts, although it was necessary on occasion to look at time series data from the buoys to assess the probability of errors.

At the FROST workshop in Hobart in March 1995, it was decided that little value had been added to the initial UKMO analysis. The special week of SOP-1 mentioned earlier was selected for closer scrutiny, and during the following months, an attempt was made to establish the limits of confidence to be placed on AWS data. Furthermore, DMSP imagery was obtained. Appropriate software for the visual and infrared DMSP data display was also obtained and modified for local use. Although a number of HRPT receivers are in use in Antarctica, it was difficult to translate their data into a form for local use.

The high-resolution DMSP data (2.7 km) revealed the location of a number of low pressure centers ~100 km or less in diameter, undetected on previous analyses, and on one occasion revealed a low crossing the Antarctic coast and proceeding inland. High-resolution images showed atmospheric features not seen in the mosaics, for example, cloud streets in air masses immediately downwind of the ice edge, which revealed surface wind direction and low-level wind shear. Jet streams were also easier to detect, because the high-resolution visual imagery very often showed cloud shadows on lower clouds, even in moonlight.

In general, DMSP satellite imagery was the most valuable source of data. In most cases, the UKMO analyses, used as first guess fields, needed little change except where late data were available to FROST analysts, for example, from Mount Siple and Possession Island.

The UKMO and Australian National Meteorological Center analyses differed markedly at times. For example, at 1200 UTC on 6 July 1994 a low near 70°S, 100°W was analyzed as having a central pressure of 948 hPa by the UKMO and above 970 hPa on the Australian product.

2) THE 1000–500-HPA LAYER THICKNESS FIELDS

These charts were analyzed with reference to upper wind, TOVS, and satellite imagery data. Again, Guymer's (1978) techniques were used in an attempt to maximize the use of satellite data. Good correlations were obtained between SOP-3 TOVS data and radiosonde data from Macquarie Island; hence, the TOVS data were the main source for these charts. DMSP images were again used to refine the positions of thermal jets and positions of thermal minima.

3) THE 500–250-HPA LAYER THICKNESS FIELDS

TOVS and radiosonde data were used to prepare the FROST SOP-1 and SOP-3 analyses, with few changes made for the SOP-1 special week reanalysis. TOVS data were supplied in the form of a text file from which the observations were plotted. Each observation was supplied with a reliability estimate: high, low, or unassigned. Good correlations were found between high- (and unassigned) reliability TOVS data and nearby radiosonde data over the oceans, although poorer correlations were found near the Antarctic coast. Over the oceans TOVS data were considered as mostly reliable, especially those data so designated.

Satellite images were used to supplement the data, since they often permitted accurate location of jet streams. Use of TOVS data alone would not have allowed analysis of jet maxima, because of poor resolution. Satellite images could not be used alone for placement of thermal jets, because of the lack of a clear relationship between 500–250-hPa shears and satellite imagery.

b. East Antartica

1) THE 500-HPA FIELDS

The FROST monthly mean 500-hPa contour field over East Antarctica for July 1994 (SOP-1) showed greater than normal geopotential heights compared to long-term winter mean heights. The monthly mean field for January 1995 (SOP-3) was markedly below normal.

The 500-hPa chart sequence for SOP-1 showed that the broad-scale 500-hPa contour fields over the Antarctic region obtained from the ECMWF, the UKMO, and the Australian GASP models were all reasonably consistent. The trough and ridge systems could be identified moving around the polar vortex; the movement was fairly regular in a west–east sense north of about latitude 60°S, but systems poleward of 60°S and over the Antarctic continent moved much more slowly. Accordingly, changes in alignment occurred between pressure systems at the two latitude bands. There was little clearly defined movement of continental lows observed in the analyses.

2) THE 500–250-HPA LAYER THICKNESS FIELDS

These analyses, unlike the 1000–500-hPa layer thickness analyses, were extended to include the Antarctic continent. Some problems were encountered, however, with some data from both McMurdo and the South Pole not finding their way to either Bracknell or Melbourne nodes of the GTS during SOP-1. It was also found that some profile data from the South Pole showed unrealistic variations in speed and direction with height.

A comparison between Amundsen-Scott (South Pole) radiosonde data and nearby 500–250-hPa TOVS data during SOP-3 yielded a correlation of slightly under 0.6 between the two datasets, significant at the 1% level, but the linear fit had a slope of about 0.3. The effect of this slope was to associate a range of 16 dm (444–460) in the TOVS data with a range of 4 dm (458–462) in the radiosonde data. Thus, although TOVS data were used to attempt to locate minima over East Antarctica, little credence could be given to the value of the minimum suggested by the TOVS data. Instead, minima were estimated by maintaining continuity of gradients suggested by geostrophic shear calculations, using the available shears, and by correcting the central values according to the linear relationship mentioned above. A more comprehensive discussion on the performance of TOVS retrievals over the Antarctic continent is given by Adams et al. (1999).

c. West Antarctica

1) THE 700-HPA FIELDS

In section 3c above it was explained how the technique developed by Phillpot (1991) to estimate 500-hPa heights from surface pressure and temperature data at high-elevation AWS sites in East Antarctica was adapted to estimate 700-hPa heights over West Antarctica.

Radok and Brown (1996) reported a related technique for the calculation of 500-hPa heights from station-level data. This was modified by the FROST analyst at the time and applied to the estimation of 700-hPa data over West Antarctica for comparison with the Phillpot technique. Little difference was found between the two sets of results, and the Phillpot technique was retained to preserve continuity with earlier work on the FROST project.

Unfortunately, only the Byrd AWS was available over the inland ice sheet for the SOP-1 analyses; hence, they were prepared with the benefit of only one additional observation over those routinely available from sites adjacent to West Antarctica, that is, South Pole, McMurdo, Marambio, Bellingshausen, and Halley. Although the analyses will probably support a view that the month was characterized by unusually low geopotential height over West Antarctica, it is a generalization using data from one central point.

For SOP-3, more AWS data were available, but attempts to correlate the observed pressures to check their reliability showed that the published elevations of the AWS units were uncertain (C. R. Stearns 1996, personal communication). Byrd, occupied for nearly 20 years, appears to be best known, but the remaining station elevations depend on the altimeter of the installation aircraft. It is hoped that corrections will become available as the AWS units are revisited for maintenance, but at the time of reanalysis, no corrections were available. An attempt was made to correct the elevations on the basis of pressure variations during periods of light winds, but it is doubtful whether light winds are necessarily correlated with weak synoptic pressure gradients in Antarctica. Once again, the SOP-3 700-hPa analyses rely heavily on Byrd, since this station was used to check the consistency of data received from other AWS stations.

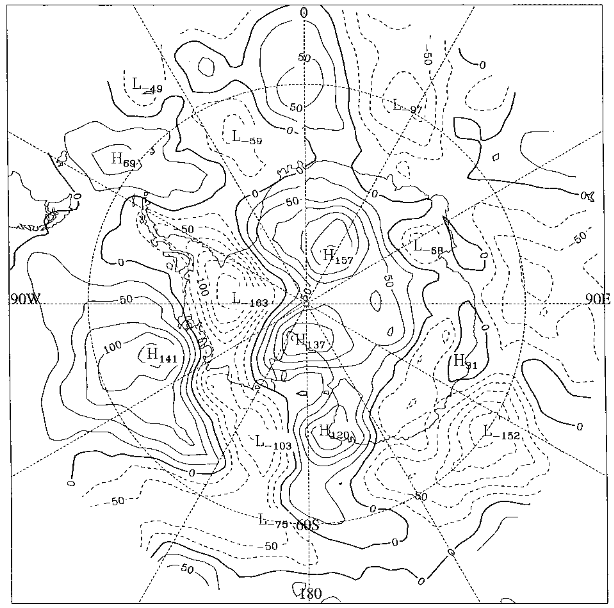

FIG. 3. FROST minus GASP 500-hPa analyses (geopotential height in m) at 0000 UTC 26 Jul 1994.

2) THE 700–500-hPA LAYER THICKNESS FIELDS

The TOVS data were used exclusively, apart from the margins of West Antarctica where the nearest radiosonde observations to West Antarctica can influence the boundary conditions. An attempt to correlate 700–500-hPa TOVS thickness with Amundsen-Scott radiosonde observations for SOP-3 gave poor results, but better correlation was found between 700–500-hPa TOVS thickness and a linear interpolation between Halley and Amundsen-Scott radiosonde observations. Thus TOVS 700–500-hPa thickness data were used over West Antarctica, but not in the vicinity of Amundsen-Scott station.

3) THE 500-HPA FIELDS

It was originally intended that the addition of the 700-hPa height and 700–500-hPa thickness fields would be accomplished from the digitized fields. It was felt, however, that better continuity with the East Antarctic 500-hPa analyses would be achieved by manual addition of the fields and manual blending of the analyses. This procedure was followed for both SOP-1 and SOP-3 data. The merging of the analyses for East and West Antarctica presented few difficulties, reassuring in view of the complete independence of the two techniques used to derive them. The seamless integration was aided by the two sets of analyses being constrained by upper-air soundings made at 12- or 24-h intervals from three staffed stations near the 0°–180° meridian (Novolazarevskaya, Amundsen-Scott, and McMurdo) that were communicating on the GTS during FROST.

4) THE 500–250-HPA LAYER THICKNESS FIELDS

Although the area covered by the West Antarctic ice sheet is much smaller than that of East Antarctica, the caveats raised above for the 700–500-hPa thickness analyses in the continuation of the analysis southward over the ice sheet to the pole are equally relevant. TOVS 500–250-hPa thickness data were not used near the Amundsen-Scott station at South Pole. SOP-3 data from Halley Station were not received until January 1997. Analysis could not commence until these data were received, because the only other stations available were Amundsen-Scott, McMurdo, Terra Nova Bay (during SOP-3), and the Antarctic Peninsula stations, leaving West Antarctica almost totally devoid of radiosonde data. Halley data were essential, both to allow analysis of the charts and to investigate the reliability of the TOVS data.

d. Final output fields

Figure 3 shows an example of the differences in geopotential height (m) between FROST and GASP analyses at 500 hPa (FROST minus GASP) for 0000 UTC on 26 July 1994, during SOP-1. At that particular time the GASP analysis was greatly different over the central plateau areas of West and East Antarctica, due to application of the Phillpot 700- and 500-hPa techniques and the incorporation of any 700–500-hPa layer thickness TOVS data over West Antarctica that may have been rejected by the global model. For a large area of the continental interior of East Antarctica FROST 500-hPa geopotential heights were higher than GASP with differences of up to +157 m. Over West Antarctica the differences were negative and as great as −163 m.

In this example, the real-time operational analysis from the Australian GASP model substantially differs from the corresponding FROST 500-hPa analysis over the Southern Ocean. This was caused by the FROST analyst drawing larger-amplitude troughs and ridges in the MSL pressure analysis based on subjective interpretation of satellite imagery. The only additional data available at 0000 UTC on 26 July 1994 were 1000–500-hPa thickness values from Gough Island, Punta Arenas, Mount Pleasant, Halley, and Neumayer radiosonde stations; these were not reported in the TEMP message and hence were missing in the real-time plotting of charts in Hobart and from the Bracknell–Melbourne merged dataset. Layer thickness values for these stations were calculated by the FROST analyst from the other information available in the TEMP messages. However, the FROST 1000–500-hPa layer thickness analysis over the Southern Ocean at 0000 UTC 26 July was not significantly different from the corresponding operational analysis that was available in real time.

5. Concluding comments

The reanalysis exercise was most useful in allowing the value of various types of data to be assessed and in providing information on our current capability to prepare analyses for the high-latitude areas of the Southern Hemisphere. Some findings include the following.

- High-resolution satellite imagery (AVHRR or DMSP) is vital in providing details on the locations of frontal systems over the Southern Ocean and in resolving the finescale structure of the mesocyclones often found off the coast of Antarctica.
- Meteorological data from conventional AWSes and from the AGOs are of great value for analysis over the continent. Further efforts should be made to ensure that quality controlled observations are transmitted on the GTS in a timely fashion (Phillpot 1997; Pook and Cowled 1999, this issue).
- The Phillpot (1991) technique was found to be very useful for preparing 500-hPa-level height charts over East Antarctica and greatly improved our knowledge of synoptic-scale variability over East Antarctica during SOP-1 and -3 (Phillpot 1997).
- The Phillpot (1997) technique for calculating 700-hPa geopotential heights over West Antarctica from surface temperature and pressure data from AWS, at elevations greater than 1000 m above sea level, was a significant finding.
- During SOP-1 high-confidence TOVS data were found to be of highest quality, particularly over the ice-free Southern Ocean. However, data flagged as low confidence and confidence unspecified were shown to be of some value to the FROST project. The comparison of TOVS with radiosonde measurements for SOP-1 indicated that TOVS could be used as a sole source of data where necessary over remote ocean areas. Data inaccuracies over the ice surface (land and sea) near the Antarctic coastline were detected (Jacka 1995).
- The TOVS retrievals made over oceanic regions south of latitude 50°S appeared to be in good agreement with radiosonde data, although there appeared to be some bias toward poor TOVS data for lower thickness values. Retrieval of TOVS data over continental areas, in general, appeared to perform poorly, although seasonal variations in performance of the retrieval technique need further study. The limited datasets for near the South Pole suggest that continental TOVS for July 1994 were useful. However, during SOP-2 when the polar vortex was beginning to break down in spring, TOVS retrievals appear to have been highly suspect, with a strong bias toward underestimating thickness values. It is still not clear whether the poorer accuracy of TOVS data over the continent during spring is a function of the radiance information itself or the retrieval scheme employed by NOAA/NESDIS at the time (Adams et al. 1999).
- Relatively low confidence was held in the TOVS data compared with the balloon-borne radiosonde vertical profiles available from 14 sites on the Antarctic continent, mostly around the coast. However, TOVS data for the 700–500- and 500–250-hPa atmospheric layers over the Antarctic were required to fill the meteorological data gaps in both in the horizontal and vertical (Adams et al. 1999).
- SOP-1 was completed in July 1994 and provided a unique opportunity to assemble a comprehensive dataset for the Antarctic region. Data obtained from this intensive collection effort have been undergoing analysis at several centers around the world, including Hobart in Australia. After the synoptic analysis program for SOP-1 was completed in Hobart, an additional reanalysis of a *special week* (22–28 July) was then undertaken, enabling 500-hPa contour fields to be constructed for the region south of 50°S. Pook and Cowled (1999) clearly show the impact of late data. DMSP satellite imagery was employed in the special-week reanalysis. Evidence was found of several vortices that moved southward over East Antarctica during the latter part of July 1994 and appeared to decay over the high plateau. Observations from the network of AWSes over East Antarctica were combined with satellite imagery to infer the movement inland of these cyclones.
- The methods of analysis devised for the FROST project utilized all data available in real time at the GTS nodes in Melbourne and Bracknell, as well as data not in the real-time system such as meteorological data from AGOs and high-resolution satellite imagery from archives operated by several research institutions.
- FROST demonstrated the need to improve the effi-

ciency of the GTS in communicating regular reports of surface synoptic and upper-air data from Antarctica. Some improvements in the delivery of World Meteorological Organization (WMO) coded SYNOP and TEMP messages via the GTS and the assimilation of data into global numerical weather prediction schemes have been achieved as a result of FROST.

- It was found more difficult to construct objective and accurate analyses over the Antarctic continent than the Southern Ocean, due primarily to the difficulty of discriminating between cloud and ice over the continent. The sparse data networks limited the detail that could be expressed in the manual analyses, but the work produced the best possible analyses in the time available that had continuity in space and time.
- The analysis team is firmly of the view that substantial progress in understanding the meteorology of high southern latitudes can be expected from a critical appraisal by meteorologists of model output fields. FROST highlighted the need to develop more representative observing networks and improved data assimilation schemes in the numerical weather prediction models.

6. Some of the questions that are still left unanswered

Many suggestions for further investigations could be offered. For example, it would be beneficial to calibrate satellite interpretation techniques, for example, Troup and Streten (1972) and Guymer (1978), for high southern latitudes. A suitable test bed is over Drake Passage to take advantage of the four staffed stations releasing balloon-borne radiosondes in that area. Other possible sites, but at lower latitudes and with only one upper-air sounding station for thousands of kilometers, is near Macquarie Island or in the vicinity of Kerguelen Island. Evans et al. (1994) show that these concepts are relevant in high northern latitudes of the Atlantic Ocean; perhaps satellite interpretation could be taken a step further south of latitude 50°S.

With respect to reduction methods such as Phillpot's (1991, 1997) 500- and 700-hPa techniques and the Radok and Brown technique (1996), Adams (1997) has found using 500-hPa techniques (three summer seasons for the Phillpot technique and one season using the Radok and Brown method at the Antarctic Meteorological Centre at Casey) that gridded data over the East Antarctic plateau from either the GASP or ECMWF models corresponding to the time of the manual analysis (either +12h GASP model data or +24h ECMWF model data) had little or no correlation with values obtained from either reduction technique.

There is room for further study of the interrelationship between the change in ice surface air temperature over the continent (the formation and breakdown of the strong and deep surface temperature inversions) and the changing vertical lapse rates of temperature between the ice surface and the 500-hPa level.

Above the 500-hPa level the annual cycle of formation and breakdown of the polar vortex is worthy of further investigation.

Consideration should be given to the formulation of a standard atmosphere over Antarctica in a manner similar to the International Civil Aviation Organization–defined standard atmosphere that has been accepted for decades and is useful particularly in middle latitudes.

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