Validation of operational numerical analyses in Antarctic latitudes

Richard I. Cullather and David H. Bromwich
Polar Meteorology Group, Byrd Polar Research Center, Ohio State University, Columbus

Robert W. Grumbine
National Centers for Environmental Prediction, Camp Springs, Maryland

Abstract. Available rawinsonde, automatic weather station (AWS), ship, and synthesized long-term observations are used to evaluate the Antarctic numerical analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.S. National Centers for Environmental Prediction (NCEP) from 1985 to 1994. Twice-daily variations in the ECMWF surface pressure analyses compare closely with AWS units of the U.S. Antarctic Program and ship observations. The NCEP analyses over the same period show substantial improvement, particularly during the period 1985-1990. Surface air temperatures and winds do not agree so closely, which may result from analyses error, the localized nature of the fields, or a combination. Validation of the analyses standard pressure level fields using available rawinsonde data reveal a general long-term decrease in RMS errors with time for both analyses. RMS errors in NCEP 200 hPa geopotential heights of over 200 geopotential meters (gpm) for central plateau stations are evident only prior to May 1986. However, a significant upward trend from 1989 to 1993 in geopotential height RMS differences is apparent at several levels. The ECMWF analyses are generally found to be superior and offer a reasonable depiction of the broadscale atmospheric circulation; however, deficiencies in midtropospheric temperatures and lower tropospheric winds are evident. Comparisons of ship data from individual cruises of the S.A. Agulhas and the R/V Nathaniel B. Palmer to the numerical analyses reveal substantial agreement for pressure and temperature variables. Observations from the Nathaniel B. Palmer in the Amundsen and Bellingshausen Seas were not available to the weather forecasting centers. Results presented here indicate that a large amount of the available data is being incorporated and that large deficiencies identified in previous studies are being addressed, although areas of concern remain. Deficiencies in comparisons to specific stations are common to both analyses, implying continued communications problems. In particular, grid values corresponding to individual stations including the now-closed Leningradskaya base and Mirnyy are found to be conspicuously deficient at the 200 hPa level for both analyses.

1. Introduction

The Antarctic First Regional Observing Study of the Troposphere (FROST) is an international project of extensive data collection and analysis poleward of 50°S latitude covering three 1-month-long special observing periods (SOPs) in 1994 and 1995 [Bromwich and Smith, 1993; Turner et al., 1996]. The primary purpose of FROST is to verify current Antarctic analyses and model forecasts. In support of this program, an evaluation of the historical proficiency of the operational numerical analyses is conducted using Antarctic rawinsonde, ship, and automatic weather station (AWS) data. Numerical analyses have been viewed as a potentially valuable tool for atmospheric study [e.g., Trenberth and Olson, 1988a]. This is particularly true of high southern latitudes, where the scarcity of data necessitates a complete assimilation of all meteorological observations available, including satellite data, to achieve an accurate depiction of the atmosphere.

In the recent past, numerical analyses have played an important role in a variety of atmospheric studies in high southern latitudes [e.g., Trenberth and Solomon, 1994; Quintanar and Mechoso, 1995; Heinemann, 1996]. Additionally, operational analyses have been utilized in computing the atmospheric moisture budget over Antarctica [Howarth, 1986; Masuda, 1990; Yamazaki, 1992, Budd et al., 1995]. Bromwich et al. [1995] evaluated the atmospheric moisture budget for three numerical analyses for the period 1985-1992 in high southern latitudes. The analyses produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) were found to be superior to those of the National Centers for Environmental Prediction (NCEP; formerly National Meteorological Center (NMC), and the Australian Bureau of Meteorology in comparisons with rawinsonde and glaciological data. Bromwich et al. [1995] limited the validation study to moisture transport variables. In
this paper, a more comprehensive evaluation of the basic
kinematic variables given by the tropospheric numerical
analyses is conducted. In section 2, a description of the
evaluated ECMWF and NCEP data sets is given. Section 3
provides results of surface and boundary layer comparisons
using AWS stations maintained by the U.S. Antarctic
Program, as well as observational climatologies. Results of
comparisons with the international rawinsonde archive are
discussed in section 4. An evaluation of the analyses using
case-study ship observations along the periphery of the
continent is given in section 5; and discussion and summary
are given in section 6.

2. Analyses Description

The evaluated analyses are those of the ECMWF
WCRP/TOGA archive II (TOGA is Tropical Oceans Global
Atmosphere, a program under the World Climate Research
Programme (WCRP)) and the NCEP analyses. Both data sets
used in this study were obtained from the National Center for
Atmospheric Research (NCAR). Both analyses are on a 2.5ø
latitude-longitude grid and are reported twice daily (0000 and
1200 UTC). The ECMWF archive consists of 14 standard
pressure levels, the lowest six of which contain relative
humidity data [Trenberth, 1992]. After 1991, a fifteenth
level, at 925 hPa, was added to the archive. The NCEP
archive consists of 12 standard pressure levels [Trenberth and
Olson, 1988c], with standard levels in the troposphere
identical to those of the ECMWF. Both archives contain
surface and boundary layer variables; however, not all
computed fields are available. For the ECMWF, boundary
layer values consist of 2 m temperature and dew point, and 10
m winds. The NCEP archive contains boundary layer
potential temperature, relative humidity, and wind
components. Prior to April 1985 the NCEP boundary layer
variables correspond to the midpoint of a 50 hPa thick
boundary layer, approximately the 200 m level. After April
1985 the boundary layer thickness was reduced to 10 hPa,
with values approximately corresponding to the 40 m level.

Both the NCEP and the ECMWF analyses are produced
from four-dimensional data assimilation incorporating
accumulated observational data, including satellite data, with
a 6-hour "initial guess" provided by a global spectral model.
A difficulty in the use of numerical analyses is the effect of
alterations in the data assimilation system on the climatic
ensemble of analyses [Trenberth, 1992]. Changes in the
analysis schemes result from resolution or parameterization
adjustments in the spectral model. The analyses scheme may
also be impacted by the discontinuation or introduction of
data sources. The NCEP Global Data Assimilation System
(GDAS) has evolved over the last 10 years [Kanamitsu, 1989;
Kalnay et al., 1990; Ballish et al., 1992; Parrish and Derber,
1992; Kalnay et al., 1996]. A list of changes to the ECMWF
data assimilation system has also been produced [Trenberth,
1992]. The analyses evaluated here are used by researchers,
operational modelers, and operational forecasters. Reanalysis
projects are under way to achieve the best possible uniform
analysis [Schubert et al., 1993; Trenberth, 1995; Gibson
et al., 1996; Kalnay et al., 1996], however operational
analyses currently remain of interest due to the higher
resolution of the operational analyses schemes.

Trenberth and Olson [1988a, b, c] and Trenberth [1992]
comprehensively evaluated the ECMWF WMO (World
Meteorological Organization) archive and the NCEP analyses
for the period 1979-1986 and found major problems in both
analyses over and around Antarctica. While data scarcity is
an acute problem for the southern hemisphere, these studies
indicate that available observations were not incorporated and
point to difficulties in communications as the primary source
of error. In particular, the rawinsonde stations at South Pole
(90.00øS) and McMurdo Station (166.67øE, 77.85øS) were
found to be frequently truncated or otherwise unincorporated
into the analyses. The NCEP analyses were found to contain
large monthly RMS differences with observations, at times
greater than 200 m for 200 hPa geopotential heights, until
May 1986 [Trenberth and Olson, 1988b]. Trenberth and
Olson [1988a] indicate that the ECMWF is the preferred
analysis for the southern hemisphere, despite the substantial
problems observed. A similar conclusion based on moisture
budget validation was given by Brown et al. [1995] for the
1985-1992 time period, although validation of the moisture
fluxes with rawinsonde and glaciological data generally
presented a more favorable comparison for this later time
period. Trenberth and Olson [1988a] note a marked
improvement with time in the ECMWF Antarctic analyses,
particularly in 1982 and 1983.

Several additional regional evaluations of the analyses
have also been conducted. Häkkinen [1995] employed the
ECMWF climatology from 1985 to 1989 in a coupled ice-
model ocean. The inadequacy of the resulting sea-ice cover
was attributed to apparent deficiencies in surface temperature
and wind fields. Arpe and Cattle [1993] evaluated wind
stresses derived from the analyses of the ECMWF and the
Although large discrepancies arose from the
acceptance of an individual observation in one analysis and
the rejection in another, the two analyses were found to be
generally similar over the Antarctic sea ice zone. Escoffier
and Provost [1995] compared observed wind forcing over the
southwestern Atlantic with the ECMWF analyses for 1986-1990.
The study found the major discrepancies to be due to
land-sea effects not resolved by the model and that agreement
with observed annual and semiannual signals was
exceptional.

Brown and Zeng [1994] have derived cyclone surface
pressures over data sparse oceanic regions using a planetary
boundary layer model incorporating ERS 1 scatterometer data
for 1992 and have made comparisons with the ECMWF and
NCEP analyses. Most storms in the southern hemisphere
were resolved by both analyses, although the scatterometer
derivation generally yielded more detailed and stronger
storms. The derived southern hemisphere minimum pressures
were found to be on average 3 hPa lower than the ECMWF,
with similar results for NCEP. Gentron and Braun [1995]
evaluated the ECMWF model used for the analyses over
Greenland and Antarctica for 1985-1991 and concluded that
the analysis and predictions "are in good agreement with
available observations." Only two fields, surface temperature
and precipitation, are presented however, and precipitation
comparisons only utilize long-term averages at manned
stations, while station observations are not employed in the
surface temperature validation. In summary, the five studies
noted above generally show an evolution in the analyses over
time and a preference for the ECMWF analyses for
atmospheric study of the southern hemisphere. They also
indicate that the suitability of the analyses is highly dependent
upon the application for which the analyses are utilized. In this context, three areas of interest are apparent: (1) whether the available data are being fully utilized by the analyses, (2) the relation of deficiencies to geographical location, or to particular variables, and (3) the significant data trends.

3. Surface and Boundary Layer Evaluation Over Antarctica

Validation Using Automatic Weather Stations

Near-surface and boundary layer conditions play a uniquely dominant role in the atmospheric circulation over Antarctica. Physical processes within the lowest few hundred meters of the atmosphere, primarily the near-surface katabatic wind regime, produce the most significant forcing of the atmospheric flows [e.g., Parish, 1988]. Consequently, the accurate reproduction of near-surface conditions is an essential component of the analyses.

About 30 automatic weather station units (AWS) have been deployed in Antarctica by the United States Antarctic Program [Stearns et al., 1993]. The AWS units and their purposes are described by Stearns and Wendler [1988] and Stearns et al. [1993]. The Scientific Committee for Antarctic Research (SCAR) Group of Specialists on Antarctic Research has recommended that the determination of moisture, heat, and momentum budgets be a primary consideration for the use of the AWS units [Allison, 1983]. However, many of the AWS units have been deployed in support of mesoscale studies on the Ross Ice Shelf and barrier wind flow along the Antarctic Peninsula. Several stations, for example, are located near Ross, White, and other islands embedded within the Ross Ice Shelf near the Transantarctic Mountains. The station, mountain range, and islands which influence surface conditions on the ice shelf may all fall into a single 2.5° analyses grid box. For purposes of validation, 15 stations have been selected based on site location and geographic dispersion, shown in Figure 1. In Figure 2 a typical AWS station configuration is shown. Optimally, AWS data set values are available every three hours via the Argos data collection and location system onboard TIROS (Television and Infrared Observations Satellite) A-G and TIROS N series polar orbiting satellites. Not all AWS units report over the GTS (Global Telecommunications System). The Parascientific pressure transducer, located in the electronics enclosure, has a resolution of 0.05 hPa; the temperature resolution is 0.125°C. The relative humidity sensor is not included on many of the AWS stations, and those stations listed that do have the sensor have very few reportings after quality control by the University of Wisconsin. Missing data result from a variety of events that may occur, while the AWS is unattended for many months at a time. Stearns et al. [1993] indicate the wind measurement system (Bendix or Belfort aerovane) is the most susceptible component of the AWS unit to damage or the reporting of suspect data. In some locations, particularly along the Adélie Coast in East Antarctica (~140°E) and Terra Nova Bay [Bromwich, 1989], the force of the wind may at times be sufficient to render structural damage to the unit. The aerovane coupling is also vulnerable to rime or ice buildup in winter months. A
significant number of AWS units are deployed in the so-called "dog house" configuration and do not measure wind speed or direction, as oceanic island sites often get quickly buried in snow and ice. It is likely that AWS pressure and perhaps temperature reports only are used by the operational weather forecasting centers. This would appear to be reasonable given the potential error and the question of local versus synoptic scales.

Some significant issues arise in the computation of the analysis values for comparison with observations. While interpolation of four grid points is sufficient for locations of smooth topography such as the interior of the continent, it often results in large height differences between the station elevation and the analysis model. The problem is confused by the false topography utilized for the analysis models, referred to as "envelope" topography by ECMWF and "silhouette" topography used by NCEP prior to 1992, and is further compounded by changes made to model resolution, which in turn results in variations in the model elevation over time. Trenberth [1992] indicates that analysis values at high latitudes are more reflective of area rather than point values. Accordingly, the elevation of the four analysis grid points adjacent to each observation are computed from monthly averaged analyses, and values from the grid point closest in elevation are used for comparison. Even after the grid point elevation comparison, large differences in elevation between observation and analyses are still apparent for some stations.

For results presented here however, no attempt was made to reduce the analyses' surface pressure values to the station datum. Genthon and Braun [1995, see their Figure 3] have examined the ECMWF analysis topography, which was found to be deficient not simply because of the envelope topography scheme but also due to the use of a comparatively old orographic database. An additional issue that arises is associated with the spectral nature of the model in close proximity to steep topography. This is clearly shown in Figure 3, where ECMWF elevations as derived by NCAR for February 1987 are contoured for values below zero. Steep topography associated with the Transantarctic Mountains (left) and the Antarctic Peninsula (right) result in large spectral topographic waves, or divots, of as much as 150 m or more below ground in the Ross and Larsen Ice Shelves, respectively. Similar topographic deficiencies exist for the NCEP analyses as seen from surface pressure comparisons with the AWS stations. Moreover, the NCEP boundary layer values correspond to approximately the 40 m level while ECMWF corresponds to the 2 m level. The AWS temperature, wind, and humidity measurements are made at the 3 m level. This likely will result in discrepancies, particularly for the interior plateau region under the intense Antarctic inversion. Consequently, the surface pressure evaluation is the least ambiguous comparison for temporal variations.

Figure 4 shows the monthly surface pressure correlation coefficients for each station. The overwhelming number of station observations are well correlated with the ECMWF analyses. Most values are above the 0.80 correlation level, and 78% are above the 0.90 level. Overall interior stations fare better than maritime or coastal stations, which generally do not have as complete a record as the continental stations. The record for Possession Island, for example (available 1992-1994), contains only half of possible 0000 and 1200 UTC reports for any given month while in operation. While this station has been included for completeness, all other data points denote at least 50 observations for the month. In general, there is a surprisingly flat trend over time in correlations with ECMWF. It is evident from Figure 4 that some months exist where multiple stations failed to correlate well with ECMWF. These months reflect changes to the analysis scheme that significantly impact correlations during the month. In contrast to the high consistency found for ECMWF, the NCEP analyses show a marked improvement.

Figure 3. Below sea-level contours of European Centre for Medium-Range Weather Forecasts (ECMWF) elevation data for Ross Ice Shelf region (left), and Antarctic Peninsula (right), contoured every 20 m.
Figure 4. Monthly correlations of ECMWF (top) and NCEP (bottom) surface pressure analyses with AWS station data.

for the 1980s. For the early portion of the time series, bad station correlations are widespread and are not limited to the period prior to analysis scheme changes in May 1986. West Antarctic coastal stations such as Gill on the Ross Ice Shelf frequently correlate poorly during the 1980s. However, interior stations such as Dome C also have several monthly correlation coefficients below 0.50. The situation improves somewhat after 1990, with most points attaining monthly correlation coefficients above 0.70. The NCEP analyses compare more favorably to observations than the ECMWF for only a handful of monthly station comparisons for the 10-year period, however.

It is suspected that the analyses tend to underestimate strong synoptic systems [Trenberth and Olson, 1988a; Brown and Zeng, 1994]. Although station comparisons indicate that monthly maximum and minimum analysis values tend to correspond to observation at least as accurately as other values in series, there is evidence that very intense lows are underestimated by one or both of the analyses when examining the strongest systems over the 10-year period. Figure 5 is an example of this, showing the lowest pressure observed at Scott Island. Here, the ECMWF analysis has overestimated the surface pressure by 15 hPa. The time series indicates that station and analyses pressures are similar for other times. Interestingly, both analyses performed reasonably well in estimating the 932 hPa low that occurred

Figure 5. Nine-day surface pressure time series for Scott Island AWS (67.37°S, 179.97°W), and corresponding ECMWF and National Centers for Environmental Prediction (NCEP) analysis values, in hektopascals, beginning October 1, 1993.
Figure 6. Average monthly ECMWF and NCEP surface pressure standard error from regression with observations from six AWS units, in hectopascals.

3½ days prior to the lowest-pressure event. Figure 5 underscores the strong variability associated with the adjacent oceanic regions.

In Figure 6 the analysis standard error from regression with AWS surface pressure observations for selected stations, averaged for the years of available data, is plotted for the annual cycle. The amount of error for a particular time and location is contingent upon the amount of synoptic or mesoscale activity encountered. West Antarctic coastal stations such as Uranus Glacier and Mount Siple as well as Gill on the Ross Ice Shelf experience significant synoptic variability during the austral winter. Error for these stations is somewhat larger than interior stations and maximizes in winter months. This is generally true of the NCEP analyses, although large standard errors are also found for some summer months, such as at Mount Siple in January. At the interior station Dome C, there is little seasonal variability for either analysis, which is not surprising as little synoptic activity penetrates far inland beyond the coastal escarpment of East Antarctica. Again the standard error for the NCEP

Figure 7. Monthly averaged surface pressure for Uranus Glacier (71.43°S, 68.93°W) and Dome C (74.50°S, 123.00°E) AWS units in comparison with corresponding ECMWF and NCEP analysis values, in hectopascals.
analysis surface pressure is larger than for the ECMWF for virtually all stations and time periods. In Figure 7, monthly mean values for Uranus Glacier and Dome C are plotted as a general reflection of analyses skill for seasonal to interannual timescales. Surface pressure over land is particularly susceptible to changes in the data assimilation scheme, due to the previously mentioned effects on topography. At both stations the substantial changes made to the NCEP analysis scheme in May 1986 are easily seen in both time series. While the corrections introduce a substantial bias, especially for Uranus Glacier, the NCEP time series, with some exceptions, appears to track reasonably well in comparison with the recorded observations. The ECMWF time series for Dome C is extremely similar to observation for the 10 years recorded, which is greatly reassuring. However, for Uranus Glacier there is marked change in the ECMWF bias after the 1990-1992 data gap, and this is almost certainly related to a change in the NWP (numerical weather prediction) model resolution which occurred in September 1991.

No other surface or boundary layer field compares as closely with AWS values as the surface pressure field. It is suggested that the surface pressure signal may be of a large enough spatial scale to be more easily reproduced by the analyses. Comparisons of near-surface temperature fields reveal a mixed bag, with skill highly variable and dependent upon each station. In Figure 8 the average monthly standard error for six AWS units is plotted for the annual cycle. Standard errors range from 0°C to 9°C depending on station and month. Coastal and/or oceanic stations again fair poorly, although interior stations also show large standard errors. Unlike the pressure comparison the NCEP analysis is found to be superior for a significant number of observations, generally during summer months. As was mentioned previously, this seasonality is in part an artifact of the NCEP boundary layer temperature product, which is affected by the Antarctic inversion. Correlations with temperature observations average 0.5 for both analyses but may be considerably more or less. There are similar trends indicating analyses improvements to those found with surface pressure. In Figure 9 the time series of monthly mean temperatures are shown for Dome C. The station contains one of the more complete records for the total time period. The ECMWF analyses...
Figure 9. Average monthly near-surface temperatures for Dome C AWS unit (74.50°S, 123.00°E), in comparison with corresponding ECMWF and NCEP analysis values, in degrees centigrade.

Figure 10. Average monthly ECMWF and NCEP near-surface zonal wind standard error from regression with observations from four AWS units, in meters per second.

As a means of further evaluating the spatial distribution, the 10-year average temperature and wind fields are evaluated against long-term climatology and modeling studies. Validation of the long-term near-surface temperature field is conducted using the synthesis of observational data by Giovinetto et al. [1990], reproduced in Figure 13. In Figure 14 the corresponding fields for the ECMWF (left) and NCEP analyses (right), averaged over 10 years, are shown. The high plateau minimum temperature in the ECMWF analyses is approximately 3°C warmer than the (-)60°C contour shown by Giovinetto et al., which may possibly result from decadal variability. The location of this minimum is also farther west in the ECMWF analyses, which is the result of topographic deficiencies. Again, the largest topographic errors found by Genthon and Braun [1995] are located near and to the west of the prime meridian, and there are some significant discrepancies in the temperature contours in this region. Apart from these discrepancies there is tremendous fidelity between the ECMWF and observed temperature fields for both distribution and magnitude. In particular, the (-)20°C contour running along the Amundsen and Bellingshausen Sea coastline in West Antarctica is exactly reproduced. There is also a clear representation of the Antarctic Peninsula in the temperature field. Overall the ECMWF temperature field compares quite well and adequately reproduces the gradients along the East Antarctic escarpment, which is consistent with the findings of Genthon and Braun [1995]. As previously
mentioned, the NCEP analysis values correspond to the boundary layer midpoint and are significantly warmer as a result. The NCEP contours are quite smooth and present a very simplified representation of the observational field. Contours are highly smoothed near the Antarctic Peninsula, and the gradient along the East Antarctic escarpment is significantly weaker than that shown by Giovinetto et al. [1990].

A realistic near-surface katabatic wind regime has been previously produced using a high resolution mesoscale model [Parish and Bromwich, 1991], results of which are reproduced in Figure 15. In Figure 16 the average July wind fields are shown from the ECMWF and NCEP analyses. The larger differences between the two analyses may be seen in the isotachs; however, there are some important differences in the vector fields as well. It may be seen from a comparison of vector fields in Figures 15 and 16 that the ECMWF adequately reproduces katabatic wind flow perpendicular to the coast near Byrd Glacier south of McMurdo Station and Terra Nova Bay to the north, while the NCEP analysis is more parallel to the coast. Neither analysis accurately reproduces the southerly barrier winds along the eastern side of the Antarctic Peninsula. There has been some interest recently in the peninsula barrier winds, which may be a chronic problem for atmospheric models. Hines et al. [1995] found that errors in the representation of these winds result from differing parameterizations of the sensible heat flux. The lower portion of Figure 16 shows a large difference in isotach detail between the two analyses. The NCEP analysis again reflects a much smoother representation of the boundary layer winds. The ECMWF analysis correctly locates maxima in the interior of West Antarctica, which is surprising given the topographic errors found by Genthon and Braun [1995] in the region adjacent to the Weddell Sea. In contrast, the NCEP plot...
Figure 14. Average annual near-surface temperature fields for the ECMWF (left) and NCEP (right), contoured every 5°C (in negative °C).

shows a greatly smoothed representation of West Antarctic features. Both analyses locate three maxima associated with katabatic airflow convergence in Wilkes Land near 95°E, 120°E, and 145°E. The analyses maxima located near 120°E is not found in the model results as depicted in Figure 15 but is associated with enhanced model katabatic flow at Porpoise Bay [Parish and Bromwich, 1991, see their Figure 3]. Both analyses show a considerably weaker field, with no values greater than 15 m s\(^{-1}\). Arpe and Cattle [1993] had similarly found ECMWF model surface wind stresses to be weak in comparison to observation. The comparison is consistent with the validation of CCM2 in the work of Tzeng et al. [1994], who speculate that difference in magnitude results from the higher resolution and better topographic treatment employed by Parish and Bromwich [1991].

4. Rawinsonde Comparisons

Figure 17 shows the distribution of Antarctic rawinsonde stations available for comparison from operational weather centers for 1985-1993, compiled by NCAR (T.R. Parish, personal communication, 1996). The Antarctic rawinsonde record has been examined by Trenberth and Olson [1989] and Connolley and King [1993]. Stations have different schedules of launches, which may vary with season. Figure 18 shows the number of monthly reports from each station. For clarity the numbers of station reports are smoothed using a 4-month running mean, divided into three plots, and normalized to a maximum of 60 per month. The decreased number of observations in the early and later part of the series may be limitations only due to the archive employed here. Observations from the South African National Antarctic Expedition Station (SANAE, 70.30°S, 2.35°W), for example, are shown to be missing in Figure 18 after 1992 but are available during July 1994 as part of the FROST SOP. However, several former Soviet stations have closed during the 1990s, including Leningradskaya, for which upper air reports became sporadic after 1990, while Vostok has apparently discontinued its rawinsonde program. Trenberth and Olson [1989] also note the loss of data from balloon

Surface wind for winter – Parish and Bromwich 1991

Figure 15. Near-surface wind vector field and isotachs, in meters per second, for winter, after Parish and Bromwich [1991].
bursts, which is higher during the polar winter, as well as previously mentioned communication problems. Connolley and King [1993] present a review the rawinsonde equipment used, which varies from station to station. The most susceptible component of the rawinsonde measurement system appears to be wind measurements, which are derived via the OMEGA VLF navigational aid for a large number of non-Russian stations. OMEGA reception is poor at some locations, and the few OMEGA stations that are received have a small angular separation, resulting in errors in the derived wind components. Issues concerning humidity measurements in cold regions have also been previously reviewed by Bromwich and Robasky [1993] and Bromwich et al. [1995], who indicate that larger moisture transports are generally associated with warmer conditions, which may reduce measurement errors.

Standard level geopotential height, temperature, zonal and meridional wind, and derived specific humidity are used for comparison to the nearest analysis grid point without regard to topography. Quality control is performed by filtering for unrealistic values and removing values greater than three standard deviations from computed monthly means. Statistics are computed for months containing at least 20 reports where both observation and archived analyses values were simultaneously available. Conservatively, specific humidity values computed from dew points colder than \(-40^\circ\) are discarded. For wind comparisons at South Pole there is some ambiguity in the meaning of analyses values, referred to as the "pole problem" [Trenberth, 1992]. For wind validations only, rawinsonde data are compared with analysis values located one grid box from the station and located on the prime meridian, which results in consistency with the rawinsonde convention of wind directions corresponding to longitude.
A summary of results is shown in Table 1, showing average monthly RMS (root mean square) errors by year, and Table 2, showing average statistical scores for selected stations and variables. Table 1 generally shows a decrease in geopotential height RMS errors with time for both analyses, with 1993 200 hPa errors approximately 11 geopotential meters (gpm) lower than in 1985 for the ECMWF analyses and approximately 22 gpm lower for the NCEP analyses. These numbers may be compared with the observed average monthly standard deviation, which is 114 gpm. The improvement in the ECMWF analyses is generally the result of incremental decreases in negative biases. Significantly, however, most of the reduction in error in the NCEP analyses resulted from the May 1986 changes, and a significant upward trend in error from 1989 to 1993 is found at several levels. Average NCEP monthly RMS for 200 hPa geopotential height increased by more than 6 gpm from 1989 to 1993. Analysis values at specific stations were found to frequently contain high RMS errors at the 200 hPa level for the period 1989 to 1993. Monthly RMS scores for both analyses at Leningradskaya and Mirnyy were found, on the average, to be greater than 40 gpm over the period. In particular, there is substantial evidence of difficulties in incorporating Leningradskaya 200 hPa values into the ECMWF analyses. More than 40% percent of ECMWF RMS values for Leningradskaya are greater than 50 gpm, while 10% are greater than 100 gpm and are the largest errors observed for the period. Similar, although slightly smaller, errors are found for the NCEP analyses for this station and communications difficulties are suspected. Figure 19 shows the monthly 200 hPa geopotential height bias for the ECMWF and NCEP analyses. Approximately 87% of ECMWF 200 hPa values are biased by less than 30 gpm. The lower portion of Figure 19 shows biases for comparisons with the NCEP analyses, which are dominated by the early errors in the continental interior at South Pole and Vostok. For 1992 to 1993 the NCEP analyses become progressively negatively biased, primarily as the result of Casey and Mirnyy stations. The 1993 NCEP analyses bias for these two stations are typically -40 gpm. While some stations are noted as being notoriously faulty in both analyses at the 200 hPa level, several stations also show tremendous fidelity. Comparisons with Mawson in particular found maximum monthly RMS errors to be 37 gpm for the ECMWF and 42 gpm for NCEP,
Table 1. Average Monthly RMS for Comparison of ECMWF and NCEP Analyses with 17 Rawinsonde Stations (15 Available for 700 and 850 hPa Levels)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T, ^\circ C$</td>
<td>850</td>
<td>ECMWF</td>
<td>3.1</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>3.9</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>2.9</td>
<td>3.0</td>
<td>4.2</td>
<td>4.2</td>
<td>3.1</td>
<td>2.6</td>
<td>2.7</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>ECMWF</td>
<td>1.5</td>
<td>1.6</td>
<td>1.7</td>
<td>1.8</td>
<td>1.9</td>
<td>1.8</td>
<td>1.6</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>2.5</td>
<td>2.1</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>ECMWF</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
<td>1.6</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>2.5</td>
<td>2.3</td>
<td>1.8</td>
<td>1.9</td>
<td>1.7</td>
<td>1.7</td>
<td>2.1</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>$q, g kg^{-1}$</td>
<td>850</td>
<td>ECMWF</td>
<td>0.38</td>
<td>0.40</td>
<td>0.39</td>
<td>0.36</td>
<td>0.38</td>
<td>0.37</td>
<td>0.37</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>0.33</td>
<td>0.38</td>
<td>0.39</td>
<td>0.38</td>
<td>0.32</td>
<td>0.31</td>
<td>0.34</td>
<td>0.32</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>ECMWF</td>
<td>0.29</td>
<td>0.25</td>
<td>0.22</td>
<td>0.21</td>
<td>0.22</td>
<td>0.22</td>
<td>0.21</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>0.21</td>
<td>0.22</td>
<td>0.23</td>
<td>0.21</td>
<td>0.20</td>
<td>0.22</td>
<td>0.22</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>$U, m s^{-1}$</td>
<td>850</td>
<td>ECMWF</td>
<td>4.8</td>
<td>4.8</td>
<td>4.7</td>
<td>4.3</td>
<td>4.4</td>
<td>4.4</td>
<td>4.7</td>
<td>4.0</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>5.5</td>
<td>5.2</td>
<td>4.8</td>
<td>4.9</td>
<td>4.8</td>
<td>4.5</td>
<td>5.3</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>ECMWF</td>
<td>4.0</td>
<td>3.7</td>
<td>3.5</td>
<td>3.6</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>6.4</td>
<td>5.2</td>
<td>4.1</td>
<td>4.5</td>
<td>4.0</td>
<td>4.0</td>
<td>4.6</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>ECMWF</td>
<td>3.2</td>
<td>2.7</td>
<td>2.5</td>
<td>2.5</td>
<td>2.3</td>
<td>2.5</td>
<td>2.5</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>6.0</td>
<td>4.6</td>
<td>3.7</td>
<td>3.8</td>
<td>3.3</td>
<td>3.4</td>
<td>4.0</td>
<td>3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>$V, m s^{-1}$</td>
<td>850</td>
<td>ECMWF</td>
<td>5.3</td>
<td>5.2</td>
<td>5.2</td>
<td>4.8</td>
<td>4.8</td>
<td>5.0</td>
<td>4.8</td>
<td>4.4</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>4.5</td>
<td>4.3</td>
<td>4.5</td>
<td>4.3</td>
<td>4.6</td>
<td>4.6</td>
<td>4.3</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>ECMWF</td>
<td>3.5</td>
<td>3.4</td>
<td>2.9</td>
<td>3.0</td>
<td>2.8</td>
<td>3.0</td>
<td>3.0</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>4.9</td>
<td>4.6</td>
<td>3.5</td>
<td>3.6</td>
<td>3.2</td>
<td>3.2</td>
<td>3.9</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>ECMWF</td>
<td>2.6</td>
<td>2.7</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>2.3</td>
<td>2.4</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>4.3</td>
<td>4.0</td>
<td>3.1</td>
<td>3.1</td>
<td>2.7</td>
<td>3.4</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>$Z, gpm$</td>
<td>850</td>
<td>ECMWF</td>
<td>18.6</td>
<td>18.4</td>
<td>18.2</td>
<td>16.6</td>
<td>16.3</td>
<td>16.9</td>
<td>17.8</td>
<td>15.8</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>27.7</td>
<td>27.2</td>
<td>24.8</td>
<td>27.5</td>
<td>19.4</td>
<td>20.7</td>
<td>26.6</td>
<td>22.4</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>ECMWF</td>
<td>25.9</td>
<td>22.6</td>
<td>20.2</td>
<td>19.3</td>
<td>21.2</td>
<td>20.2</td>
<td>19.8</td>
<td>18.6</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>47.8</td>
<td>32.5</td>
<td>20.8</td>
<td>24.1</td>
<td>19.1</td>
<td>20.3</td>
<td>28.5</td>
<td>24.5</td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>ECMWF</td>
<td>35.2</td>
<td>31.9</td>
<td>27.5</td>
<td>26.5</td>
<td>32.6</td>
<td>26.9</td>
<td>23.3</td>
<td>25.2</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>56.8</td>
<td>42.6</td>
<td>28.7</td>
<td>29.5</td>
<td>28.6</td>
<td>29.0</td>
<td>33.2</td>
<td>33.4</td>
<td>34.7</td>
</tr>
</tbody>
</table>

ECMWF, European Centre for Medium-Range Weather Forecasts; NCEP, National Centers for Environmental Prediction.

with most values for both analyses less than 17 gpm. Analyses values for Molodezhnaya and Halley Bay also show typical RMS errors of 20 gpm. This is particularly encouraging for comparisons at Molodezhnaya, which contains the most complete twice-daily archive for the Antarctic, while the result at Halley Bay is typical of the excellent results found at stations located east of the Weddell Sea.

While data truncation occurs for several stations at 200 hPa the situation improves marginally at 500 hPa. RMS errors are still large for Leningradskaya and Mirnyy comparisons, although typical values are less than 40 gpm and average approximately 28 gpm for both stations. In Figure 20 the monthly averaged 500 hPa geopotential height time series for six stations are plotted with corresponding values from the numerical analyses. With the exception of NCEP analyses, comparisons for the continental interior stations of Vostok and McMurdo prior to May 1986, mean seasonal and interannual variability is closely reproduced by both analyses. For Bellingshausen there is a notable decrease in the negative biases of both analyses. Biases incrementally improve by an average of 21 gpm in the ECMWF analyses and 52 gpm in the NCEP analyses in 1993 as compared with 1985 differences. Other stations depicted show greater accuracy in reproducing monthly mean values.
Table 2. Average Monthly Statistical Scores for Comparison of ECMWF and NCEP Analyses With Four Rawinsonde Stations for 1989-1993

<table>
<thead>
<tr>
<th>Variable</th>
<th>Station</th>
<th>Analysis</th>
<th>RMS</th>
<th>Bias</th>
<th>Correlation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>25.0</td>
<td>-4.4</td>
<td>0.939</td>
<td>17.3</td>
</tr>
<tr>
<td>Z, gpm</td>
<td></td>
<td>NCEP</td>
<td>30.1</td>
<td>2.7</td>
<td>0.913</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>13.3</td>
<td>-4.2</td>
<td>0.985</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>16.9</td>
<td>-6.5</td>
<td>0.976</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>9.4</td>
<td>-2.0</td>
<td>0.990</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>14.5</td>
<td>-6.7</td>
<td>0.979</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>33.6</td>
<td>-8.2</td>
<td>0.912</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>34.2</td>
<td>-16.5</td>
<td>0.910</td>
<td>19.0</td>
</tr>
<tr>
<td>500 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>25.3</td>
<td>-10.8</td>
<td>0.971</td>
<td>19.8</td>
</tr>
<tr>
<td>Z, gpm</td>
<td></td>
<td>NCEP</td>
<td>31.5</td>
<td>-9.1</td>
<td>0.951</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>13.1</td>
<td>-3.1</td>
<td>0.987</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>18.2</td>
<td>-4.4</td>
<td>0.976</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>10.7</td>
<td>-0.7</td>
<td>0.992</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>15.7</td>
<td>-4.7</td>
<td>0.981</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>28.9</td>
<td>-6.5</td>
<td>0.949</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>31.1</td>
<td>-15.2</td>
<td>0.953</td>
<td>21.6</td>
</tr>
<tr>
<td>200 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>34.1</td>
<td>-25.5</td>
<td>0.981</td>
<td>19.6</td>
</tr>
<tr>
<td>Z, gpm</td>
<td></td>
<td>NCEP</td>
<td>41.9</td>
<td>-25.5</td>
<td>0.965</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>14.5</td>
<td>-0.3</td>
<td>0.990</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>21.8</td>
<td>3.0</td>
<td>0.977</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>15.8</td>
<td>-4.9</td>
<td>0.991</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>21.2</td>
<td>-4.9</td>
<td>0.983</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>43.3</td>
<td>-17.8</td>
<td>0.943</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>48.0</td>
<td>-15.5</td>
<td>0.940</td>
<td>28.1</td>
</tr>
<tr>
<td>500 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>1.7</td>
<td>-0.4</td>
<td>0.899</td>
<td>1.4</td>
</tr>
<tr>
<td>T, °C</td>
<td></td>
<td>NCEP</td>
<td>2.0</td>
<td>-1.1</td>
<td>0.893</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>1.1</td>
<td>0.3</td>
<td>0.949</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>1.0</td>
<td>0.1</td>
<td>0.950</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>1.1</td>
<td>0.3</td>
<td>0.961</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>1.1</td>
<td>-0.1</td>
<td>0.959</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>1.9</td>
<td>-0.6</td>
<td>0.859</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>1.9</td>
<td>-0.3</td>
<td>0.854</td>
<td>1.3</td>
</tr>
<tr>
<td>500 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>4.9</td>
<td>-2.0</td>
<td>0.909</td>
<td>3.7</td>
</tr>
<tr>
<td>U, m s⁻¹</td>
<td></td>
<td>NCEP</td>
<td>5.8</td>
<td>-1.4</td>
<td>0.851</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>2.8</td>
<td>0.4</td>
<td>0.912</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>3.2</td>
<td>0.2</td>
<td>0.893</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>2.4</td>
<td>0.2</td>
<td>0.962</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>3.3</td>
<td>0.2</td>
<td>0.930</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>3.8</td>
<td>0.2</td>
<td>0.789</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>4.2</td>
<td>-0.1</td>
<td>0.787</td>
<td>3.3</td>
</tr>
<tr>
<td>500 hPa</td>
<td>Casey</td>
<td>ECMWF</td>
<td>3.9</td>
<td>-0.8</td>
<td>0.859</td>
<td>3.1</td>
</tr>
<tr>
<td>V, m s⁻¹</td>
<td></td>
<td>NCEP</td>
<td>5.0</td>
<td>-0.4</td>
<td>0.743</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Halley Bay</td>
<td>ECMWF</td>
<td>3.2</td>
<td>0.0</td>
<td>0.923</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>3.4</td>
<td>-0.4</td>
<td>0.920</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Molodezhnaya</td>
<td>ECMWF</td>
<td>2.2</td>
<td>0.0</td>
<td>0.953</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>2.7</td>
<td>0.3</td>
<td>0.930</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>McMurdo</td>
<td>ECMWF</td>
<td>4.3</td>
<td>0.2</td>
<td>0.805</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NCEP</td>
<td>4.0</td>
<td>-1.2</td>
<td>0.839</td>
<td>3.0</td>
</tr>
</tbody>
</table>
above the semi-permanent Antarctic inversion over the plateau. For 1989 to 1993 the average analyses RMS is greater than 2°C for both stations. Other stations depicted in Figure 21 generally have smaller discrepancies in monthly mean values and in RMS. As with geopotential height, both analyses appear to have great success in reproducing values for stations located on the eastern coast of the Weddell Sea (Halley Bay, Neumayer, and SANAE) for which typical RMS values are less than 1.5°C.

RMS errors in winds found in Table 1 show similar trends in analyses improvements as was found for other variables. Zonal wind RMS is generally larger for both analyses, which is an indication of the differences in magnitudes between zonal and meridional winds that is generally found in high southern latitudes. At 500 hPa the wind bias averaged for all stations is essentially zero for zonal and meridional components after 1989. There is large variability between perimeter stations which is characterized by over or underestimation of zonal winds. Among stations with unique difficulties are South Pole and Vostok. At South Pole the major problem is with the mean direction, where observations since 1987 indicate that average winds at 500 hPa are from the Weddell sector, while analyzed winds are more parallel with the prime meridian. This record is highly biased by a lack of winter reports however. From the available reports at South Pole the magnitude of the ECMWF analyses are about 7% weaker while the NCEP analyses are in near parity with observation. At Vostok both analyses are very similar in producing 500 hPa winds that are more zonal than those observed, with average magnitudes in agreement with observations. Meridional RMS errors for Vostok average 4 m s⁻¹ for the ECMWF and 4.6 m s⁻¹ for NCEP. A feature of interest in the upper air wind analyses is the meridional wind field at 850 hPa, the first coastal standard level above the katabatic wind flow, and the only wind field for which the NCEP analyses are found to be consistently superior to the ECMWF. Figure 22 shows the mean value time series for six stations, again reflecting the tremendous variability in skill from station to station. Although values generally reflect interannual trends, biases are large, as is evident for Davis.

5. Maritime Surface Evaluation

As has been noted in the previous section, the majority of rawinsonde stations are located along the perimeter of the East Antarctic continent. These stations are periodically
visited by supply ships and research vessels. Observations taken by the supply ships may be available for incorporation into the analyses via the global telecommunications system (GTS). Although such observations by themselves are inadequate for a numerical analysis of the Southern Ocean, which represents a major void of conventional data, they are necessary for the augmentation of the satellite data that are primarily used. In Figure 23 ship tracks of the S.A. Agulhas [Petry, 1995] are shown during the years 1991-1993. The S.A. Agulhas resupplies SANAE from Cape Town, South Africa. In Figure 24 the ship pressure and temperature reports are compared with numerical analysis values for the time period over which data are available. The pressure correlation is 0.95 for the ECMWF analyses and 0.86 for NCEP, and standard errors are 5.2 and 8.1 hPa for the ECMWF and NCEP analyses respectively. Disturbingly, however, a low-pressure reading on October 28, 1992 (observation 60) of 946.1 hPa is overestimated by more than 30 hPa in the ECMWF analyses and 32 hPa in the NCEP analyses. The low-pressure value was attained near 60°S. In the comparison of temperature data, there again is general agreement with many data values. Correlation for the ECMWF analyses with temperature observations is 0.94, while the NCEP correlation is 0.93. In early March 1993 (observations 126-132) the observations differ sharply with the analyses during a period of time when the ship is in close proximity to the Antarctic coast, possibly as a result of localized phenomena associated with the coastline. All other values are closely matched by the analyses. There is the general conclusion that available supply ship data are being incorporated into the analyses, however several caveats are apparent. On the basis of this example, the maximum intensity of mid-ocean cyclones may be underestimated by the analyses. Additionally, a comparison of the wind values found little correlation with the analyses.

As an analog to the S.A. Agulhas, results are presented for three ship cruises of the R/V Nathaniel B. Palmer [Jeffries, 1994] in the Bellingshausen and Amundsen Seas region for 1993-1994. Ship data for the three cruises were obtained from the University of Wisconsin and Antarctic Support Associates. Figure 25 shows ship tracks departing Punta Arenas, Chile, for round trip shuttle to and from Palmer Station, McMurdo Station, and Auckland, New Zealand. Unlike Antarctic supply shipping, the Nathaniel B. Palmer
was primarily engaged in physical and biological studies of the pack ice in the region. A large majority of the observations occurred near 70°S. No meteorological observations were transmitted via the GTS (W.M. Connolley, British Antarctic Survey, personal communication, 1996) and were not available to operational weather centers. Table 3 presents results of computed statistics for the comparison to the analyses. Figure 26 shows comparisons of pressure readings with the analyses (Cruise 1 comparison after Cullather et al. [1996]). The comparisons are exceptional given the scarcity of data in the region. The observed low pressure of 934.3 hPa is again overestimated in the analyses. The ECMWF analyses produce a value of 946 hPa, while NCEP shows 940 hPa. The other two cruises do not exhibit the tremendous range found in Cruise 1, but it may be seen that the analyses closely reproduce the observed values. In comparison with Cruises 1 and 2 the performance of the analysis pressure values during Cruise 3 is not so close to observation. There is no directly attributable reason for this, although it may be seen from Figure 26 that the observational record for Cruise 3 is not so complete.

Figure 27 shows the temperature comparisons to the observed ship values. In Cruise 2, as depicted in Figure 25, the ship is observed to follow sea ice leads to within a very close proximity to the continent. In fact, the ECMWF topography contains no grid points adjacent to the ship track that are near sea level, and this has an obvious detrimental effect on temperature comparisons. This problem is not shared by the NCEP analyses which compare more closely to observation. In Cruises 1 and 3 it may be seen that the ECMWF produces a greatly smoothed representation of the temperature variability. The NCEP analyses contain a temperature variability similar to the analyses but at some cost to accuracy. The standard error for the NCEP analyses is substantially larger than for the ECMWF for Cruises 1 and 3. Further study indicates that the observational temperature is approximately 60% correlated with wind direction. This is not surprising given the contrast between the cold southern continental air and relatively warm oceanic air to the north of the sea ice edge. The ECMWF analyses are not so closely correlated. This may be due to the lack of initialization in the ECMWF analyses. Averaged for all cruises, however, the analyses are within approximately 1.0°C of the observed values. In Figure 28, comparisons with the observed relative humidity are shown. Some of the observed trends are similar to variations in the ECMWF, however the values are...
approximately 10% too high. The ECMWF analyses report 2 m dew point, rather than relative humidity, and the conversion to relative humidity requires accuracy in both temperature and dew point fields. The overestimation of moisture near the surface, however, is consistent with results from Bromwich et al. [1995] from comparisons against rawinsondes. NCEP relative humidity values show unusual variability throughout each cruise. While mean values for each cruise are similar to observation, the average standard error approaches 10%. Figures 29 and 30 present results for zonal and meridional wind comparisons respectively. The wind comparisons are very reasonable, with correlations of about 0.65 for the ECMWF and 0.57 for NCEP, which should be considered exceptional given the ship observations are translating through the analyses grid. The only significant departures from wind values occurred in Cruise 3 as the ship was under way for Auckland.

6. Summary

An evaluation of the Antarctic numerical analyses has been conducted using available rawinsonde, AWS, ship, and synthesized long-term observations. A comparison of ECMWF analyses with pressure readings from AWS units of the U.S. Antarctic Program reveals tremendous agreement using a variety of statistical measures for the 10-year period from 1985-1994. The NCEP analyses over the same period show substantial improvement, particularly during the period 1985 to 1990. Other AWS-observed variables do not agree so
closely, which may result from analyses error, the localized nature of the fields, or a combination. A validation of the near-surface temperature and wind fields with synthesized long-duration studies also show the ECMWF to be superior to the NCEP analyses, which generally shows a smoothed representation of the observations. In particular, the ECMWF compared closely to the long-term temperature field synthesized from observational data. Neither analysis was able to adequately reproduce barrier winds near the Antarctic Peninsula, although several other features of the katabatic wind field are adequately reproduced by the ECMWF analyses.

Validation of the analyses standard pressure level fields using available rawinsonde data reveal a general long-term decrease in RMS errors with time for both analyses. Unacceptable errors in the NCEP analyses prior to May 1986 over the central plateau of the continent have largely been removed, however a significant upward trend from 1989 to 1993 in geopotential height RMS differences is apparent at several levels. Grid values at specific stations including the now-closed Leningradskaya base and Mirny were found to be conspicuously deficient at the 200 hPa level for both analyses, while generally excellent results were obtained at Mawson and stations located east of the Weddell Sea. NCEP midtropospheric temperature analyses were generally found to be superior to the ECMWF after 1987. Positive biases between 4° and 7°C were found in the ECMWF temperature analyses at Vostok, although both analyses show large RMS errors for interior stations. Statistical scores computed for wind component validation show large variability between stations at all levels.

Comparisons of analysis values with supply ship
observations were made using observations from the S.A. Agulhas during the years 1991-1993. Pressure, temperature, and relative humidity variables were in close agreement, although a low pressure of 946.1 hPa was greatly overestimated by both analyses. In general, however, there was substantial evidence that the majority of data was being incorporated into the analyses. Further ship comparisons were made using data from the R/V Nathaniel B. Palmer for three 1-month-long cruises in 1993-1994. Observations made by the Nathaniel B. Palmer were not transmitted via the GTS. Comparisons again show substantial agreement, despite the substantial conventional data void. Comparisons of pressure, temperature, relative humidity, and wind fields find the ECMWF to be in substantial agreement with the observational data, with the NCEP analyses also in adequate agreement.

Although the ECMWF analyses appear to be remarkably consistent over the time period examined, this study highlights the hazards of using operational analyses for climatic study. A preliminary investigation of the NCEP reanalysis product shows improvement over the corresponding operational fields including the near-surface temperature; however, there are several caveats. An error was incurred during the assimilation of PAOBs (paid observations) data (E. Kalnay, personal communication, 1996), which are southern hemisphere point estimates of sea level pressure obtained from manually analyzed charts [Seaman et al., 1993]. The effect of this error on Antarctic
Figure 26. Comparison of mean sea level pressure from three R/V Nathaniel B. Palmer cruises with corresponding values from ECMWF and NCEP analyses, in hectopascals.

Figure 27. As in Figure 26 but for temperature, in degrees centigrade.
Figure 28. As in Figure 26 but for relative humidity, in percent.

Figure 29. As in Figure 26 but for the zonal wind component, in meters per second.
fields is not known. Additionally, a spectral distortion in high-latitude moisture fields has been found [Cullather et al., 1996], and this requires further examination.

Several conclusions of this study are drawn with regard to the FROST program. There is the general determination that a large amount of the observational data is being incorporated, and the comparisons to ship data not available to the numerical weather centers imply that the satellite data are having a major beneficial impact on the analyses. Although significant improvements are found, procedures for transferring available observational data to the GTS require further refinement. The authors have been in contact with station meteorological personnel at South Pole during the July 1994 FROST SOP. The transmission of South Pole rawinsonde reports has been found to be unusually eventful. Reports are first transmitted to McMurdo for forwarding to New Zealand and eventual transmission onto the GTS. This procedure of interstation data transfer through McMurdo is not always successful, however, and sometimes results in data exclusion from the analyses. In November 1991 an alternative route via Casey was established (S. Warren, personal communication, 1996). The Casey link has since been abandoned due to an apparent increase in reliability at McMurdo; however, preliminary FROST results indicate losses still occur.

In addition to communication problems it is clear that the total amount of non-AWS direct observational data for Antarctica, particularly the number of upper air reports, is presently in decline as a result of former Soviet base closures. It is hoped that this is only a temporary trend and will eventually reverse. Data scarcity and the loss and/or appearance of observational sites places additional priorities on the availability of satellite data and the NWP models for proper data assimilation. The evaluation of the global models used in the data assimilation will be addressed as part of the FROST exercise, and this may shed light on some of the deficiencies identified here.

Acknowledgments. The authors thank Grant Petty for providing data from the S.A. Agulhas, originally obtained from the South African Weather Bureau; Thomas Parish for unpacking and formatting the Antarctic rawinsonde data; William Connolley for examination of the GTS archive; and Linjuan Gong for assistance in data processing. Antarctic AWS station data were obtained from the University of Wisconsin, and numerical analyses and rawinsonde
data were obtained from NCAR. This research was sponsored by the National Science Foundation under grant ATM-9422104, and by the National Aeronautics and Space Administration under grant NAGW 3677. This is contribution 1025 of the Byrd Polar Research Center.

References


(Received March 8, 1996; revised September 6, 1996; accepted October 8, 1996.)

D. H. Bromwich and R. I. Cullather, Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210-1002.

R. W. Grumbine, NOAA/NWS/NCEP, W/NMC21, Room 206, 5200 Auth Road, Camp Springs, MD 20746-4304.