A Comparison of Five Numerical Weather Prediction Analysis Climatologies in Southern High Latitudes

WILLIAM M. CONNOLLEY AND STEPHEN A. HARANGOZO

British Antarctic Survey, Cambridge, United Kingdom

(Manuscript received 13 August 1999, in final form 6 February 2000)

ABSTRACT

In this paper, numerical weather prediction analyses from four major centers are compared—the Australian Bureau of Meteorology (ABM), the European Centre for Medium-Range Weather Forecasts (ECMWF), the U.S. National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR), and The Met. Office (UKMO). Two of the series—ECMWF reanalysis (ERA) and NCEP–NCAR reanalysis (NNR)—are “reanalyses”; that is, the data have recently been processed through a consistent, modern analysis system. The other three—ABM, ECMWF operational (EOP), and UKMO—are archived from operational analyses.

The primary focus in this paper is on the period of 1979–93, the period used for the reanalyses, and on climatology. However, ABM and NNR are also compared for the period before 1979, for which the evidence tends to favor NNR. The authors are concerned with basic variables—mean sea level pressure, height of the 500-hPa surface, and near-surface temperature—that are available from the basic analysis step, rather than more derived quantities (such as precipitation), which are available only from the forecast step.

Direct comparisons against station observations, intercomparisons of the spatial pattern of the analyses, and intercomparisons of the temporal variation indicate that ERA, EOP, and UKMO are best for sea level pressure; that UKMO and EOP are best for 500-hPa height; and that none of the analyses perform well for near-surface temperature.

1. Introduction

Meteorological data series in southern high latitudes and over the southern oceans are sparse, and studies of these regions often rely on numerical weather prediction (NWP) analyses. These are convenient in that they are available uniformly in time and densely in space and can provide a full set of meteorological parameters. However, it is necessary to verify that these analyses represent the true state of the atmosphere rather than the internal climatology of the model used to produce them. This is especially important in data-sparse regions where there may be little observational data to keep the analyses “on track.” To some extent the analyses can be verified against observations. However, there are now a sufficient number of analyses available that intercomparison of these analyses in data-sparse regions can help to decide which analyses are likely to be correct (on the basis of consistency) and which should be used with caution. Although it might seem obvious that the reanalyses are better, in that they are more consistent and use more modern analysis schemes, they do not benefit

from the manual intervention possible in the operational analyses that can, for example, allow a varying “black-list” of stations temporarily reporting bad values.

Our primary focus in this paper is on the period of 1979–93 (the period used for the reanalyses) and on climatology (long-term means and interannual variation) rather than on synoptic comparisons of individual events. However, we are also interested in the period before 1979. Only the Australian Bureau of Meteorology (ABM, which began in 1972) and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (NNR, which extends back to 1966 at the time of writing and is planned to go back further) cover pre-1979. Until recently only ABM was available for this early period, and in consequence it has been a primary source for many studies (Trenberth 1979; Karoly 1989; Hurrell and van Loon 1994). The recently produced NNR reanalysis can now be used as a cross-check on the early ABM analyses.

A synoptic study of NWP and high-quality manual analyses near Antarctica for July 1994 is described in Turner et al. (1996), and a detailed treatment of the NCEP operational analyses for this same period is given by Bromwich et al. (1999). A comparison of European Centre for Medium-Range Weather Forecasts (ECMWF) operational (called here EOP) and NCEP operational anal-

Corresponding author address: W. M. Connolley, British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET United Kingdom.
E-mail: wmc@bas.ac.uk

TABLE 1. Periods covered by the (re)analyses, and notes.

Analysis	Period	Notes
ERA	Jan 1979–Feb 1994	Reanalysis
EOP	Dec 1985–current	
NNR	1966–current	Reanalysis
UKMO	May 1983–current	Some days missing from early monthly averages
ABM	Apr 1972–Jun 1994	Southern Hemisphere only

yses (not used here), for the period of 1985–95, is presented by Cullather et al. (1997). Their focus is almost entirely over the Antarctic continent, where they find EOP to be generally superior. However, the NCEP operational analysis evolves considerably during their period and for some fields (e.g., midtropospheric temperatures, not covered here) they found it to be superior to EOP by the end of their period. Karoly and Oort (1987) compare ABM analyses from 1972 to 1982 with circulation statistics compiled by the Geophysical Fluid Dynamics Laboratory for the period of 1963–73. They find large differences in 500-hPa height and 200-hPa zonal wind between the analyses away from radiosonde stations, which they attribute mostly to the differences in the analysis methods used rather than the different time periods of the two datasets.

In this paper we shall be concerned with basic variables—mean sea level pressure (MSLP), height of the 500-hPa surface, and near-surface temperature—that are available from the basic analysis step, rather than more derived quantities (such as precipitation), which are available only from the forecast step. Several studies have used (re)analyses to examine precipitation over Antarctica (Cullather et al. 1998; Genthon and Krinner 1998; Turner et al. 1999) and have generally found problems with this field: there is considerable difference between ECMWF reanalysis and operational, with NNR markedly inferior.

2. Data and methods

The analyses used here are the ECMWF reanalysis (ERA; Gibson et al. 1997); ECMWF operational (EOP; ECMWF 1992); NCEP–NCAR reanalysis (NNR; Kalnay et al. 1996); The Met. office operational [UKMO; Cullen (1993), and references therein], and ABM operational (Le Marshall et al., 1985). The periods for which data are available to us are summarized in Table 1.

Although several analyses are available after 1993, we are interested in a wide intercomparison so we shall only use data up to 1993. All data have been interpolated from their native grids onto a common grid of 2.5° lat $\times$ 3.75° long.

Both ERA and NNR are “reanalyses”: unlike UKMO and EOP, the analysis system has been fixed for the entire period. This does not guarantee complete consistency: the quality and coverage of the input data have

FIG. 1. Zonal mean of the pointwise interannual (a) rms in JJA, (b) std dev in JJA, and (c) rms in DJF of the difference between the 1988–93 MSLP in the analyses against ERA. NNR solid; UKMO dotted; EOP dashed; ABM dot-dash.

varied. In most cases, it has improved: for example, Uppala (1997) notes that the rms fit of radiosonde heights to ERA improves from 1979 to 1993 and is shown by closer inspection to be due to improvements in the radiosondes. The analysis scheme used in ERA is not the same as EOP at any given date, but does correspond roughly to the EOP scheme in late 1994 (J. K. Gibson 1998, personal communication). The ABM scheme (Le Marshall et al. 1985) is not formally a reanalysis but has remained substantially unchanged. Note that the ABM analyses ceased production in 1994 and that the analysis method used in their production (based on the Cressman successive correction method) was less sophisticated than that used in the other datasets. The ECMWF reanalysis is not guaranteed to be better than the operational analysis [e.g., Bromwich et al. (1999) point out problems with the 500-hPa height field near Vostok in ERA; this is examined in section 4a]. The operational analysis allowed for more manual intervention and the use of a variable “blacklist” of bad stations; for the reanalyses, this flexibility is removed.

NNR and ERA both used the “PAOB” synthetic MSLP observations originated for the ABM analysis. Due to an error, the NNR reanalysis for the period 1979–

FIG. 2. Difference in the mean 1988–93 MSLP for (a) JJA and (b) DJF of (i) NNR, (ii) UKMO, and (iii) ABM – ERA. Contour interval 1 hPa; zero contour bold; negative contours dashed; filled above ± 1 hPa; darker filled above ± 3 hPa.

92 introduced the PAOBs at 180° from their true position; this degrades NNR somewhat, particularly between 40° and 60°S . However, the degradation is not great, since the PAOBs were given a low weight and often rejected by the quality control scheme. Uppala (1997; his figure 208) shows that PAOBs have only a slight impact on the quality of ERA: their fit to the first-guess field is much worse than drifting buoys and their impact on the analysis much less.

Note that we have data only for the ABM scheme from the Southern Hemisphere and it has a native polar stereographic grid, which becomes very coarse toward the equator; values for ABM north of 15°S have not been used.

For initial consideration we shall use 1988–93 as a reference period because it is late enough to avoid early problems with the nonreanalysis schemes, but is still within the reanalysis period. There are various possible measures of “difference” between analyses that we could use: we shall concentrate on rms {defined, for a sample $\{x_i\}$ of size n , as $[\sum x_i^2/(n-1)]^{1/2}$ }, which measures bias and variation, and std dev $\{[\sum (x_i - \mu)^2/(n-1)]^{1/2}$, where μ is the sample mean}, which just mea-

sures variation. None of the analyses can claim to be a completely accurate standard. Nonetheless, to avoid having to plot all possible pairs, it is convenient to choose one scheme as a reference. It is natural to choose one of the reanalyses (ERA or NNR) for this purpose, and would perhaps be sensible to avoid NNR because of its known potential problems with PAOBs. If we assume that the analyses can be represented as “truth + bias + error,” where bias is time-invariant and error is time-varying with zero mean at each point; and that the bias (spatially) and error (temporally) are uncorrelated between pairs of analyses (an assumption that, in practice, will not be strictly true), then the analysis closest to the truth will show as having the lowest std dev or rms differences against other schemes.

3. Mean sea level pressure

Figure 1a shows the zonal mean of the pointwise interannual rms of the difference between the analyses, Fig. 1b the std dev, for Southern Hemisphere winter (June–August, JJA). Differences are shown against ERA. Points over high orography (greater than 500 m)

FIG. 2. (Continued)

FIG. 3. Difference of analyzed (65°S , 112.5°E) and observed (66.3°S 110.5°E ; Casey) MSLP in JJA. Solid line: NNR; dotted: UKMO; dashed: ERA; dot-dash: ABM; dot-dot-dot-dash: EOP. Note that Aug 1989 observations are not available.

are masked out before the zonal mean is applied, and latitudes with less than 50% unmasked are not plotted. Examination of all possible pairs (not shown) supports the choice of ERA as a reference: for most latitudes, for both rms and std dev, differences are lower when the pairs include ERA than when they do not.

For most analyses Figs. 1a (rms) and 1b (std dev) are similar in form, although values in Fig. 1a, which include the bias in the mean at each point, are of course larger. The exception to this is ABM, which has a large bias between 30° and 60°S , which will be investigated further in later sections.

Excluding the bias in ABM, there is a strong increase

TABLE 2. Comparison of analyses and observations at Russkaya for JJA 1986–87.

Scheme	Value (hPa)	Difference from observations (hPa)
Observations	984.2	—
ERA	985.8	1.6
EOP	984.8	0.6
NNR	990.8	6.6
UKMO	983.5	−0.7
ABM	983.1	−1.1

FIG. 4. Difference of analyzed and observed MSLP at Kerguelen for (a) JJA and (b) DJF. Line types as for Fig. 3.

in difference from about 30°S to the southern limit. No such increase is seen between corresponding latitudes in the Northern Hemisphere in Figs. 1a and 1b. Some of this is due to the paucity of observations in the Southern Hemisphere and some to the greater degree of variability in the winter hemisphere. Figure 1c [as Fig. 1a, but for Southern Hemisphere summer, December–February (DJF)] shows that differences are still larger in the Southern Hemisphere in this case, though not by as much as in JJA.

ERA and EOP are the most similar in both seasons. NNR – ERA differences are not much larger than ERA – EOP north of 30°S but become large south of 50°S: this is possibly related to the PAOBs problem. UKMO differences peak at about 1.5 hPa (in the zonal mean) and are consistently about 0.4 hPa larger than EOP south of 40°S. ABM differences are similar to UKMO between the equator and 30°S, and south of 60°S, but are much larger between 30° and 60°S.

ERA and EOP differences do not exceed 1 hPa in the zonal mean in Fig. 1; pointwise, the differences in the 1988–93 means, for each of the four seasons, are less than this level almost everywhere. To the level of accuracy we are considering here they can be considered the same for the MSLP field, though not for the 500-hPa height field (Bromwich et al. 1999), and we shall generally omit EOP MSLP from further analysis.

The differences are seen to be substantially larger in

FIG. 5. Variation by year of the area-averaged rms difference of MSLP in (a) JJA and (b) DJF, between selected pairs of analyses, for the region from 45°S to the pole, excluding land areas. Solid line: NNR – ERA; dotted: ERA – EOP; dash: ABM – NNR; dot-dash: UKMO – ERA; dot-dot-dot-dash: ERA – ABM.

the Southern Hemisphere than the Northern Hemisphere poleward of 30°S (Fig. 1). In the following sections we shall restrict our attention to the region south of 45°S and consider that differences larger than 1 hPa are above the “noise level.”

a. Differences in the seasonal mean

We now consider differences in the seasonal means of the analyses, again for the reference period 1988–93. Figures 2a and 2b show the differences from ERA in winter and summer, respectively. The differences are generally less than 1 hPa for NNR and UKMO, but almost always larger than 1 hPa for ABM. Indeed differences with ABM exceed 2 hPa over large areas in winter, although differences are somewhat less in summer. This, and Figs. 1a and 1c, suggest that the ABM analyses are biased over the southern oceans where the differences occur—this is considered further in section

FIG. 6. Difference between the mean of ABM and NNR MSLP in JJA for the periods of (a) 1973–78 and (b) 1988–93. Contour interval 1 hPa; filled above ± 1 hPa and darker filled above ± 3 hPa.

3b. Note that the differences are notably lower over Australia, New Zealand, and South America.

Differences between UKMO and ERA in both summer and winter are less than 1 hPa almost everywhere, with peak values of 3 hPa in summer at 150°W. In both winter and summer the difference pattern appears to have a wave-2 structure, which may reflect a bias in the model climatology. The areas of large difference are in unobserved regions, so no direct verification against observations is possible.

For NNR, differences are larger, although substantial differences (above 3 hPa) are mostly confined to the unobserved seas between 90° and 180°W, in both summer and winter. As for the UKMO – ERA differences, there is a suggestion of a wave-2 pattern to the difference structure. Unlike UKMO, NNR has substantial differences from ERA around the East Antarctic coast in winter, where observations are available for verification. Unfortunately the model orographies are unable to resolve the relatively steep coastal slopes and so stations that are in reality near sea level are represented in the model by points at heights of hundreds of meters [the differences seen in Fig. 2a (i) are not confined to over orography, however, so they do represent a real difference]. This makes direct comparison difficult, since the problem of reduction to sea level is introduced. To make a comparison we choose a location, Casey (66.3°S, 110.5°E) where the problem is quite marked and compare with model values just off the coast, at (65°S, 112.5°W) which should (in reality) be little different from the station values. Figure 3 shows this comparison in winter, and shows that the NNR values are generally 4 hPa too high, and the other three analyses are approximately correct. In fact, UKMO and ABM values appear to be better than ERA at this station, suggesting that the positive differences seen near Casey in Figs. 2a (ii) and 2a (iii) indicate a slight bias in ERA.

NNR MSLP is more than 4 hPa higher around west Antarctica than the other analyses [Fig. 2a (i)]. Data from this region are quite sparse, but some observations from Russkaya (74.8°S, 136.9°W) are available. Table 2 indicates that it is NNR that is wrong (more than 6 hPa too high), with the other analyses broadly correct: UKMO and EOP are closest (within 1 hPa), but there is (not shown) considerable year-to-year variation.

Bromwich et al. (1999) show (their Fig. 11b) that, for the operational NCEP MSLP during July 1994, there are positive differences between forecast and analysis particularly at 45°E and in the Ross Sea. This tendency would reduce the difference seen in Fig. 2a (i), insofar as the NCEP operational scheme resembles the reanalysis scheme.

b. Investigation of the bias in ABM

Kerguelen station (49.3°S, 70.2°E) is conveniently located to allow a direct comparison against observations in the seas around Antarctica. Figure 4 shows a comparison from 1973 to 1993 of analyses and observations at Kerguelen [Marion Island (46.9°S, 37.9°E) shows similar results] in winter and summer (1989 is omitted from 4a because the given MSLP value for Kerguelen for June 1989 is wrong: it appears to be a repeat of the 1988 value). Figures 1 and 2 suggested a mean bias at the latitude of Kerguelen Island in the ABM analysis. Figure 4 confirms that the difference is fairly constant year-to-year. The ABM analysis is interpolated from a polar stereographic grid and there could be some worry

FIG. 7. Interannual std dev of MSLP in JJA for (a) ABM and (b) NNR for (i) 1973–82 and (ii) 1984–93. Contour interval 1 hPa; filled above 2 hPa and darker filled above 4 hPa.

that the interpolation is introducing errors, particularly in a region where the MSLP gradient is steep. However, we have checked that the interpolation errors are not significant.

Another potential problem is diurnal variation. The ABM fields used here are averages of fields for 0000 and 1200 UTC. Trenberth (1979) warned that, because of differences in data coverage, spurious differences existed between the 0000 and 1200 UTC fields. However, such differences are small, particularly in the latter period examined here (averaging less than 0.4 hPa in JJA between 1988 and 1993), and cannot explain the bias seen.

c. Yearly variation

The variation by year of the area-averaged rms difference of MSLP between selected pairs of analyses, for the region from 45°S to the pole, excluding land areas, is shown in Fig. 5. As seen in the previous sections, the differences are larger in JJA than in DJF. There is a rough trend of convergence from about 1980 onward. Before 1979, there is no evident trend in NNR – ABM in summer or winter. However, the variability in NNR – ABM is larger in the early period.

The difference between a 6-yr JJA mean of ABM and NNR for the period 1973–78 is shown in Fig. 6a, and can be compared with Fig. 6b, which is for the period 1988–93. Differences in the early period, especially over the poorly observed South Pacific sector, are very large in 1973–78, exceeding 7 hPa in winter. Between 10°W and 180°E, however, the differences appear to be marginally less during the earlier period. Differences in summer (not shown) are also larger than for the later period for the area off west Antarctica. This indicates that at least one of the analyses is less reliable in the early years in the South Pacific area, but cannot tell us which of the two analyses is more nearly correct.

There are no station data to verify the differences in the South Pacific. However, comparison of the analyses against observations at Kerguelen (Fig. 4) shows that the bias in ABM is marginally lower in the early period (1973–79) in both summer and winter, whereas the bias of NNR is larger in summer, with particularly poor years in 1974, 1976, and 1977. At Marion Island there is no significant change apparent before 1979: NNR remains less biased than ABM, in both summer and winter.

One particular interest in using ABM has been for variability studies (e.g., Hurrell and van Loon 1994), for which long time series are needed. However, Con-

FIG. 8. Zonal mean of the pointwise interannual (a) rms in JJA, (b) std dev in JJA, and (c) rms in DJF of the difference between the H500 in the analyses against ERA. NNR solid; UKMO dotted; EOP dashed; ABM dot-dash.

nolley (1997) has pointed out that although recent analyses (including ABM) and climate models agree on the pattern of variability, the early ABM analyses are somewhat different. Figure 7 compares the JJA NNR and ABM interannual std dev fields for the first decade (1973–82) and the last (1984–93) available. There is excellent agreement for the later period, but clear disagreement (especially over the South Pacific north of 60°S) in the early period. Connolley (1997) showed that high variability in this region is a very robust feature in climate models, which suggests that the low variability of the ABM between 1973 and 1982 in the region is doubtful.

4. Geopotential height at 500 hPa

Geopotential height at 500 hPa (H500) is a useful diagnostic of the large-scale circulation of the middle troposphere. The 500-hPa level is above the continental surface and boundary layer for all of Antarctica and so, unlike MSLP, we can meaningfully examine the field over the continent.

Figure 8 is similar to Fig. 1 except showing H500.

FIG. 9. Zonal mean of the pointwise interannual rms in JJA of the difference between the H500 in the analyses against UKMO. NNR solid; ERA dotted; EOP dashed; ABM dot-dash.

In the Northern Hemisphere, which (as for MSLP, we take as an approximate measure of the level of similarity possible with a dense observing network), differences are higher in the winter than the summer season. The std dev and rms differences are quite flat between the equator and 60°N, and from there they tend to increase toward the pole. In the Southern Hemisphere differences are larger and increase considerably from the equator poleward, both in the rms (which includes bias) and the std dev (which only measures interannual changes). In winter there is a clear minimum in the rms (but not std dev) at about 65°S (Fig. 8a), which is probably because this is the average latitude of the radiosonde stations around the coast of Antarctica and data from these stations can constrain the models. Uppala (1997) provides more detail on the distribution of rms error and bias in the ERA analysis and first guess fields: his Fig. 54 shows a poleward increase similar to our Fig. 8.

Figure 8c shows the same presence of bias in ABM in H500 as was shown in Fig. 1 from MSLP. However, Fig. 8a shows ERA and ABM agreeing, with large differences from NNR, UKMO, and EOP. Figure 9, which is similar to Fig. 8a but referenced to UKMO, suggests that this is a bias in ERA between 30° and 60°S, since ERA is substantially different from EOP, UKMO, and NNR, whereas these three analyses agree closely among themselves.

Differences in the seasonal mean

The differences in H500 for the period of 1988–93 are shown in Fig. 10, with UKMO selected as the reference. UKMO is selected because it has the smallest difference against all other analyses south of 30°S. In winter, over the southern oceans, there are large differences against ERA and ABM (greater than 1 dm over most of the region and greater than 3 dm in places) and relatively small differences (generally less than 1 dm) against NNR and EOP. Kerguelen station provides data for verification but the data we have available (from CLIMAT TEMP messages) are unfortunately very sparse. However, the pattern of differences from July 1992 and

FIG. 10. Difference in the mean 1988–93 H500 for (a) JJA and (b) DJF of (i) ERA, (ii) NNR, (iii) ABM, and (iv) EOP – UKMO. Contour interval 10 m; zero contour bold; negative contours dashed; filled above ± 10 m and darker filled above ± 30 m.

1993 (Table 3) is quite consistent and implies that it is, indeed, ERA and ABM that are in error.

In summer (Fig. 10b), only differences against ABM are large (greater than 1 dm over a substantial area), just as for MSLP. For both winter and summer, differences tend to be smallest over the east Antarctic coast and the tip of the Antarctic Peninsula, where radiosonde data keep the analyses on track. Exceptions to this are the substantial discrepancies at about 140°E between NNR and UKMO. This area is covered by the station Dumont D'Urville (66.7°S , 140°E). Table 4 shows that NNR differs from observations at this location, more strongly in winter, whereas the other analyses have smaller differences, with EOP being the most consistent.

Figure 10 also shows significant interanalysis differences over the interior of Antarctica, stronger in winter but significant in summer. A comparison with Vostok (78.5°S , 106.9°E) shows that only ABM and EOP are close to observations. The value of the comparison at Vostok is somewhat reduced by problems determining the height of the station, which affects the height of the 500-hPa surface. Values from 3420 to 3500 m have been used, and the current best estimate is 3495 ± 10 m (N. Young 1998, personal communication). In the case of

ERA, the height of Vostok was incorrectly specified by 30 m, which is consistent with the differences shown in Table 4. EOP used the same wrong height for Vostok, but implemented a more rigorous “blacklist,” which meant that the Vostok observation was usually rejected. The low difference at Vostok for EOP is thus a result of a good model climatology or the remote influence of other stations. UKMO used a height of 3420 m for Vostok until 1995, which is also consistent with the bias shown in Table 4. NNR used 3488 m.

5. Near-surface temperature

Near-surface temperature is, in observations, temperature at “screen height,” that is, about 1.5 m. In the NWP models this quantity is computed from surface and lowest-model-level temperature. It is generally very close to surface temperature (within a degree or so unless a very strong surface inversion is present), and obviously is heavily influenced by surface temperature. It is not available from ABM, which is omitted from the analysis in this section. Over the ocean, surface temperature is analyzed from satellite retrievals, ship and buoy observations and is essentially the same in all

FIG. 10. (Continued)

analyses, so we shall consider only the temperatures over the continent and sea ice.

Unlike MSLP or H500, which are large-scale fields with dynamical constraints that allow the field to be influenced and constrained by quite distant observations, the surface temperature field is less constrained and, as we shall show, subject to larger errors than, say, MSLP. This is in agreement with the results of Cullather et al. (1997), who compared EOP and NCEP operational schemes with observations. Further, near-surface temperatures are not used in the analysis schemes on the grounds that surface temperature is (over most of the world) too much affected by the local situation to be representative of a model grid point. Therefore, the sur-

face temperature is only weakly constrained in the analyses.

Surface temperature is strongly affected by height and all the analyses use different orography fields, which in a few areas differ substantially. In order to try to remove spurious differences, the analyses have been adjusted for orography differences by reference to the “BAS” digital elevation model for Antarctica (SCAR 1993) assuming a lapse rate of $0.006^{\circ}\text{C m}^{-1}$ (Schwerdtfeger 1984, his Fig. 4.4.). This leads to temperature corrections that are generally less than 2°C and improves agreement between the analyses.

a. Differences in the mean temperature

There are significant differences between near-surface temperature in all pairs of analyses, in both winter and summer. Figure 11 shows the JJA climatology for EOP, and the difference from this for the other analyses. EOP is chosen as a reference for Fig. 11, not because it is known to be correct but because it is closest to the mean of other analyses. In addition, Fig. 12 shows the difference between the least similar pair, ERA and NNR. These are of particular interest because they are the two reanalyses.

TABLE 3. Observed and analyzed H500 (dam) at Kerguelen in July for 1992 and 1993.

	1992	Analysis– Obs.	1993	Analysis– Obs.
Observation	518.7	—	532.0	—
UKMO	517.5	–1.2	531.0	–1.0
ERA	515.5	–3.2	528.8	–3.2
ABM	515.4	–3.3	529.5	–2.5
EOP	518.4	–0.3	531.8	–0.2

TABLE 4. Observed and analyzed H500 (dm) at Dumont D'Urville and Vostok.

Station, season	Dumont, JJA	Dumont, DJF	Vostok, JJA	Vostok, DJF
Obs	498.0	516.4	496.7	512.9
NNR - Obs	-3.0	-1.7	-6.4	-2.6
UKMO - Obs	1.1	-0.5	-8.9	-5.7
ERA - Obs	0.8	1.6	-5.2	-2.7
ABM - Obs	-0.5	-1.2	-1.7	1.0
EOP - Obs	0.7	0.5	-1.2	-1.6
Years (19XX)	88, 89, 90, 93	92	83-88, 90, 91	83, 86, 88, 90

The most similar pair, EOP and UKMO (Fig. 11d) are similar (errors less than 4°C) over most of the sea-ice regions and much of the continental interior, and even the Antarctic peninsula. However, there are significant differences around the edges of East Antarctica of more than 8°C, with EOP warmer. To some extent the agreement between EOP and UKMO is fortuitous, because there is a substantial “jump” in UKMO at 1991 [when a new model was introduced; Cullen (1993)], as will be seen in the next section.

ERA is warmer than EOP (Fig. 11b) over the sea ice from 180°W around West Antarctica to the Weddell Sea, and somewhat cooler over most of the continent except for the highest orography. NNR shows the opposite pat-

tern (Fig. 11c), although differences are smaller over the continent and larger over the sea ice.

In winter, differences between ERA and NNR are greater than 8°C over substantial areas of the continent and the sea ice zone (Fig. 12). Some of these differences might be explained by errors in the specification of the boundary conditions: for example NNR has the sea ice 3 m thick (R. Grumbine 1998, personal communication) instead of the more plausible value of 1 m used in ERA. Both ERA and NNR have the Ross and Ronne-Filchner ice shelves as 100% sea ice rather than land ice, and ERA is up to 20°C warmer in these regions. Both re-analyses use sea ice at 100% cover, which will artificially reduce sea-air heat fluxes (Watkins and Sim-

FIG. 11. Near-surface (1.5 m) temperature for (a) EOP, (b) ERA - EOP, (c) NNR - EOP, and (d) UKMO - EOP. Contour interval (a) 10°C, (b)-(d) 4°C; negative contours dashed.

FIG. 12. Near-surface (1.5 m) temperature for NNR – ERA. Contour interval 4°C; shaded where differences exceed 4°C and darker shaded above 12°C.

monds 1995) and thereby introduce a negative bias in near-surface temperatures.

b. Interannual variation

The differences in the mean discussed in the previous section do not show which, if any, of the analyses are correct; nor do they reveal any possible evolution with time, which might be expected from the operational analyses. Figure 13 shows a comparison of station observations at three stations in the interior of East Antarctica: Vostok (78.5°S, 106.9°E), Amundsen–Scott (90°S), and Dome C (74.5°S, 123°E) in winter and summer. Unfortunately Vostok data becomes sparse after 1991 and Dome C data are not available before 1982. The data have been adjusted for orographic errors as mentioned above. For Amundsen–Scott the adjustment is small; for Vostok and Dome C the models are adjusted down by about 1° and 1.5°C, respectively.

In Fig. 13 there is a clear rise of about 10°C in the UKMO values between 1990 and 1991, corresponding to the introduction of a completely new model (Cullen 1993). This illustrates the potential problems of working with operational data. Early UKMO values were clearly far too low; the values past 1990 appear in line with the other analyses, but with only 3-yr data nothing more definitive can be said.

ERA is consistently colder than the observations by between 5° and 10°C at all three locations in winter. It also appears to be biased cold, but only by a few degrees, in summer. NNR is roughly correct in winter, except at Dome C where it is too cold; and too warm by about 5°C in summer. EOP is reasonable in both summer and

winter at Vostok but too cold in winter at Amundsen–Scott in winter after 1990, and somewhat too cold in summer at Dome C before 1991 [cf. Cullather et al. (1997), their Fig. 10].

There are large differences in winter over the Ross and Ronne-Filchner ice shelves (Fig. 11). The Ross, but not Ronne-Filchner, has a reasonable network of automatic weather stations (AWSs; Stearns et al. 1993), which allow us to verify the analyses. AWSs may be less reliable than manned stations: they are checked less often, generally once a year. We have only used years when an adequate number of observations are available: the AWS reports are available at 3-h intervals so there should be 736 observations for JJA. We have not used years with less than 500 observations; for all AWSs more than two-thirds of the years used for the comparison had more than 700 observations in JJA. Figure 14 shows a comparison with data from the Ferrell (78°S, 170.8°E), Gill (80°S, 178.6°W), and Lettau (82.6°S, 174.3°W) AWSs. Figure 11 showed substantial differences between ERA and NNR in this region with ERA much warmer; Fig. 14 shows that NNR is more nearly correct, although still substantially too warm at the most southerly station, Lettau. The warm bias in ERA is probably explained by the incorrect specification of the ice shelf as sea ice. UKMO is somewhat too warm at Gill but agrees with NNR at Ferrell; the discontinuity in UKMO seen in the interior in Fig. 13 is not obvious here. EOP is curiously invariant year to year at these locations: the other analyses, even when considerably biased, do at least tend to move in phase with variations in the observations.

6. Summary and conclusions

MSLP fields, as would be expected, are less well constrained in the Southern Hemisphere than the Northern (even taking into account seasonal effects) and differences increase toward the pole. However, the largest differences in rms are still only about 3 hPa, and north of 60°S rms differences are less than 1.5 hPa, if ABM is excluded (Fig. 1). Between 30° and 60°S there is a clear bias in ABM relative to the other analyses (Figs. 1 and 2) and station observations (Fig. 4). There is a smaller bias in NNR in both summer and winter that is largest in the Bellingshausen Sea region and near Antarctica at about 100°E (Fig. 2). The bias is confirmed as an error in NNR by observations from Russkaya (Table 2) and Casey (Fig. 3). This bias is unlikely to be due to the problems with PAOBs, which would be expected to affect the mean bias, if at all, in a wave-1 pattern. UKMO, EOP, and ERA are quite similar in the zonal mean, with maximum differences of 1 hPa and generally much less. When interannual variation is considered (Fig. 1) EOP and ERA are the closest; however, comparisons with station observations (Figs. 3 and 4) marginally favor UKMO.

An evaluation of the early years (before 1979) of

FIG. 13. Near-surface (1.5 m) temperature at three interior stations: (a) Vostok, (b) Amundsen-Scott, and (c) Dome C in (i) JJA and (ii) DJF from 1979 to 1993. Solid line observations; ERA dotted; NNR dashed; UKMO dot-dash; EOP dot-dot-dot-dash.

ABM and NNR showed that major changes occurred in the South Pacific region. A consideration of variability, where the early ABM shows reduced variation in this region between 40° and 50°S, suggests that NNR is more nearly correct.

H500 fields are less well analyzed than MSLP, presumably because fewer observations are available to correct the analyses. However, the ratio of increase in std dev and rms in the Southern Hemisphere over the northern is of the same order as for MSLP. For the reference period, UKMO and EOP appear to be better (measured as difference between the analyses or as comparison with observations) than ERA (which shows a bias in winter), ABM (which shows a bias as for MSLP), or NNR. However, UKMO (and some other analyses) are biased in the interior, due to incorrect specification of the height of Vostok station.

Near-surface temperature fields are only weakly constrained by the analysis procedure and differ widely between the various analyses. A comparison with observations shows that all analyses have faults, varying with time of year. The reanalyses are not better than the operational analyses, and indeed the largest difference between pairs of analyses is between NNR and ERA. Over Antarctica and the surrounding sea ice, the near-surface temperature fields from the analyses should be used with caution, or perhaps better not used at all. ERA has used an incorrect land-sea mask that causes large positive temperature errors over the Ross and Ronne-Filchner ice shelves. NNR has used a sea-ice thickness of 3 m (where 1 m would be more nearly correct), which is more appropriate to the Arctic, and which causes negative biases in winter. Both reanalyses use sea ice at 100% cover, which is known to artificially reduce

FIG. 14. The 1.5-m winter temperature for three AWS stations on the Ross ice shelf: (a) Ferrell, (b) Gill, and (c) Lettau. Line types as for Fig. 13.

sea-air heat fluxes and thereby to introduce a negative bias.

ERA, EOP, and UKMO are found to be best for MSLP; UKMO and EOP are best for 500-hPa height; and none of the analyses perform well for near-surface temperature, but EOP is probably the least bad.

Acknowledgments. We thank John King for helpful discussions; Coleen de Villiers of the South African Weather Bureau for the Marion Island data; Phil Jones of the Climate Research Unit, University of East Anglia, for supplying the Kerguelen data; the Australian Bureau of Meteorology, and the assistance of David Jones formerly at the University of Melbourne, Australia, for the ABM analyses; the ECMWF and the British Atmospheric Data Centre for ERA analyses; Steven Leonard for retrieving EOP analyses from ECMWF; and The Met. Office for access to the UKMO analyses.

REFERENCES

- Bromwich, D. H., R. I. Cullather, and R. W. Grumbine, 1999: An assessment of the NCEP operational global spectral model forecasts and analyses for Antarctica during FROST. *Wea. Forecasting*, **14**, 835–850.
- Connolley, W. M., 1997: Variability in annual mean circulation in southern high latitudes. *Climate Dyn.*, **13**, 745–756.
- Cullather, R. I., D. H. Bromwich, and R. W. Grumbine, 1997: Validation of operational numerical analyses in antarctic latitudes. *J. Geophys. Res.*, **102**, 13 761–13 784.
- , —, and M. L. Vanwoert, 1998: Spatial and temporal variability of antarctic precipitation from atmospheric methods. *J. Climate*, **11**, 334–367.
- Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteor. Mag.*, **122**, 81–94.
- ECMWF, 1992: ECMWF data assimilation. Research Manual 1, 93 pp. [Available from ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX United Kingdom.]
- Genthon, C., and G. Krinner, 1998: Convergence and disposal of energy and moisture on the Antarctic polar cap from ECMWF reanalyses and forecasts. *J. Climate*, **11**, 1703–1716.
- Gibson, J. K., P. Kallberg, S. Uppala, A. Nomura, A. Hernandez, and E. Serrano, 1997: ERA description. ECMWF Re-Analysis Project Report Series 1, 72 pp. [Available from ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX United Kingdom.]
- Hurrell, J. W., and H. van Loon, 1994: A modulation of the atmospheric annual cycle in the Southern Hemisphere. *Tellus*, **46A**, 325–338.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Karoly, D. J., 1989: Southern Hemisphere circulation features associated with El Niño–Southern Oscillation events. *J. Climate*, **2**, 1239–1252.
- , and A. H. Oort, 1987: A comparison of Southern Hemisphere circulation statistics based on GFDL and Australian analyses. *Mon. Wea. Rev.*, **115**, 2033–2059.
- Le Marshall, J. F., G. A. M. Kelly, and D. J. Karoly, 1985: An atmospheric climatology of the Southern Hemisphere based on ten years of daily numerical analyses (1972–82). Part I: Overview. *Aust. Meteor. Mag.*, **33**, 65–85.
- Schwerdtfeger, W., 1984: *Weather and Climate of the Antarctic*. Elsevier, 261 pp.
- Scientific Committee on Antarctic Research (SCAR), 1993: Antarctic digital database and user's guide and reference manual. Scott Polar Research Institute, British Antarctic Survey and the World Conservation Monitoring Centre, 101 pp.

- Stearns, C. R., L. M. Keller, G. A. Weidner, and M. Sievers, 1993: Monthly mean climatic data for Antarctic automatic weather stations. *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations. Antarctic Research Series*, Vol. 61, D. H. Bromwich and C. R. Stearns, Eds., Amer. Geophys. Union, 1–21.
- Trenberth, K. E., 1979: Interannual variability of the 500 mb zonal mean flow in the Southern Hemisphere. *Mon. Wea. Rev.*, **107**, 1515–1524.
- Turner, J., and Coauthors, 1996: The Antarctic First Regional Observing Study of the Troposphere (FROST) Project. *Bull. Amer. Meteor. Soc.*, **77**, 2007–2032.
- , W. M. Connolley, S. Leonard, G. J. Marshall, and D. G. Vaughan, 1999: Spatial and temporal variability of net snow accumulation over the Antarctic from ECMWF re-analysis project data. *Int. J. Climatol.*, **19**, 697–724.
- Uppala, S., 1997: Observing system performance in ERA. ECMWF Re-Analysis Project Report Series 3, 261 pp. [Available from ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX United Kingdom.]
- Watkins, A. B., and I. Simmonds, 1995: Sensitivity of numerical prognoses to Antarctic sea-ice distribution. *J. Geophys. Res.*, **100**, 22 681–22 696.