Artificial Surface Pressure Trends in the NCEP–NCAR Reanalysis over the Southern Ocean and Antarctica*

KEITH M. HINES

Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, Ohio

DAVID H. BROMWICH

Polar Meteorology Group, Byrd Polar Research Center, and Atmospheric Sciences Program,
Department of Geography, The Ohio State University, Columbus, Ohio

GARETH J. MARSHALL

British Antarctic Survey, Cambridge, United Kingdom

(Manuscript received 21 June 1999, in final form 2 March 2000)

ABSTRACT

An examination of 50 years of the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis from 1949 to 1998 reveals that significant spurious trends occur in the surface pressure field. Long-term surface pressure reductions are apparent south of 45°S. The largest trend in surface pressure is near 65°S where an approximately steady long-term pressure reduction of about 0.20 hPa yr^{-1} (10 hPa in 50 yr) is located. The negative pressure trend represents a gradual reduction in a positive bias for the reanalysis. Observations at Antarctic stations do not support this long-term trend, although short-term interannual variations are reasonably well captured after about 1970. The negative pressure tendency near 65°S continues well into the 1990s although a reasonable number of stations between 65° and 70°S began taking observations along the coast of east Antarctica during the 1950s and 1960s. Few Antarctic observations, however, are used by the reanalysis until about 1968, and the quality of the pressure field for the reanalysis appears poor in high southern latitudes prior to then. The trend in high southern latitudes appears to be a component of global temporal variations in the reanalysis, some of which are supported by observations but others are not.

In the Southern Hemisphere, the sea level pressure difference between 40° and 60°S, an indicator of westerly wind intensity, increases approximately from 20 hPa in the early 1950s to 25 hPa in the early 1970s and 28 hPa in recent years. The relatively high density of observing stations along the Antarctic Peninsula, however, results in an approximately steady local surface pressure after the pressure fell about 4 hPa during the late 1950s. Based upon these findings, researchers should account for jumps and long-term trends when making use of the NCEP–NCAR reanalysis.

1. Introduction

In recent years, several multiyear, state-of-the-art reanalyses of many global meteorological fields have been performed. These include the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center)–National Center for Atmospheric Research (NCAR) reanalysis from the late 1940s to present (Kalnay et al. 1996), the European Centre for Medium-Range Weather Forecasts reanalysis (ERA-15) from 1979 to 1993 (Gibson et al. 1997), and the National Atmospheric and Space Administration Data Assimilation Office from 1980 to 1995 (Schubert 1998). One of the primary motivations for these ambitious projects is reducing the climate jumps believed to be included in previous operational analyses due to many model updates. To achieve this aim, the same ‘‘frozen’’ data assimilation system is used over the entire reanalysis time period. Naturally, the reanalyses are still dependent on the quality and quantity of available data. Kistler et al. (2000) show that observational data available for the reanalysis do increase over time, and significant increases in the quantity of data do occur about the time of the International Geophysical Year (IGY) during 1957–58 and the First GARP Global Experiment (FGGE) during 1979.

---

* Contribution Number 1165 of the Byrd Polar Research Center.

Corresponding author address: Keith M. Hines, Polar Meteorology Group, Byrd Polar Research Center, 1090 Carmack Road, Columbus, OH 43210-1002.
E-mail: hines@polarmet1.mps.ohio-state.edu

Reanalysis fields are expected to have extensive usage in the near future and should be valuable for many purposes (e.g., Trenberth 1995; World Climate Research Programme 2000). This is especially true for 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. The performance of the NCEP–NCAR reanalysis and the NCEP operational forecasts have recently been tested in the Antarctic region by making use of the increased data availability from the Antarctic First Regional Observing Study of the Troposphere (FROST, Bromwich and Smith 1993; Turner et al. 1996) project during winter, spring, and summer Special Observing Periods (SOPs) in 1994–95 (Bromwich et al. 1999; Hines et al. 1999). In high southern latitudes, the performance of operational numerical analyses and forecasts is limited by a variety of obstacles including the scarcity of available data and communications problems associated with long distances and auroral effects. Extreme weather phenomena and sharp topographic contrasts also create unique difficulties for Antarctica. These factors result in numerical forecasts and analyses that are of lower quality as compared with other parts of the world (Bourke 1996).

The FROST project provides an opportunity for model testing leading to improvements in NCEP's numerical products that administer to the need for reliable global atmospheric numerical analyses in climate research and to NCEP's hemispheric obligations for weather prediction, which extend to South America. A recent issue of *Weather and Forecasting* focuses on the FROST project with two papers considering the success of NCEP forecasts and analyses in high southern latitudes. Bromwich et al. (1999) evaluate the July 1994 operational forecasts with a version of the NCEP Medium Range Forecast (MRF) spectral model prior that used for the reanalysis. They find that inadequate parameterization of horizontal diffusion leads to spurious ‘‘cloud streets’’ surrounded by dry areas over Antarctica. An update of the MRF during November 1997 has corrected this problem. However, this update was too late for inclusion in the reanalysis. Hines et al. (1999) find that both the NCEP operational forecasts and the NCEP–NCAR reanalysis include significant errors in the surface energy balance over Antarctica for all three FROST SOPs. The energy balance over Antarctica in the NCEP–NCAR reanalysis is, in general, degraded from that of the NCEP operational forecasts.

2. The NCEP–NCAR reanalysis

The methodology of the NCEP–NCAR reanalysis data assimilation is discussed in detail by Kalnay et al. (1996). Kistler et al. (2000) give a more recent review of the reanalysis. Therefore, only a brief description is provided here. The main components of the reanalysis are the NCEP MRF (Kanamitsu 1989; Kanamitsu et al. 1991) and the operational NCEP spectral statistical interpolation (SSI; Parrish and Derber 1992) with improvements (Kalnay et al. 1996). As the observations do modify the global fields, Kistler et al. (2000) note that strict conservation laws are not obeyed during the assimilation. The SSI scheme, which replaced an earlier optimal interpolation analysis scheme, led to major improvements in analyses and forecasts, particularly in the Tropics. The analysis with SSI is designed to produce balanced fields. Consequently, an initialization procedure is not required for NCEP forecasts. Robert Grumbine (1999, personal communication) of NCEP, however, notes that the spectral interpolation allows the numerous Northern Hemisphere observations to modify distant Southern Hemisphere fields. This may contribute to analysis errors in data-sparse regions of the Southern Hemisphere.

The NCEP–NCAR reanalysis system is the same as the version of the NCEP analysis system implemented operationally in January 1995, with the exception that the horizontal resolution is set at T62 instead of T126. In the vertical, 28 sigma levels are used. Details of the numerical procedures are given by Kalnay et al. (1996) and Betts et al. (1996). The output consists of gridded, global fields of all prognostic variables and many diagnostic fields produced four times a day, as well as longer-term averages. The initial time of the reanalysis is now before 1949, so that at least 50 years of analyzed fields are publicly available with the same frozen-in-time data assimilation system. Kistler et al. (2000) indicate that the reanalysis fields prior to 1957 are intended primarily for Northern Hemisphere use as very few observations are incorporated from the Southern Hemisphere during this period. The reanalysis would appear to be ideal for the study of many Earth science problems, especially climate variability (Higgins et al. 1996). Several recent studies of Southern Hemisphere climate have been performed with the NCEP–NCAR reanalysis. In their study of global teleconnections to Antarctic sea ice, Yuan and Martinson (2000) accounted for long-term temporal variability by detrending their data, while Kidson (1999) found that the representation of the Southern Hemisphere circulation by the reanalysis is quite different between the periods 1958–69 and 1970–97. Renwick and Revell (1999) found trends in the 500-hPa height field that exceed 1 m yr^{-1} for some locations in high southern latitudes during the years 1958–96. Updated NCEP global reanalyses are anticipated every 8–10 yr (Kistler et al. 2000). Hines et al. (1999) note that it is important for the meteorological analyses and forecasts to be carefully analyzed, and any deficiencies detailed so that corrections can be applied in the future.

Several important developments have occurred since the production of the original NCEP–NCAR reanalysis. Several errors have been discovered and are reported on the NCEP–NCAR reanalysis Web page (http://wesley.wwb.noaa.gov/reanalysis.html). Two, in particular, could significantly impact the surface pressure pattern in the Southern Hemisphere. The Australian Surface Pressure Bogus Data for the Southern Hemisphere (PAOBS) for 1979–92 were read with a 180° error in longitude. This error primarily affected the area south of 40°S. The effect is thought to be significant on synoptic timescales, but not on climatological timescales (Kistler et al. 2000). A different error affected both hemispheres for 1948–67. An incorrect decoding of pressure observations resulted in many values being read as 100 hPa too large. Both errors resulted in the quality control checks rejecting many pressure observations. A very recent development is the performance of the NCEP–Department of Energy (DOE) Atmospheric Modelling Intercomparison Project 2 (AMIP-2) reanalysis, which will eventually cover the years 1979–97. This improved reanalysis is made with an updated forecast model and data assimilation system. Model resolution is the same as the earlier reanalysis. Fixes are included for several problems discovered in the earlier NCEP–NCAR reanalysis. In particular for the Southern Hemisphere, the PAOBS problem has been rectified.

3. Evaluation of NCEP–NCAR reanalysis pressure tendency

To evaluate the pressure trends in the reanalysis, we look at the time evolution of the annual-average sea level pressure for several latitudes. Figure 1 displays the zonal-average values from 1949 to 1998 of the sea level pressure for the equator, 90°N, 65°S, and 45°S, and the surface pressure for 90°S. Pressures from the ERA-15 and the recent NCEP–DOE AMIP-2 reanalysis are also shown. Reanalysis surface pressure should be equal to or near the sea level pressure for 65°S, 45°S, the equator, and 90°N. For high northern latitudes, Walsh et al. (1996) have previously analyzed sea level pressure anomalies from buoy observations. The generally reduced pressure from 1988 to 1994 seen Fig. 1a is the main focus of their paper. The maxima and minima of sea level pressure at 90°N for the reanalysis well match those for 70°–90°N given by Walsh et al. (1996, see their Fig. 5).

The reanalysis is much less successful in capturing realistic variations of annual-average pressure in high southern latitudes, as a large, spurious pressure decrease over time occurs south of about 45°S. This trend has a maximum magnitude near 65°S over the Southern Ocean where the surface pressure falls about 10 hPa over the time period of the reanalysis (Fig. 1b). Remarkably, the long-term trend at 65°S continues from early years of the reanalysis to the present. There are, however, a few years of decreased pressure at 65°S from the IGY to 1962. Evidence from recent observations at Antarctic automatic weather stations (not shown) supports the distinct pressure minimum at 65°S during 1998. Linear regression values of the pressure tendency at 65°S and other latitudes are given in Table 1. The regression uncertainty values in Table 1 are based upon a Student's t-test at 95% confidence that is adjusted for the annual autocorrelation between the residuals from the linear regression. Due to autocorrelation, the effective sample size for the regression is reduced (Smith et al. 1996). Only lags of 1–4 yr are used to adjust the effective sample size as in Angell (1981).

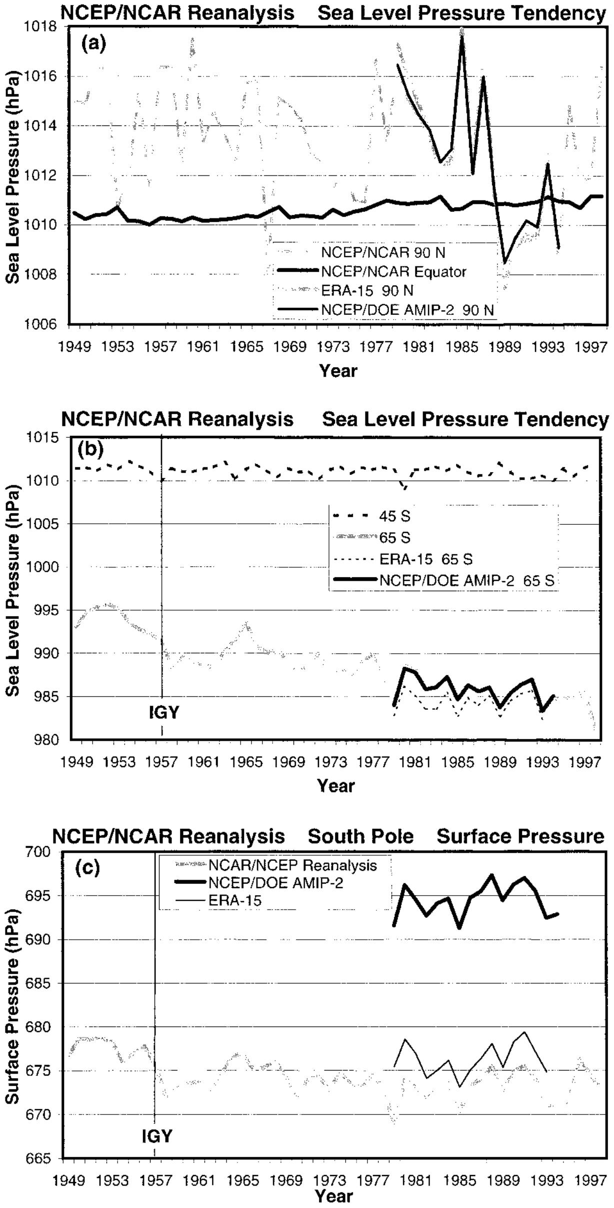


FIG. 1. Time evolution of annual and longitudinally averaged pressure (hPa) from the NCEP–NCAR reanalysis, the NCEP–DOE AMIP-2 reanalysis, and the ERA-15 at (a) sea level for 90°N and the equator, (b) sea level for 45° and 65°S, and (c) surface level for 90°S. The international geophysical year (IGY) is shown by the vertical lines in (b) and (c).

The sea level pressure tendency at 65°S is -0.166 ± 0.039 hPa yr^{-1} for the period 1957–98 and $-0.177 \pm$

TABLE 1. Reanalysis of sea level pressure trends.

Source	Location	Years*	Average (hPa)	Trend (hPa yr^{-1})	Uncertainty (hPa yr^{-1})
NCEP–NCAR reanalysis	65°S	1957–98	987.57	−0.166	0.039
NCEP–NCAR reanalysis	65°S	1969–98	986.54	−0.177	0.062
NCEP–NCAR reanalysis	65°S	1979–93	986.01	−0.123	0.221
ECMWF reanalysis	65°S	1979–93	984.29	−0.011	0.193
NCEP–DOE AMIP-2	65°S	1979–93	985.86	−0.103	0.203
NCEP–NCAR reanalysis	45°S	1969–98	1011.06	−0.005	0.028
NCEP–NCAR reanalysis	65°S	1969–98 DJF	987.97	−0.202	0.082
NCEP–NCAR reanalysis	65°S	1969–98 MAM	986.19	−0.181	0.092
NCEP–NCAR reanalysis	65°S	1969–98 JJA	988.40	−0.224	0.116
NCEP–NCAR reanalysis	65°S	1969–98 SON	983.62	−0.100	0.085
NCEP–NCAR reanalysis	90°S	1957–98	673.65†	−0.031†	0.044†
NCEP–NCAR reanalysis	90°S	1969–98	673.27†	0.004†	0.073†
NCEP–NCAR reanalysis	90°N	1969–98	1012.75	−0.067	0.109
NCEP–NCAR reanalysis	90°N	1979–93	1012.57	−0.430	0.311
ECMWF reanalysis	90°N	1979–93	1012.91	−0.469	0.353
NCEP–DOE AMIP-2	90°N	1979–93	1012.89	−0.412	0.292
NCEP–NCAR reanalysis	Equator	1969–98	1010.79	0.022	0.009

* DJF is December, January, and February average; MAM is March, April, and May average; JJA is June, July, and August average; and SON is September, October, and November average.

† Surface pressure.

0.062 hPa yr^{-1} for 1969–98. The negative tendency weakens somewhat with time to -0.123 ± 0.221 hPa yr^{-1} for 1979–93. The latitude where the largest magnitude trend is located is near the center of the deep Antarctic circumpolar trough. To the north of the circumpolar trough, on the other hand, the pressure tendency is very small at 45°S with a value of -0.005 ± 0.028 hPa yr^{-1} for 1969–98. Furthermore, trends, typically of smaller magnitude than at 65°S, are also seen for latitudes north of 45°S. For example, Fig. 1a shows that the long-term pressure tendency is positive at the equator between 1960 and 1980. Smith et al. (2000) find that the reanalysis has a slight negative bias compared to research vessel observations of about 0.2 hPa in the Tropics for 1990–95.

At the South Pole, the surface pressure decreases noticeably until about 1970 (Fig. 1c). Thus, the surface pressure has a linear regression slope of -0.031 ± 0.044 hPa yr^{-1} for 1957–98. After 1969, however, the long-term tendency is apparently small, only 0.004 ± 0.073 hPa yr^{-1}. The difference in surface pressure in Fig. 1c between the NCEP–NCAR reanalysis and the NCEP–DOE AMIP-2 reanalysis is due to different surface heights, 2833 and 2682 m, respectively, on the interpolated 2.5° by 2.5° output grid.

The large pressure fall at 65°S between 1977 and 1979 in Fig. 1b is noted by van Loon et al. (1993). They describe a fall in the minimum pressure of the subantarctic trough in the late 1970s by as much as 2 hPa accompanied by a slight northward movement of the trough. Figure 1b suggests, however, that much of pressure reduction described by van Loon et al. (1993) was a relatively short-term event, and the 1980 sea level pressure had reverted to a value similar to those of the mid-1970s.

There may have been an actual pressure decrease of about 1 hPa near Antarctica during the late 1970s. We averaged the observed sea level pressure for the 10-yr periods 1969–78 and 1981–90 at nine Antarctic stations. The ensembles do not include the minimum pressure year 1979 or the maximum pressure year 1980. The nine Antarctic stations are Casey, Davis, Dumont d'Urville, Faraday, Halley, Mawson, Novolazarevskaya, Scott Base, and Syowa. All nine stations had lower average sea level pressure for 1981–90 than for 1969–78, with the maximum difference of 1.35 hPa at Scott Base (77.85°S, 166.75°E) and the minimum difference of 0.20 hPa at Syowa (69.00°S, 39.58°E). The average decrease between the 10-yr ensembles was 0.86 hPa. This observed difference is not large enough to account for the equivalent average difference in the reanalysis pressure (2.03 hPa).

The long-term decrease in reanalysis sea level pressure near the Antarctic circumpolar trough is demonstrated by Fig. 2, which shows the 10-yr averages for 1949–58, 1959–68, 1969–78, 1979–88, and 1989–98. The earliest 10-yr average is primarily, but not entirely, before IGY, and the 1979–88 average begins with FGGE. The largest long-term changes in sea level pressure for the reanalysis are near the pressure minimum in high southern latitudes. There is also a large change between the 1979–88 and 1989–98 averages in high northern latitudes which is in agreement with the earlier work of Walsh et al. (1996). In Fig. 2, the sea level pressure at 65°S is at least 1.5 hPa less for each successive 10-yr average. The most recent period shown, 1989–98, has an average surface sea level pressure of 984.78 hPa at 65°S. This value is just slightly more than the 1979–88 average, 984.35 hPa, for the ERA-15. It will be seen later that the large, long-term pressure de-

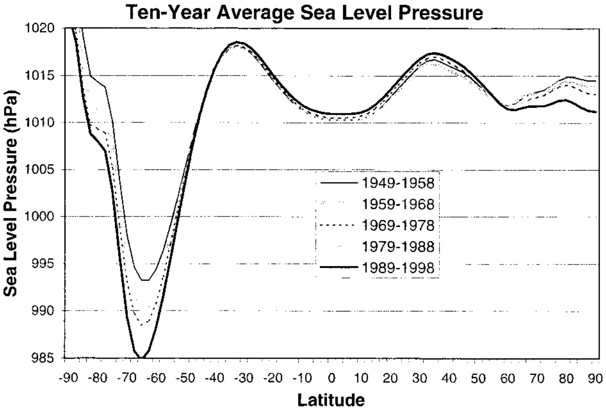


FIG. 2. Plot of decadal average sea level pressure (hPa) of the NCEP–NCAR reanalysis vs latitude for 1949–58, 1959–68, 1969–78, 1979–88, and 1989–98.

crease near the Antarctic circumpolar trough is not supported by observations. Therefore, a probable explanation is that the NCEP–NCAR reanalysis contains a large positive bias in pressure near the circumpolar trough until recent years. The bias gradually weakened from about 8 hPa in the 1950s and about 6 hPa in the 1960s to about 4 hPa in the 1970s before FGGE and about 2 hPa in the 1980s. Smith et al. (2000) suggest that a positive bias is also present during 1990–95.

The origin of the positive bias is probably due to the model climate for the NCEP MRF. A forecast drift will occur when the model climate differs from that initialized with input from observations. Bromwich et al. (1999) show that a slightly earlier version of the MRF simulates an average increase of several hectopascals near 70°S during the first few days of its medium-range forecasts for the winter SOP (July 1994) of the FROST study. This pressure increase is due to a transfer of mass from Southern Hemisphere middle latitudes to high latitudes. Large adjustments in the surface energy balance over Antarctica also occur during forecasts of the MRF (Hines et al. 1999). The maximum 500-hPa height increase during the MRF forecasts is along 130°E–180° near the coast of Wilkes Land, Antarctica (Bromwich et al. 1999). Consequently, the impact of the forecast drift is likely to be a maximum there.

One may be tempted to attribute the temporal changes seen in the Southern Hemisphere to a lack of observations, especially in the early years of the reanalysis. Indeed, very few observations, except along the Antarctic Peninsula near 65°W, are available in high southern latitudes until about 1957. Researchers of Southern Hemisphere climate are quite familiar with this limitation, and it would be unreasonable to expect a quality analysis of high southern latitudes until a reasonable number of stations became available. Nevertheless, the downward trend in reanalysis sea level pressure at 65°S has continued into the 1990s, many years after abundant stations began taking observations between 65° and 70°S along the coast of east Antarctica. In support of IGY, an international effort established observing stations for Antarctica, especially along the coast, during the 1950s. An extensive list of Antarctic stations is given by Schwerdtfeger (1970). Furthermore, Roy Jenne (1999, personal communication) of NCAR used the work of Taljaard et al. (1969) to compile a list of more than 20 radiosonde stations over and near Antarctica that began operating in the 1950s or early 1960s. Thus, a sufficient number of stations appear to be in place to reasonably establish the climatological pressure field near the coast of Antarctica from the late 1950s to the present.

Most of the Antarctic surface observations prior to the late 1960s, however, are not incorporated into the reanalysis. Roy Jenne (1999, personal communication) notes that the compilation of older meteorological data for the reanalysis is a highly complicated process, and that meteorological observations transmitted through the Global Telecommunications System (GTS) are not available to the reanalysis prior to 1967. Furthermore, the GTS data for 1967–1975 exclude many observations. The output of diagnostic software provided on the NCEP–NCAR reanalysis web page demonstrates these limitations. Figure 3 shows the average density of observations received in a month by the assimilation scheme per 2.5° lat by 2.5° long grid box for the 225° long wide section between 60°–75°S and 45°W–180°. The number of 2.5° by 2.5° grid boxes in this region is 540, and observations from west Antarctica and the Antarctic Peninsula are outside this area. Therefore, the observation count in Fig. 3 will primarily reflect measurements from East Antarctic coastal stations. For this region, very few surface observations are received by the reanalysis prior to 1969 (Fig. 3a). The number of surface observations generally increases from 1969 to the present. It should be noted here that surface pressure observations are poorly retained by the reanalysis compared to other meteorological observations, due to the geostrophic adjustment process (Kistler et al. 2000). Therefore, it may require a relatively large number of surface observations to establish the surface pressure field.

Some upper-air observations are incorporated into the reanalysis during the 1950s and 1960s (Fig. 3b). There is a distinct peak in upper-air observations near the IGY, then a minimum about 1965. Notice in Fig. 1b that the pressure at 65°S is smaller when more observations are available such as near the IGY and after 1970. This indicates that the reanalysis has a large positive bias near the Antarctic circumpolar trough, unless a sufficient number of observations are available. Similar to the surface observations, the upper-air observations increase significantly at the end of the 1960s. After peaking in 1990, the observations in Fig. 3b decreased, especially near 1992, probably associated with the closure of rawinsonde stations operated by the former Soviet Union. In summary, the limited quantity of incorporated

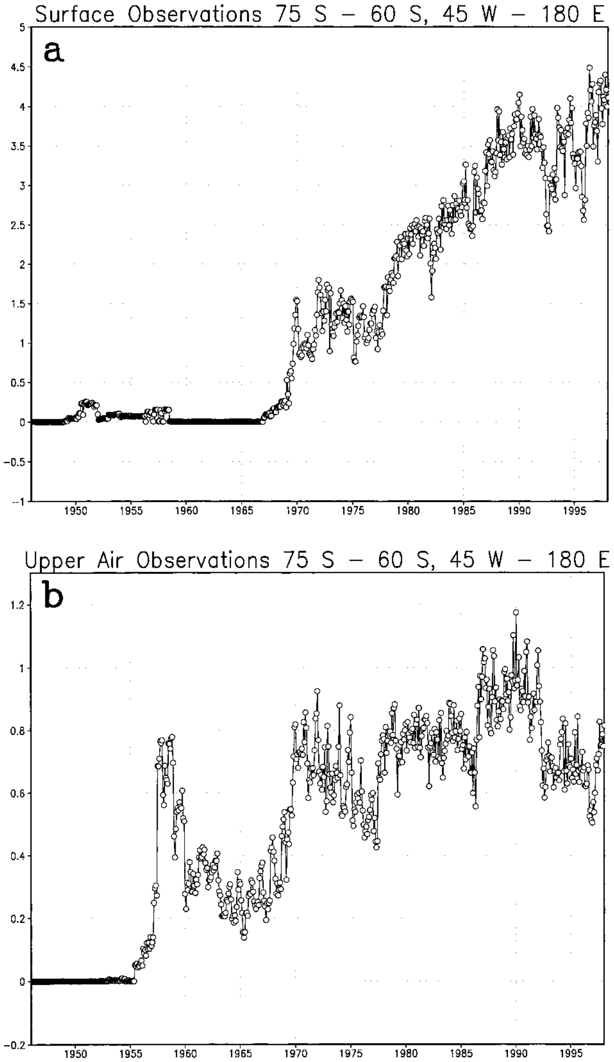


FIG. 3. Plot of average observations per 2.5° by 2.5° grid box per month between 75°–60°S and 45°W–180° vs time for 1948–98. (a) Surface observations and (b) upper-air observations.

observations from prior to about 1970 suggests that reanalysis fields are unreliable near Antarctica during that time period. Researchers should use caution in the application of reanalysis fields for high southern latitudes prior to the late 1960s.

Wesley Ebisuzaki of NCEP (1999, personal communication) notes that the quantity of available observed data for Antarctica varies seasonally. Fewer observations are available during the Polar Night. This seasonal effect has an influence on the reanalysis trends shown in Table 1. The seasonal average trend the period 1970–98 has larger magnitude during the austral winter months of June–August (JJA) than that for December–February (DJF), March–May (MAM), and September–November (SON). Curiously, austral spring (SON) has a much smaller magnitude tendency than for austral summer (DJF) when a larger number of Antarctic observations may be available. This further indicates that the large trend in pressure tendency at 65°S is not a simple manifestation of a low quantity of observations.

The ERA-15 from 1979–93 should be based on approximately the same observations incorporated by the NCEP–NCAR reanalysis. Thus, it is interesting to compare the sea level pressure tendency of the NCEP–NCAR reanalysis to that of the ERA-15. Unfortunately, this relatively short period for comparison results in a relatively large statistical uncertainty for the regression lines. The sea level pressure from the NCEP–NCAR reanalysis during 1979–93 has a negative linear regression slope at 65°S of -0.123 ± 0.221 hPa yr^{-1} (Table 1). The NCEP–DOE AMIP-2 reanalysis appears to be only slightly improved with a tendency of -0.103 ± 0.203 hPa yr^{-1}. The ERA-15, on the other hand, has a small tendency of -0.011 ± 0.193 hPa yr^{-1}.

Largely due to interannual variability during the 15-yr period, the uncertainties in the trends are large for 1979–93. Fortunately, most of the interannual variability cancels when the difference in sea level pressure is taken between two reanalyses. The difference, NCEP–NCAR reanalysis minus ERA-15, does have a negative trend, -0.113 ± 0.071 hPa yr^{-1}, that is significantly different from 0.

The NCEP–NCAR reanalysis sea level pressure has an average value of 986.0 hPa at 65°S during 1979–93, 1.7 hPa larger than that of the ERA-15, 984.3 hPa. As the magnitude of the difference in Fig. 1b decreases with time, it appears that the decrease in reanalysis surface pressure over the Southern Ocean represents a change toward more realistic values. Furthermore, the year-to-year differences in Fig. 1 are well matched between ERA-15 and the NCEP–NCAR reanalysis.

Figure 1 also shows that the annual and zonal average sea level pressure of the NCEP–DOE AMIP-2 reanalysis, which includes several improvements in the assimilation scheme, is nearly identical to that of the earlier NCEP–NCAR reanalysis. The similarity in short-term variations suggests that recent decades of NCEP–NCAR reanalysis data are useful for study of climate variations over the Southern Ocean if the spurious long-term trends are accounted for. Slightly weakened trends are apparently also included in the NCEP–DOE AMIP-2 reanalysis. Some caution must be given to these results considering the three analyses are compared for only 15 yr.

An example of how the analyzed climatological pressure field in the Southern Hemisphere changes with time is provided by Fig. 4, which displays 5-yr averages of the sea level pressure for 1968–72 and 1993–97. In Fig. 4, three high pressure centers at 30°S in the Indian, Atlantic and eastern Pacific Oceans are similarly located for 1968–72 and 1993–97, and the center pressures change by less than 1 hPa. There is a large change, however, in sea level pressure within the Antarctic circumpolar trough, which is typically near 65°S. The minimum pressure near the Ross Sea decreases from 986.8 hPa for 1968–72 to 980.6 hPa for 1993–97. Further-

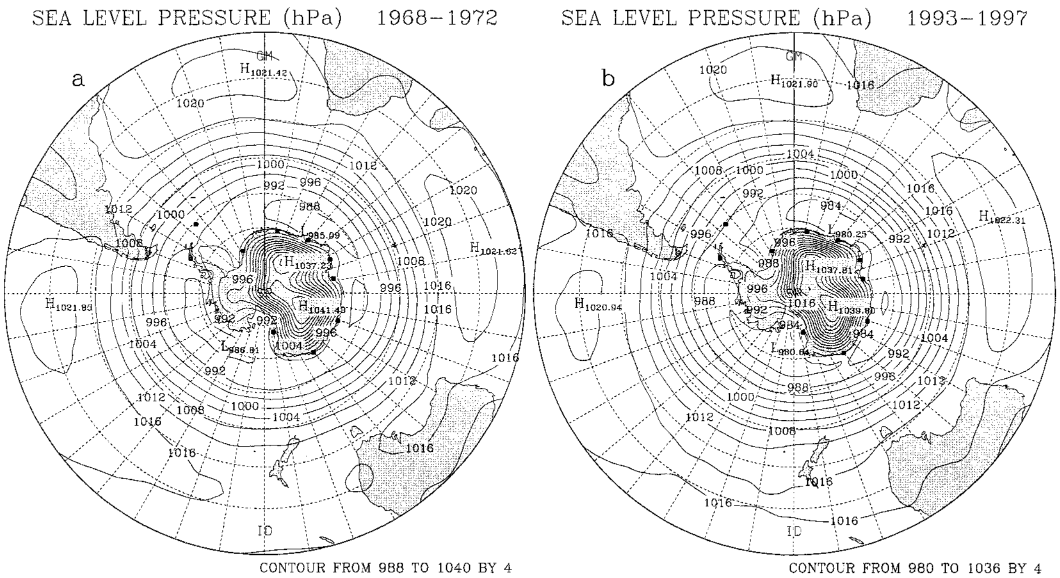


FIG. 4. Plot of NCEP–NCAR reanalysis sea level pressure (hPa) for 20°–90°S averaged during (a) 1968–72 and (b) 1993–97. Contour interval is 4 hPa. Dots show the locations of selected observing stations.

more, the location of the minimum moves from near 145°W in Fig. 4a to near 160°W in Fig. 4b. The minimum in the western Indian Ocean near 30°E decreases from 985.1 hPa for 1968–72 to 980.3 hPa for 1993–97.

Figure 5 shows the horizontal distributions of the linear regression for surface pressure and 500-hPa height. The 1969–98 trend in surface pressure has a roughly axisymmetric distribution about the South Pole (Fig. 5a). The downward trend in surface pressure is largely confined south of 45°S, with small positive trends to the north, except over the Pacific Ocean. The magnitude of the trend is largest slightly north of Antarctica and is very small at the South Pole. There are maxima in the magnitude of the downward trend in excess of 0.3 hPa yr^{-1} near 145°E and over the eastern Ross Sea at 160°W. The 500-hPa heights also decrease at high southern latitudes from 1969 to 1998 (Fig. 5e) with a maximum magnitude over 2 m yr^{-1} at 130°E. There is a positive trend in middle latitudes, generally less than 1 m yr^{-1} at 500 hPa due to a slight increase in temperature (not shown). The 500-hPa pattern for 1969–98 is approximately similar to the 1958–1996 trends found by Renwick and Revell (1999).

The surface pressure trend for 1979–93 is shown in Figs. 5b–d for the NCEP–NCAR reanalysis, the NCEP–DOE AMIP-2 reanalysis, and the ERA-15, respectively. The distribution of minima and maxima agrees reasonably well for the three reanalyses. While the exact locations of the extrema vary somewhat, there are minima approximately near 67.5°S, 170°E; 55°S, 80°E; 65°S, 15°E; and 60°S, 75°W and maxima approximately near 50°S, 130°E; 57.5°S, 130°W; and 50°S, 35°W. The trends are much more positive, however, for for the ERA-15. A unique feature for the ERA-15 is the maximum 0.26 hPa yr^{-1} over East Antarctica near 130°E. The ERA-15 pressure trend in that region may have been influenced by an error in the surface height for Vostok (Bromwich et al. 2000). For the other two reanalyses, Fig. 5b demonstrates that the negative trend in pressure continues after FGGE near the coast of Antarctica. The NCEP–DOE AMIP-2 reanalysis trends are very similar to that of the NCEP–NCAR reanalysis, with the latter being slightly more negative on the average. The correction of some errors in the NCEP–NCAR reanalysis appears to have a very minor effect on the trends in the NCEP–DOE AMIP-2 reanalysis. This indicates that the PAOBS problem did not have had a large effect on the climatological fields of the NCEP–NCAR reanalysis.

As the circumpolar trough shown in Fig. 4 deepens over time, the pressure gradient north of the trough also intensifies for the reanalysis. Figure 6 displays the time evolution of the sea level pressure difference (hPa) between 40° and 60°S. At sea level, the zonal geostrophic wind speed averaged between 40° and 60°S is proportional to this difference. Within this range of latitudes, Smith et al. (2000) find that there is a negative bias of about 1 m s^{-1} of reanalysis wind speed compared to research vessel observations for 1990–95. As the reanalysis shows little long-term trend in the sea level pressure near 40°S, long-term changes in the surface geostrophic wind between 40° and 60°S are largely the result of decreasing pressure at 60°S. The deepening of the Antarctic circumpolar trough with time in the NCEP–NCAR reanalysis results in the geostrophic speed increasing by about 18% from 1957 to 1970 and about 10% from 1970 to the late 1980s. The sea level pressure differences between 40° and 60°S for the ERA-15 during 1979–93 and the NCEP–DOE AMIP-2 reanalysis during 1979–94 are also shown in Fig. 6. The pressure difference between 40° and 60°S is always larger for the ERA-15 than for the NCEP–NCAR reanalysis. The average value for the ERA-15, 27.8 hPa, is 4.4% larger than the NCEP–NCAR reanalysis average, 26.6 hPa, during 1979–93. Figure 6 suggests that the difference between the ERA-15 and NCEP–NCAR reanalysis decreases with time. The pressure difference for the very recent NCEP–DOE AMIP-2 reanalysis is nearly identical to that of the NCEP–NCAR reanalysis. Furthermore, the year-to-year changes for ERA-15 and the NCEP–NCAR reanalysis are very well matched during 1979–93. This similarity supports the validity of short-term interannual variability produced by the two different data assimilation systems.

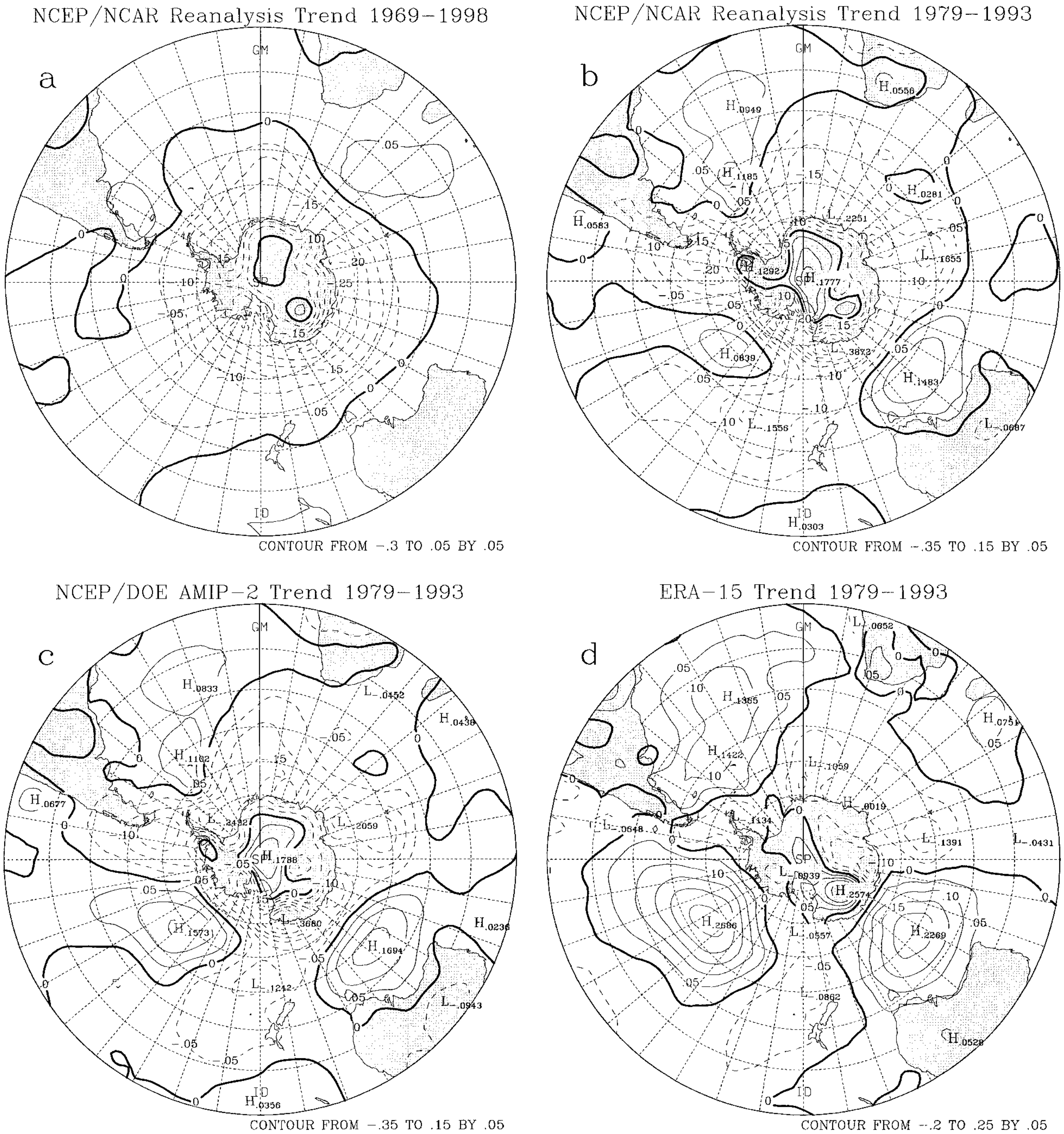
The vertical distribution of the trends in the NCEP–NCAR reanalysis is shown by Table 2, which displays the 1969–98 trends in geopotential height at 45° and 65°S for the levels at 850, 700, 500, 300, 200, and 100 hPa. The trends in the Southern Hemisphere are baroclinic. The trend at 65°S increases with height from -1.28 ± 0.52 m yr^{-1} at 850 hPa until the trend is not significantly different from 0 above 500 hPa. At 45°S, on the other hand, the trend is not significantly different from 0 at 850 hPa. At this latitude, the trend increases with height and becomes large near the tropopause. The trend at 45°S is 2.05 ± 0.77 m yr^{-1} and 2.66 ± 0.108 m yr^{-1} at 200 and 100 hPa, respectively.

Another check of the long-term pressure tendencies included in the reanalysis is performed by comparing gridpoint values for the reanalysis against Antarctic observations. Jo Jacka of the Australian Antarctic Cooperative Research Centre has provided monthly surface pressure and surface temperature observations at many Southern Hemisphere stations. Brad Murphy and Paul Pettré of Centre National de Recherches Météorologiques also provided data for the Antarctic stations Dumont d'Urville (66.40°S, 140.01°E), Mawson (67.60°S, 62.87°E), and Casey (66.28°S, 110.53°E). The third author obtained Antarctic data from the Jones and Limbert dataset (Jones and Limbert 1987). From these data, we can compute the sea level pressure. The time evolution of sea level pressure for several Antarctic coastal stations and interpolated from the NCEP–NCAR reanalysis is shown in Fig. 7. Additionally, Table 3 gives linear regression slopes of sea level pressure for both observations and the reanalysis for the time periods 1969–98 and 1979–98; station locations indicated by the dots in Fig. 4. The former period is the approximate time over which Antarctic surface observations are available over the GTS. The latter period, which begins with FGGE, has increased satellite data available for the assimilation. Some difference due to resolution will naturally occur between the point value observations and the NCEP model results at T62. The next to last column in Table 3 gives the calculated statistical uncertainty of the trend at 95% confidence, and the last column gives the statistical confidence that the trend of difference sea level pressure (NCEP–NCAR reanalysis—observed) is different from 0. The trend of the difference pressure is convenient for statistical testing as its standard deviation is about half that of the reanalysis pressure.

It is apparent from Fig. 7 that short-term interannual variations in reanalysis sea level pressure agree reasonably well with observations beginning about 1970. At Orcadas (60.75°S, 44.72°W), the year-to-year variations are reasonably captured by the reanalysis after 1955 and very well captured beginning in 1972. The downward trend in reanalysis sea level pressure compared to that of the observations can clearly be seen at all the sites shown in Fig. 7, except for near Orcadas after 1970. The reanalysis apparently well captures the sea level pressure tendency after about 1970 near the northern Antarctic Peninsula, where the density of observing stations is relatively high. For east Antarctic stations, the reanalysis pressure decrease is particularly large, about 6 hPa, from 1968 to 1970 near Mawson and near Syowa. Near Casey, Mawson, Scott Base, and Syowa the pressure is reasonably captured or well captured beginning in 1969 or 1970, although there is about a 2-hPa negative bias at Syowa during 1990. The general downward trend in reanalysis sea level pressure, however, is still evident.

Significantly, the Antarctic observing stations do not support the large negative trends included in the reanalysis pressure field. Eugenia Kalnay (1999, personal communication) notes that reanalysis trends should not be taken at face value without independent verification from observations. All the sites listed in Table 3 have statistically significant negative tendencies for reanalysis sea level pressure during 1969–98 with values ranging from -0.084 ± 0.073 at Syowa to -0.298 ± 0.070 at Dumont d'Urville. Furthermore, the tendency of the difference sea level pressure (NCEP–NCAR reanalysis—observed) is statistically significant at 99% for seven of the nine sites and statistically significant at 95% for Syowa. The best estimated values of observed sea level pressure tendency are all greater than the corresponding reanalysis values for 1969–98. There is some evidence, however, of a decrease in observed sea level pressure. Statistically significant negative tendencies during 1969–98 of observed surface pressure with values of -0.078 ± 0.072, -0.105 ± 0.060, -0.072 ± 0.071, and -0.090 ± 0.068 hPa yr^{-1} are found at Casey, Davis, Dumont d'Urville, and Novolazarevskaya, respectively (see also Murphy and Pettré 1995). Overall, however, the observations do not support the large negative tendency found in the reanalysis during 1969–98. Figure 7 indicates that the NCEP–NCEP reanalysis pressure in high southern latitudes continues to fall relative to nearby Antartic observations from the 1950s into the 1990s.

The 1979–98 period beginning with FGGE also shows the downward trend in reanalysis pressure near Antarctica. This is particularly true near Casey where the reanalysis trend is -0.362 ± 0.223. The difference sea level pressure (NCEP–NCAR reanalysis—observed) has a 1979–98 trend different than 0 at 99%


NCEP/NCAR Reanalysis Trend 1969–1998

NCEP/NCAR Reanalysis Trend 1979–1993

NCEP/DOE AMIP-2 Trend 1979–1993

ERA-15 Trend 1979–1993

CONTOUR FROM −.3 TO .05 BY .05

CONTOUR FROM −.35 TO .15 BY .05

CONTOUR FROM −.35 TO .15 BY .05

CONTOUR FROM −.2 TO .25 BY .05

FIG. 5. Plot of linear regression trends of NCEP–NCAR reanalysis surface pressure (hPa yr^{-1}) for 20°–90°S for the years (a) 1969–98, (b) 1979–93, (c) NCEP–DOE AMIP-2 reanalysis trend in surface pressure for 1979–93, (d) ERA-15 trend in surface pressure for 1979–93, and (e) NCEP–NCAR reanalysis 500-hPa geopotential height trend (m yr^{-1}) for 1969–98. Contour interval is 0.05 hPa yr^{-1} in (a)–(d) and 0.25 m yr^{-1} in (e).

confidence at Casey, Halley, and Mawson. This trend is also significant with lower confidence at Davis, Dumont d'Urville, and Scott Base. The decrease of reanalysis sea level pressure compared to observed values is clearly seen in Fig. 7. The positive bias for the reanalysis appears to have largely disappeared in very recent years. The station observations do suggest an actual decrease in sea level pressure during 1979–98, although none of the observed trends are statistically significant for this period. We must conclude, therefore, that the large amplitude decrease in reanalysis surface pressure is spurious.

Reanalysis trends are also apparent at higher levels of the atmosphere. The 500 hPa height at 65°S (not

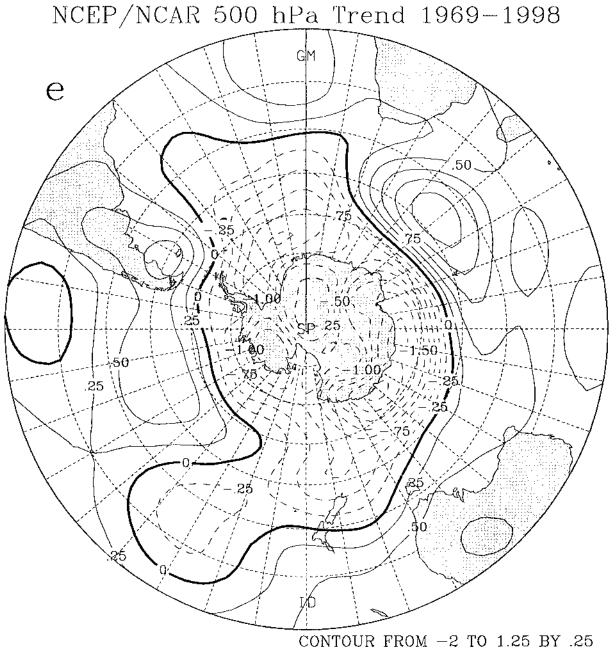


FIG. 5. (*Continued*)

shown) has an approximately 30 m decrease in 500-hPa height between the mid 1960s and the mid 1990s. Compared to radiosonde observations, the reanalysis heights at Casey (66.28°S, 110.53°E) and Mawson (67.60°S, 62.87°E) changed from positive biases of 26.2 and 19.2 m, respectively, during 1969 to negative biases of −10.6 and −7.6 m, respectively, during 1998. The regression trends of the difference between the reanalysis and observed heights are statistically significant at 99% for Mawson and 95% for Casey. At Halley (75.52°S, 27.00°W), however, the change from 1969 to 1998 was smaller, from a bias of −4.1 m to a bias of −12.8 m. The regression trend of the difference in 500-hPa heights is not quite large enough to be statistically significant there. Furthermore, low amplitude temporal changes in the temperature and mass fields occur elsewhere in the Southern Hemisphere. For example, Kistler et al. (2000) find that temperature in the upper troposphere and upper stratosphere, particularly south of 60°S, increased after new satellite observations became available during FGGE.

Apparently spurious climate variability in the NCEP–NCAR reanalysis also occurs in the Northern Hemisphere as well as in the Southern Hemisphere. There is an approximately 2-hPa sustained pressure increase from 1975 to 1977 over much of midlatitude East Asia from 70°E to 110°E that is not supported by station data (not shown). Therefore it is important that researchers using reanalysis products also use observed data where possible to supplement and verify the results.

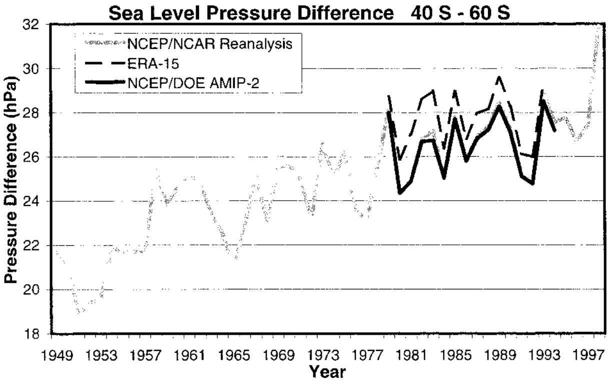


FIG. 6. Time evolution of difference of the annual mean sea level pressure (hPa) between 40° and 60°S for the NCEP–NCAR reanalysis (gray solid line), the ERA-15 (dashed line), and the NCEP–DOE AMIP-2 reanalysis (thick solid line).

4. Discussion and conclusions

An examination of 50 yr of the NCEP–NCAR reanalysis from 1949 to 1998 reveals that significant spu-

TABLE 2. NCEP–NCAR reanalysis geopotential height trends at 65° and 45°S for 1969–98.

Isobaric level (hPa)	Trend 65°S (m yr^{-1})	Uncertainty 65°S (m yr^{-1})	Trend 45°S (m yr^{-1})	Uncertainty 45°S (m yr^{-1})
850	−1.28	0.52	0.01	0.23
700	−1.22	0.55	0.10	0.27
500	−0.96	0.63	0.30	0.37
300	−0.21	0.75	0.86	0.54
200	0.34	0.92	2.05	0.77
100	−0.27	1.57	2.66	1.08

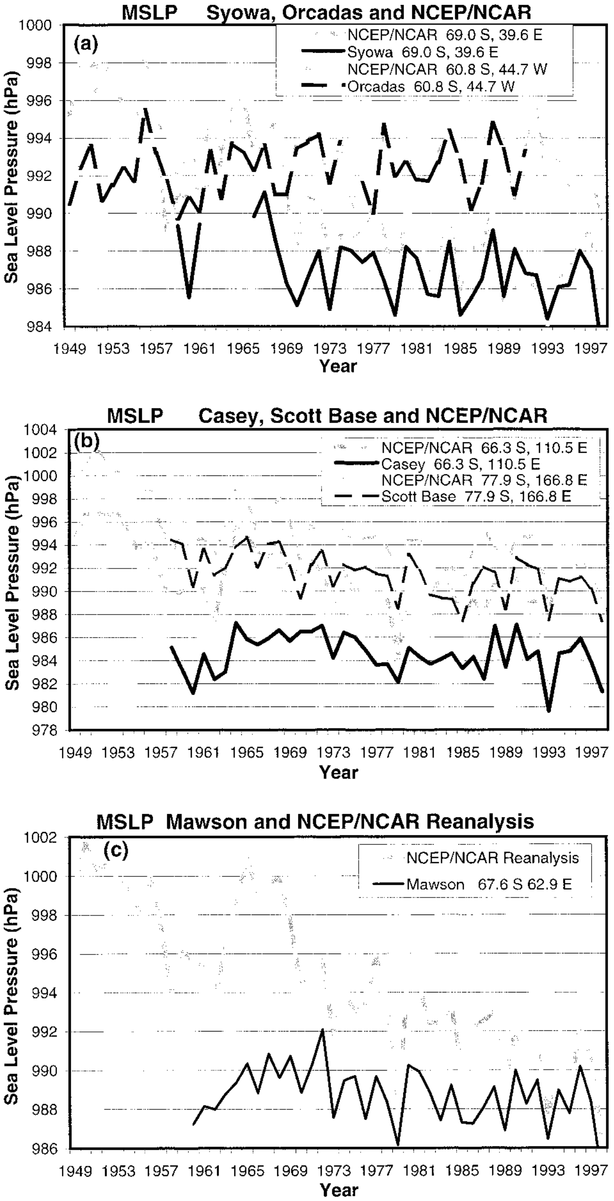


FIG. 7. Time evolution of annual-average sea level pressure (hPa) during 1949–98 at observing Antarctic stations and nearby grid points of the NCEP–NCAR reanalysis. (a) Orcadas (60.75°S, 44.72°W) and Syowa (69.00°S, 39.58°E), (b) Scott Base (77.85°S, 166.75°E) and Casey (66.28°S, 110.53°E), and (c) Mawson (67.60°S, 62.87°E).

rious trends occur in the surface pressure field. Long-term surface pressure reductions are apparent south of 45°S. The largest trend in surface pressure is a steady pressure reduction of about 0.20 hPa yr^{-1} (10 hPa in 50 yr) near 65°S. The long-term trend there appears to weaken only slightly with time and results in a gradual reduction of a positive bias. The trend varies seasonally, with the largest magnitude in austral winter and the smallest magnitude in austral spring. Observations at Antarctic stations do not support a trend of such large magnitude, although short-term interannual variations are reasonably well captured starting about 1970. Thus, the reanalysis from 1970 to present should be acceptable for studies of climate variability in high southern latitudes, provided that the long-term trend is properly accounted for.

It is suggested here that the spurious trend over the Southern Ocean may be a particularly large component of global temporal variations in the reanalysis. For example, slight positive and negative surface pressure tendencies occur in the Tropics and Northern Hemisphere high latitudes, respectively. The latter tendency is a consequence of an actual Arctic pressure reduction in the late 1980s. The reanalysis also includes a spurious surface pressure jump of about 2 hPa and a 500-hPa height jump of about 20 m over East Asia around 1976.

In the Southern Hemisphere, the steady surface pressure reduction south of 45°S gradually reduces a positive bias in the reanalysis. Correspondingly, the sea level pressure difference between 40° and 60°S increases approximately from 20 hPa in the early 1950s to 25 hPa in the early 1970s and 28 hPa in recent years. The negative tendency in the surface pressure at 65°S is accompanied by a reduction in the 500-hPa geopotential height field. These spurious trends cannot be explained as simply a manifestation of insufficient observations in the Southern Hemisphere. The maximum amplitude trend at 65°S is located just north of the typical latitude of the east Antarctic coast. This location is striking considering that the number of Antarctic coastal stations that became available in the 1950s and 1960s should have been sufficient to reasonably represent the zonally averaged pressure.

It appears, however, that few Antarctic surface observations are incorporated into the reanalysis prior to the late 1960s, although a few upper-air observations are incorporated. Furthermore, the amount of incorporated data from surface and upper-air sources has generally increased over time starting in the late 1960s. A steady increase in incorporated data could explain the gradual rather than sudden change to lower pressure in the Antarctic circumpolar trough. In the early years of the reanalysis, the surface pressure field should reflect the NCEP MRF climatology. The reanalysis pressure decrease in the Antarctic circumpolar trough appears to be an adjustment toward a more realistic field. This decrease coincides with a steadily increasing reanalysis skill on synoptic scales for the Southern Hemisphere that was noted by Kistler et al. (2000). The reasons for the decreasing pressure may be complicated, as the trend appears to continue after FGGE in 1979, when significantly enhanced satellite observations provide additional data for the reanalysis. A known error in the incorporation of historical pressure data is apparently not responsible for the trends, as the recent NCEP–DOE AMIP-2 reanalysis has a negative pressure tendency at 65°S of only slightly less magnitude than that of the NCEP–NCAR reanalysis. The PAOBS pressure data in the Southern Hemisphere were correctly incorporated

Table 3. Sea level pressure trends for Antarctic stations and the NCEP–NCAR reanalysis.

Source	Location	Years	Average hPa	Trend hPa yr^{-1}	Uncertainty hPa yr^{-1}	Statistical confidence %
Casey	66.28°S, 110.53°E	1969–98	984.49	−0.078	0.072	99
NCEP–NCAR		1969–98	988.09	−0.269	0.101	
Casey		1979–98	984.02	−0.014	0.159	99
NCEP–NCAR		1979–98	986.94	−0.362	0.223	
Davis	68.58°S, 77.97°E	1969–98	987.09	−0.105	0.060	99
NCEP–NCAR		1969–98	989.47	−0.218	0.092	
Davis		1979–98	986.52	−0.085	0.131	85
NCEP–NCAR		1979–98	988.30	−0.173	0.202	
Dumont d'Urville	66.67°S, 140.02°E	1969–98	988.04	−0.072	0.071	99
NCEP–NCAR		1969–98	990.48	−0.298	0.070	
Dumont d'Urville		1979–98	987.66	−0.058	0.153	95
NCEP–NCAR		1979–98	988.72	−0.188	0.131	
Faraday/Vernadsky	65.25°S, 64.27°W	1969–98	989.58	−0.043	0.069	99
NCEP–NCAR		1969–98	989.72	−0.111	0.074	
Faraday/Vernadsky		1979–98	989.47	−0.093	0.158	no
NCEP–NCAR		1979–98	989.19	−0.126	0.165	
Halley	75.52°S, 27.00°W	1969–98	988.74	−0.057	0.065	99
NCEP–NCAR		1969–98	991.17	−0.145	0.069	
Halley		1979–98	988.46	−0.030	0.132	99
NCEP–NCAR		1979–98	990.52	−0.167	0.153	
Mawson	67.60°S, 62.87°E	1969–98	988.30	−0.061	0.065	99
NCEP–NCAR		1969–98	992.23	−0.228	0.082	
Mawson		1979–98	987.93	−0.017	0.132	99
NCEP–NCAR		1979–98	991.07	−0.214	0.174	
Novolazarevskaya	70.77°S, 11.83°E	1969–98	987.35	−0.090	0.068	no
NCEP–NCAR		1969–98	991.23	−0.112	0.090	
Novolazarevskaya		1979–98	986.83	−0.080	0.148	no
NCEP–NCAR		1979–98	990.43	−0.027	0.202	
Scott Base	77.85°S, 166.75°E	1969–98	990.81	−0.063	0.073	99
NCEP–NCAR		1969–98	993.26	−0.119	0.076	
Scott Base		1979–98	990.37	−0.019	0.158	95
NCEP–NCAR		1979–98	992.60	−0.088	0.173	
Syowa	69.00°S, 39.58°E	1969–98	986.55	−0.027	0.065	95
NCEP–NCAR		1969–98	987.61	−0.084	0.073	
Syowa		1979–98	986.38	−0.038	0.138	no
NCEP–NCAR		1979–98	987.29	−0.040	0.159	

by the former, but not by the latter. It is recommended that researchers should account for jumps and long-term trends when making use of reanalysis products. A similar warning is given by Kistler et al. (2000). They recommend caution in interpreting reanalysis climate changes that could have resulted from the detailed global satellite data introduced during FGGE.

It is unfortunate that a considerable amount of Antarctic data from about the time of the IGY to about 1970 was unavailable to the NCEP–NCAR reanalysis. Thus the quality of the reanalysis in high southern latitudes was reduced for the 1960s. In response to this, Antarctic and Southern Hemisphere meteorologists should focus on compiling a digitized dataset of regional observations that are convenient for future global reanalyses. The authors have contributed to one current effort to obtain more data that can be used for this purpose.

Acknowledgments. This research was supported by NASA via Grant NAG5-7750 and by the NSF–NCEP Joint Program in Numerical Weather Prediction via National Science Foundation Grant ATM-9422104. The data analysis was performed from data made available from the NCEP–NCAR reanalysis, the NCEP–DOE AMIP-2 reanalysis, the ERA-15, and the Global Historical Climatology Network. Communications with Roy Jenne, Eugenia Kalnay, and Wesley Ebisuzaki are appreciated for their contribution to this work. The authors also thank Phil Jones, Jo Jacka, Brad Murphy, and Paul Pettré for supplying Antarctic surface pressure data.

REFERENCES

Angell, J. K., 1981: Comparison of variations in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific. *Mon. Wea. Rev.*, **109,** 230–243.

Betts, A. K., S.-Y. Hong, and H.-L. Pan, 1996: Comparison of NCEP–NCAR reanalysis with 1987 FIFE data. *Mon. Wea. Rev.*, **124,** 1480–1498.

Bourke, W. P., 1996: Review of the performance of the Bureau of Meteorology global assimilation and prediction system (GASP). 1994 Modelling Workshop, Bureau of Meteorology, BMRC Research Report 52, 47 pp. [Available from Bureau of Meteorology Research Centre, GPO Box 1289K, Melbourne, Victoria 3001, Australia.]

Bromwich, D. H., and S. R. Smith, Eds., 1993: U.S. FROST: Data and Science Plan, Report from the U.S. FROST Workshop. BPRC Report 7, 40 pp. [Available from Byrd Polar Research Center, Ohio State University, 1090 Carmack Rd., Columbus, OH 43210.]

——, 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.

——, A. N. Rogers, P. Kållberg, R. I. Cullather, J. W. C. White, and K. J. Kreutz, 2000: ECMWF analyses and reanalyses depiction of ENSO signal in Antarctic precipitation. *J. Climate,* **13,** 1406–1420.

Gibson, J. K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1997: ECMWF re-analysis project report series. Part 1. ERA description. ECMWF Re-Analysis Project Report Series 1, 72 pp. [Available from European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX United Kingdom.]

Higgins, R. W., Y.-P. Yao, M. Chelliah, W. Ebisuzaki, J. E. Janowiak, C. F. Ropelewski, and R. E. Kistler, 1996: Intercomparison of the NCEP/NCAR and the NASA/DAO reanalyses (1985–1993). *NCEP/Climate Prediction Center Atlas No. 2.,* U.S. Department of Commerce, 169 pp.

Hines, K. M., R. W. Grumbine, D. H. Bromwich, and R. I. Cullather, 1999: Surface energy balance of the NCEP MRF and NCEP/NCAR reanalysis in Antarctic latitudes during FROST. *Wea. Forecasting,* **14,** 851–866.

Jones, P. D., and D. W. S. Limbert, 1987: A data bank of Antarctic surface temperature and pressure data. Tech. Rep. TR038, Office of Energy Research, U.S. Department of Energy, Carbon Dioxide Research Division, Washington, DC, 52 pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., 1989: Description of the NMC global data assimilation and forecast system. *Wea. Forecasting,* **4,** 335–342.

——, and Coauthors, 1991: Recent changes implemented into the global forecast system at NMC. *Wea. Forecasting,* **6,** 425–435.

Kidson, J. W., 1999: Principal modes of Southern Hemisphere low frequency variability obtained from NCEP–NCAR reanalyses. *J. Climate,* **12,** 2808–2830.

Kistler, R., and Coauthors, 2000: The NCEP–NCAR 50-Year Reanalysis. *Bull. Amer. Meteor. Soc.,* in press.

Murphy, B. F., and P. Pettré, 1995: Observed changes in the interannual variability and the annual cycle at Antarctic coastal stations. Note de Centre 45, Météo-France, CNRM, 22 pp. [Available from Météo-France, CNRM/GMGEC/UDC, 42 Avenue Gustave Coriolis, 31057 Toulouse, CEDEX, France.]

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical interpolation analysis system. *Mon. Wea. Rev.,* **120,** 1747–1763.

Renwick, J. A., and M. J. Revell, 1999: Blocking over the South Pacific and Rossby wave propagation. *Mon. Wea. Rev.,* **127,** 2233–2247.

Schubert, S., 1998: The *GEOS-1* reanalysis overview. *Proc. First WCRP Int. Conf. on Reanalyses,* Silver Spring, MD, World Meteorological Organization, 8–11.

Schwerdtfeger, W., 1970: The climate of the Antarctic. *Climates of the Polar Regions,* H. E. Landsberg, Ed., Vol. 14, *World Survey of Climatology,* Elsevier, 253–355.

Smith, R. C., S. E. Stammerjohn, and K. S. Baker, 1996: Surface air temperature variations in the western Antarctic Peninsula region. *Foundations for Ecological Research West of the Antarctic Peninsula,* R. M. Ross, E. E. Hofmann, and L. B. Quetin, Eds., *Antarctic Research Series,* Vol. 70, Amer. Geophys. Union, 105–121.

Smith, S. R., D. M. Legler, and K. V. Verzone, 2000: Quantifying uncertainties in NCEP reanalyses using high-quality research vessel observations. *Proc. Second WCRP Int. Conf. on Reanalyses,* 23–27 Reading, England, World Meteorological Organization, 133–136.

Taljaard, J. J., H. van Loon, H. L. Crutcher, and R. L. Jenne, 1969: *Temperature, dew points, and heights at selected pressure levels.* Vol. 1, *Climate of the upper air. Part I: Southern Hemisphere.* NAVAIR Atlas 50-1C-55, 135 pp. [Available from National Climatic Data Center, Asheville, NC 28801-5001.]

Trenberth, K. E., 1995: Atmospheric circulation climate changes. *Climatic Change,* **31,** 427–453.

Turner, J., and Coauthors, 1996: The Antarctic First Regional Observing Study of the Troposphere (FROST) Project. *Bull. Amer. Meteor. Soc.,* **77,** 2007–2032.

van Loon, H., J. W. Kidson, and A. B. Mullan, 1993: Decadal variation of the annual cycle in the Australian dataset. *J. Climate,* **6,** 1227–1231.

Walsh, J. E., W. L. Chapman, and T. L. Shy, 1996: Recent decrease of sea level pressure in the central Arctic. *J. Climate,* **9,** 480–486.

World Climate Research Programme, 2000: *Proceedings of the Second WCRP International Conference on Reanalyses.* WMO/TD-NO. 985, 452 pp.

Yuan, X., and D. G. Martinson, 2000: Antarctic sea ice extent variability and its global connectivity. *J. Climate,* **13,** 1697–1717.