19.7 A COMPARISON OF TRENDS IN THE SOUTHERN ANNULAR MODE FROM OBSERVATIONS AND REANALYSES

Gareth J. Marshall*
British Antarctic Survey, Cambridge, UK

1. INTRODUCTION

The principal mode of variability in the atmospheric circulation of the Southern Hemisphere (SH) extra-tropics and high latitudes is an annular structure, with synchronous anomalies of opposite signs in Antarctica and the mid-latitudes. It has most recently been referred to as the Southern Annular Mode (SAM).

Several papers have reported a trend in the SAM towards its positive phase, that is when pressures over Antarctica are relatively low compared to those in the mid-latitudes. This trend entails a strengthening of the circumpolar vortex and intensification in the westerlies that encircle Antarctica. In the significant majority of these studies workers have utilized data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (hereinafter NNR); e.g. Kidson (1999), Gong and Wang (1999), Mo (2000) and Thompson et al. (2000).

However, there is a fundamental problem with the results pertaining to recent changes in the SAM that are based on NNR data. This is because significant errors exist in the pressure fields at high southern latitudes in the NNR (Hines et al. 2000; Marshall and Harangozo 2000). Figure 2 of Hines et al. (2000) indicates marked temporal decreases in mean sea level pressure (MSLP) south of ~50˚S in the NNR, which are greatest at 65˚S, the latitude of the circumpolar trough. Here, zonal MSLP has decreased by 8 hPa in the decade 1989-98 compared to 1949-58, the result of improvements in data availability at high southern latitudes in the NNR. This has led to a bias in the derived trends in the SAM towards its positive phase.

In this study we are interested in calculating the 'true' changes in the SAM so that we may properly interpret and evaluate GCM output. Studies examining changes in the SH atmospheric circulation regime under predicted future 'Global Warming' scenarios using coupled General Circulation Models (GCMs) also predict a change towards the positive phase of the SAM (Fyfe et al. 1999, Kushner et al. 2001) Subsequently, we can ascertain the impact that errors in the NNR have caused in previously calculated trends in the SAM; have they simply exaggerated the magnitude of the trend towards the positive phase or actually produced a spurious trend where none exists? We also compare the MSLP trends with two reanalyses from the European Centre for Medium range Weather Forecasts (ECMWF).

* *Corresponding author address:* Dr Gareth J. Marshall, British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK, CB3 0ET; e-mail: gjma@pcmail.nbs.ac.uk

In order to calculate a 'true' unbiased measure of the SAM we utilize the empirical definition proposed by Gong and Wang (1999), which is based upon the zonal MSLP at 40˚S and 65˚S. This definition is adjusted to values based on the mean of six station records near each of the two latitudes used in the definition, for which good long-term records — the period 1958-2000 is used — are available.

2. DATA

2.1 Reanalysis Data

The NNR project is described in detail by Kalnay et al. (1996) and Kistler et al. (2001). In this study we use MSLP data from 1958-2000, which corresponds to the availability of the observational records utilised. The ECMWF ERA-15 project was a reanalysis of 15 years of meteorological data from 1979-93 (Gibson et al. 1996). The newer ERA-40 encompasses the 44-year period from mid-1957 to 2001. Data from two periods of ERA-40 are utilised here; 1958-68 and 1973-81. Further details of ERA-40 can be found at http://www.ecmwf.int/research/era/Project/.

2.2 Observations

The numerical definition of the SAM by Gong and Wang (1999) is as follows:

$$\mathrm{SAM} = P^*_{40^\circ S} - P^*_{65^\circ S} \qquad (1)$$

where $P^*_{40^\circ S}$ and $P^*_{65^\circ S}$ are the normalized monthly zonal MSLP at 40˚S and 65˚S, respectively. In this study we modify this definition slightly, and use the mean MSLP observations from six stations located approximately at each of the two latitudes to provide a proxy zonal mean: hence, utilizing this version of Eq. 1, we are able to calculate a SAM from observations against which we can compare the reanalyses. The stations were chosen for the following criteria: (i) a location close to the latitude band; (ii) taken as a group they provided a good spread of longitudes; and (iii) a reasonably long time-series of monthly data with few missing values was available.

3. METHODOLOGY

For the SAM derived from observations to be considered a reasonable facsimile of the SAM defined by Eq. 1 it is necessary to check that the two proxy zonal means have similar characteristics to the 'true' zonal means. This comparison was undertaken using 2.5˚ lat/lon NNR data. The 'true' zonal mean was simply the mean MSLP of the 144 points along the appropriate parallel, while data equivalent to station observations were determined by interpolating the NNR MSLP fields to the station location to the nearest 0.1˚ lat/long. While there are significant differences — a mean bias of –1.6 hPa and +3.7 hPa in the proxy zonal means exists at 40˚S and 65˚S, respectively, — there is no significant trend in the magnitude or variability of this difference through time. The standard deviations of the two estimates are similar at each latitude band; 1.7 hPa against 1.9 hPa at 40˚S and 5.0 hPa against 6.0 hPa at 65˚S.

The linear trends in SAM derived from NNR data for 1958-2000 as calculated from Eq. 1 and using zonal means estimated from the two methods are 0.0039 ± 0.0015 a^{-1} and 0.0045 ± 0.0014 a^{-1}, both significant at <1% level. Thus, we conclude that using the six observations at each latitude band provides an appropriate methodology for comparing the SAM in reanalysis datasets and observations. All further use of the terms zonal mean and SAM in this paper assumes that they are, or have been derived from, the two proxy zonal means — calculated from observations or equivalent reanalysis data (i.e. interpolated to station locations).

4. RESULTS

Due to the incomplete or comparatively short nature of the ECMWF reanalyses available at the time of this study, a comparison of these data against observations and the NNR was undertaken using the two sets of zonal means rather than the SAM itself. Trends in the zonal MSLP at the two latitude bands derived from station observations are only +0.08 hPa a^{-1} and –0.15 hPa a^{-1} at 40˚S and 65˚S, respectively; these changes are most pronounced since the late 1970s. The correlation coefficient of the 516 individual months is –0.53, statistically significant at well below the 1% level.

The difference in the zonal mean as calculated from observations and equivalent NNR and ECMWF data are shown in Figs. 1 and 2, respectively, with the mean and root mean square (rms) differences for the appropriate periods given in Table 1. All three reanalyses do a good job at characterizing the mean values and variability in MSLP at 40˚S. Note that between 1958-68 the NNR is superior to ERA-40, while the latter is slightly better for 1973-81. The bias the NNR and ERA-15 for 1979-93 are essentially identical (cf. Table 1A).

At 65˚S the reanalyses are much poorer, especially the NNR. In Fig. 1 it is apparent that there is a distinct annual cycle in the difference between the zonal means in this reanalysis and observations. A greater trend in winter is apparent from Fig. 1, which shows that while the summer bias has remained relatively constant, a clear decrease in the winter bias has led to the improved overall bias and smaller rms errors in the NNR data through time. Although ERA-40 is better than NNR for the 1958-68 period there are still some very large single discrepancies (spikes) in the zonal MSLP, the largest being –15.5 hPa in July 1964 (cf. Fig. 2).

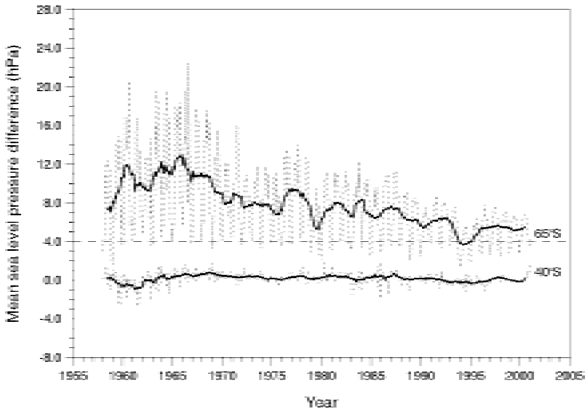

Figure 1. Differences in zonal MSLP at 40˚S and 65˚S as derived from NNR data and observations. Note that the data for 65˚S are offset by +4 hPa.

However, for the 1973-81 period ERA-40 has improved considerably at 65˚S, especially after 1979, with a mean positive bias of <1 hPa and deviations away from this being much smaller than previously (cf. Fig. 1 and Table 1B). The NNR has also improved from the earlier period examined but remains poor; it has a larger mean bias and similar rms error in 1973-81 than ERA-40 during 1958-68. ERA-15 has a very small (–0.7 hPa) consistent bias in the zonal MSLP at 65˚S.

The SAM, of course, is a means of quantifying differences in atmospheric anomalies at SH extra-tropical and high latitudes. Therefore, trends in the difference between zonal MSLP at 40˚S and 65˚S were examined for the 1958-2000 period. Both datasets reveal a statistically significant positive trend in the difference, which is towards the positive phase of the SAM. However, the NNR trend is approximately three times larger and consequently significant at <1% rather than <10% level. Furthermore, the NNR data demonstrate trends in every season that are statistically significant, most at <1% level. In contrast,

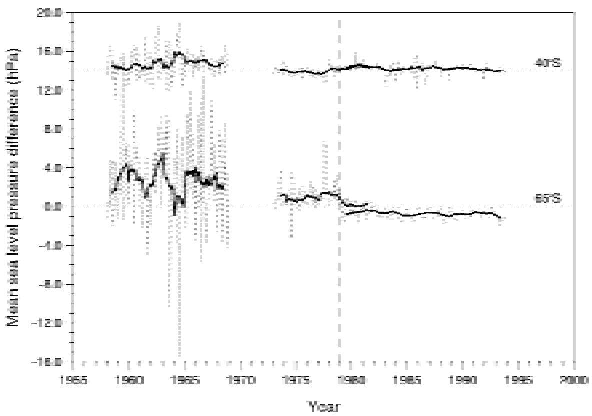

Figure 2. Differences in zonal MSLP at 40˚S and 65˚S as derived from ECMWF data and observations. ERA-40 data encompass the periods from 1958-68 and 1973-81 and ERA-15 data from 1979-93. Note that the data for 40˚S are offset by +14 hPa.

SOURCE	1958-2000	1958-1968	1973-1981	1979-1993
NNR	+0.17 (0.61)	+0.11 (0.86)	+0.27 (0.47)	+0.21 (0.55)
ERA-40	-	+0.76 (1.63)	+0.07 (0.45)	-
ERA-15	-	-	-	+0.25 (0.52)

TABLE 1A. Mean and rms differences (in parentheses) in the zonal MSLP at 40˚S compared to observations. Units are hPa.

SOURCE	1958-2000	1958-1968	1973-1981	1979-1993
NNR	+3.74 (5.34)	+6.51 (8.12)	+3.72 (4.83)	+2.64 (3.63)
ERA-40	-	+2.59 (5.17)	+0.73 (1.35)	-
ERA-15	-	-	-	–0.72 (0.87)

TABLE 1B. As Table 1A, but for 65˚S.

none of the equivalent seasonal trends derived from observations are statistically significant. NNR MSLP in winter, and to a lesser extent the equinoctial seasons, has led to both the exaggerated increase in the trend in the MSLP difference between 40S and 65˚S and errors in the seasonal cycle of such changes.

The SAM, as defined in Eq. 1 and based on the zonal MSLP data derived from the 12 stations, is shown in Fig. 3. This reveals that the general long-term trend towards the positive phase of the SAM began in the mid-1960s, following a period of positive SAM in the first half of that decade. This change is marked by the lowest (highest) MSLP values at 40˚S (65˚S) in the 1958-2000 period giving the lowest values of the SAM itself. The NNR-derived SAM (not shown) is broadly similar to Fig. 3 with the exception of the values prior to 1965. Errors in the zonal MSLP at 65˚S at this time mean that the smoothed SAM values are negative rather than positive. Bearing in mind that normalized values are utilized to define the SAM, this in turn means that the positive SAM values in the 1990s are somewhat larger and hence the resultant trend is greater. The current study indicates that for the 1958-2000 period the use of NNR data exaggerates the trend in the SAM by a factor of two.

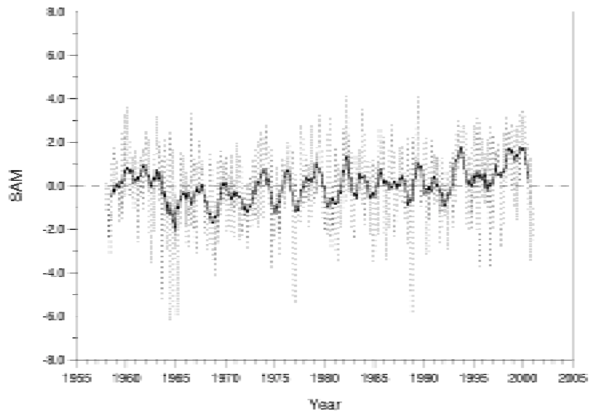

Figure 3. The SAM as calculated from observations. Monthly data are shown as a dotted line and a running 12-month filter as a full line.

5. CONCLUSIONS

1. An empirical definition of the SAM based on observational data indicates that during 1958-2000 there has been an increase in the SAM (a shift towards its positive phase); the trend in the difference between zonal MSLP at 40˚S and 65˚S is statistically significant at <10% level.

2. This trend has been occurring since the mid-1960s until the present day. However, the greatest change has occurred since the late 1970s, coincident with and perhaps related to the formation of the ozone hole (e.g. Thompson and Solomon 2002)

3. Errors in the NNR cause the trend in the difference between MSLP at 40˚S and 65˚S to be exaggerated by a factor of three for the 1958-2000 period and in the SAM, in which the data are normalized, by a factor of two. The seasonality of the magnitude of these trends is also incorrect in the NNR.

4. ERA-40 provides an improved representation of SH high latitude atmospheric circulation variability that can be used with very high confidence, at least as far back as 1973, and with higher confidence than the NNR right back to 1958.

References

Fyfe, J. C., G. J. Boer, and G. M. Flato, 1999: The Arctic and Antarctic oscillations and their projected changes under global warming. *Geophys. Res. Lett.,* **26,** 1601–1604.

Gibson, R., P. Kållberg, and S. Uppala, 1996: The ECMWF re-analysis (ERA) project. *ECMWF Newsletter,* **73,** 7–17.

Gong, D., and S. Wang, 1999: Definition of Antarctic oscillation index. *Geophys. Res. Lett.*, **26**, 459–462.

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.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77,** 437–441.

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, 2001: The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Kushner, P. J., I. M. Held, and T. L. Delworth, 2001: Southern Hemisphere atmospheric circulation response to global warming. *J. Climate,* **14**, 2238–2249.

Marshall, G. J., and S. A. Harangozo, 2000: An appraisal of NCEP/NCAR reanalysis MSLP data viability for climate studies in the South Pacific. *Geophys. Res. Lett.,* **27**, 3057–3060.

Mo, K. C., 2000: Relationships between low-frequency variability in the Southern Hemisphere and sea surface temperature anomalies. *J. Climate,* **13**, 3599–3610.

Thompson, D. W. J., and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change. *Science,* **296**, 895–899.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl, 2000: Annular modes in the extratropical circulation. Part II: trends. *J. Climate,* **13**, 1018–1036.