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Trends in the Southern Hemisphere polar vortex in NCEP and ECMWF reanalyses

James A. Renwick
National Institute of Water and Atmospheric Research, Wellington, New Zealand

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[1] A comparison of tropospheric and stratospheric height fields from ECMWF and NCEP/NCAR reanalyses during 1958–2001 indicates a trend towards a strengthening Antarctic polar vortex. The reanalyses agree well on a daily basis over the Southern Hemisphere, after the advent of satellite observations in 1979. Linear trends in 500 hPa and 50 hPa geopotential height are in close spatial agreement in the period 1980–2001 (correlations >0.8), showing falling heights over Antarctica and strengthening zonal winds above the southern oceans during summer and autumn. Prior to 1980, stratospheric trends agree well (spatial correlations ≥0.7), suggesting a rise in heights over Antarctica and a weakening polar vortex since the late 1950s. Tropospheric trends are not as consistent prior to 1980, but show similar qualitative features. The strong trends observed in the past 20 years dominate the full record, but there are suggestions of cyclical components on the decadal time scale. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Renwick, J. A. (2004), Trends in the Southern Hemisphere polar vortex in NCEP and ECMWF reanalyses, *Geophys. Res. Lett.*, *31*, L07209, doi:10.1029/2003GL019302.

1. Introduction

[2] Global reanalysis efforts at major modeling centers [*Kalnay et al.*, 1996; *Kistler et al.*, 2001; http://www.ecmwf.int/research/era/] have given the research community unprecedented opportunities to study large scale atmospheric circulation variability, especially in the data-sparse Southern Hemisphere. Unfortunately, it has been found that model biases and shortcomings, combined with the temporal evolution of observational data sets (notably the onset of satellite observations) have resulted in secular changes in reanalysis time series of such magnitude to render the reanalyses of dubious value for long-term climate change studies [*Kistler et al.*, 2001]. The impacts of observational data set changes have been especially obvious over the Southern Hemisphere, where traditional surface and upper air data coverage is sparse. The NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalyses (NRA), the first such long global time series to become available, was further compromised by a number of problems with the incorporation of observational data, such as positional errors with Australian "PAOB" data [*Kistler et al.*, 2001], and errors in the use of Antarctic observations [*Hines et al.*, 2000; *Marshall*, 2002].

[3] Significant linear trends have been found in the NRA data, in the strength of the tropospheric and stratospheric polar vortex in the Southern Hemisphere [*Renwick and Revell*, 1999; *Thompson and Wallace*, 2000; *Marshall*, 2003]. The tropospheric circulation was seen to be trending towards the positive polarity of the Antarctic Oscillation (AAO), with strengthening westerlies over the Southern Oceans and reduced geopotential heights over Antarctica, consistent with trends observed in Antarctic radiosonde data [*Thompson and Solomon*, 2002]. However, analysis of surface measurements and comparison with the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-year reanalysis (ERA15) suggested the NRA trend may be over-stated [*Connolley and Harangozo*, 2001; *Hines et al.*, 2000; *Marshall*, 2002, 2003].

[4] The ERA15 reanalysis has recently been extended to over 40 years, from the late 1950s. The availability of the longer period ECMWF reanalysis (ERA40) provides a new opportunity to assess the form and magnitude of circulation trends over the middle and high latitudes of the Southern Hemisphere, and to evaluate the level of agreement between two key reanalysis data sets over a multi-decadal time span. This paper presents a brief comparison of NRA and ERA40 height fields over the 1958–2001 period (44 years), in the mid troposphere (500 hPa) and lower stratosphere (50 hPa).

2. Data and Methodology

[5] Data come from the NCEP/NCAR and ECMWF reanalyses, over the 44-year period 1958–2001. Once-daily (1200UTC) time series of 500 hPa and 50 hPa heights were extracted from each set. The 500 hPa level is representative of the mid-tropospheric circulation and is the first standard level to lie wholly above the East Antarctic ice sheet. The 50 hPa level is representative of the lower stratospheric circulation and is the highest level in the NCEP/NCAR reanalyses to be mostly unaffected by the analysis problems identified by *Trenberth and Stepaniak* [2002]. Fields were projected from their original 2.5° latitude/longitude resolution onto a 21 × 21-point Southern Hemisphere polar stereographic grid covering all latitudes south of 20°S. The average grid spacing is around 600 km.

[6] Before computing trends, the level of agreement between data sets was assessed by comparing daily data in terms of root mean-square differences (RMSD) and spatial anomaly correlations (ACC). The ACC values were calculated using anomalies from respective daily-resolution

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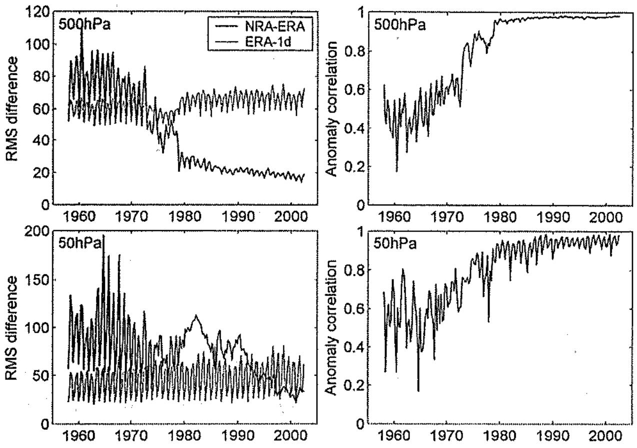

Figure 1. Seasonally averaged daily values of root mean-square difference (RMSD, in metres, left column) and anomaly correlation (ACC, right column) between NRA and ERA40 fields, for 500 hPa heights (top row) and 50 hPa heights (bottom row). In the RMSD plots, the grey line shows RMSD values for consecutive ERA40 fields (spaced one day apart).

mean annual cycles. For presentation, daily statistics were averaged into seasonal means, for March–May (MAM), June–August (JJA), September–November (SON), and December–February (DJF). Linear trends were calculated from each data series by least squares regression [*Draper and Smith*, 1981], in specified time windows.

3. Results

3.1. Comparison of Daily Fields

[7] Values of RMSD and ACC averaged into three-month seasons are shown in Figure 1. The RMSD plots also contain values of the one-day RMSD calculated from ERA40 fields. As expected, there is a clear impact from the onset of satellite observations [*Kistler et al.*, 2001; *Marshall*, 2002; *Randel et al.*, 2002]. From 1979 onwards, RMS differences and anomaly correlations improve dramatically, indicating that both reanalyses agree closely in the presence of sufficient observational data. Figure 1 also shows an increase in the amplitude of the height fields since 1979, most evident at 500 hPa, in the one-day-difference RMSD. At 50 hPa, rather than a step change in 1979, the one-day RMSD has been trending upwards throughout the record.

[8] Prior to 1979, ERA40 and NRA are rather dissimilar, with RMSD values generally larger than those found from ERA40 fields one day apart. The mean RMS amplitude of daily height anomaly fields is around 80 m at 500 hPa, and 100 m at 50 hPa, comparable to the mean RMSD at either level in the first 10 years of the record. Daily values of the ACC regularly dropped below zero, up to the early 1970s. Since 1980, the minimum daily ACC at 500 hPa was 0.83. At 50 hPa the improvement has not been so consistent. Mean ACC has risen from 0.64 in the first half of the record to 0.92 in the latter half, but daily values still drop below 0.6 at times, even in recent years. The relative lack of observations above the tropopause still allows the models to diverge in the stratosphere, especially during the southern summer when the stratospheric circulation is weakest.

[9] There are differences in behavior between levels in terms of changes to the comparison statistics. At 500 hPa, agreement between models improved markedly in 1979, and the seasonal cycle in the statistics reduced dramatically or disappeared all together. At 50 hPa, the seasonal cycle of RMSD largely disappeared in 1979, but there was strong interannual variability in RMSD through the 1980s and early 1990s not seen at 500 hPa. The seasonal cycle in 50 hPa ACC has reduced since 1979, but has also reversed phase, from a minimum in the southern winter to a weak minimum in summer. Such changes appear related to contrasting changes in the seasonal cycle of variance in both models.

3.2. Comparison of Trends

[10] Linear trends were calculated in a number of 15–25 year time windows. Here, results are shown only for the two 22-year periods 1958–1979 and 1980–2001, since these two divide the full data period evenly, and break around the time of large change in comparison statistics between the reanalyses (Figure 1). Statistics for other periods are mentioned where appropriate.

[11] Trends for DJF during 1980–2001 are shown in Figure 2. The southern summer season is shown as this is when trends are most marked. Autumn (MAM) is the season of next strongest trends, as noted by a number of authors [e.g., *Gillett and Thompson*, 2003]. At both levels, the form of the trends is consistent between NRA and ERA40, though the magnitude is larger in NRA, especially at 500 hPa. Consistent with this, *Marshall* [2003] found that the NRA trend in the Southern Annular Mode (SAM) was strongly over-stated compared to estimates based on surface

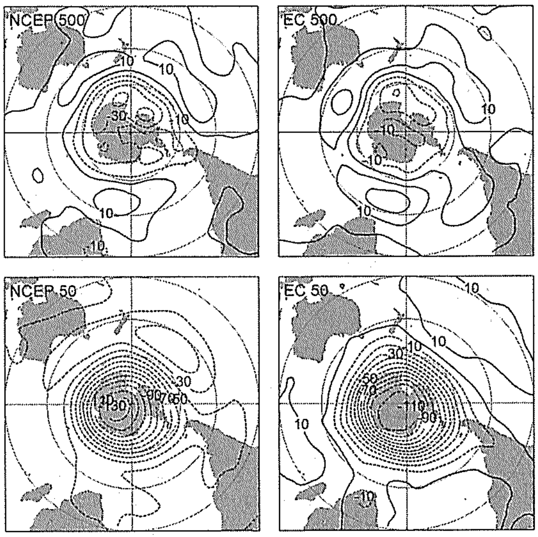

Figure 2. Linear trends in geopotential height during DJF, 1980–2001. The left column uses NCEP/NCAR reanalyses and the right uses ECMWF reanalyses. Trends at 500 hPa are shown on the top row, and trends at 50 hPa are shown on the bottom row. Contours are geopotential metres per decade, with a 10 m decade^{-1} interval. Negative contours are dashed.

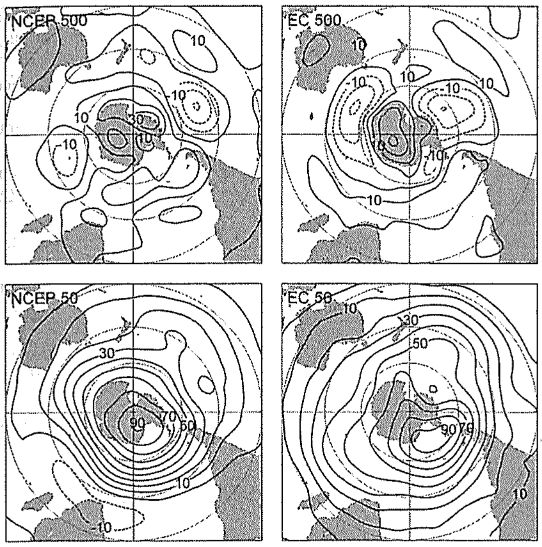

Figure 3. As in Figure 2, but for the period, 1958–1979.

observations. For DJF, the two sets of trends are spatially correlated at greater than 0.9 during 1980–2001. The weakest agreement for 1980–2001 occurs during MAM at 50 hPa, where the spatial correlation coefficient is 0.7. There, NRA shows a downward trend in height over the whole hemisphere while ERA40 shows decreases only south of about 50°S (not shown).

[12] In the stratosphere, the trend is dominated by large decreases over the Pole, likely to be associated with stratospheric ozone depletion [*Gillett and Thompson*, 2003; *Thompson and Solomon*, 2002]. The mid-tropospheric trend has a similar form to that at 50 hPa, with increasing zonal winds over the southern oceans. Such a trend in the troposphere is possibly a response to potential vorticity changes in the lower stratosphere and to associated changes in tropospheric wave propagation [*Black*, 2002; *Gillett and Thompson*, 2003].

[13] A different picture emerges for the prior 22-year period 1958–1979, as illustrated in Figure 3. The stratospheric trend is the reverse of that seen since 1980, with mean height rises over the Pole and through most of the hemisphere. Even here, the two reanalysis sets agree well, with a spatial correlation in the 50 hPa trend pattern of 0.83, despite often large day-day differences in fields. At 50 hPa there is good agreement between trend patterns in all seasons, with a minimum spatial correlation of 0.67 in MAM. The NRA exhibits a cold bias in the lower stratosphere during the early years of the period [*Marshall*, 2002], which contributes to the upward trend in height seen here. It may be that the apparent agreement between reanalyses is at least partly related to the lack of observations over Antarctica prior to the satellite era. At 500 hPa, the situation is less clear, though there are some similarities between data sets. Both NRA and ERA40 show height rises over Antarctica, and both show height falls over the eastern South Pacific and across parts of the southern Indian Ocean. The spatial correlation between 500 hPa trend patterns is only 0.36 for DJF during 1958–1979. Spatial correlations are higher in all other seasons (0.4–0.7).

[14] Taken over the whole 44-year period, the trends seen in the latter two decades dominate, especially during the southern summer. To illustrate the time evolution of the trend, anomalies (from the seasonal cycle) averaged over the months of strongest trend (December–May) were projected onto the DJF 1980–2001 trend patterns (Figure 2) and the resulting time series normalized, as shown in Figure 4.

[15] At 500 hPa, there is a gradual upward trend in the amplitude over the full period, in both reanalysis sets, from negative values in the 1960s (positive height anomalies over Antarctica) to mostly positive values since the early 1980s (negative height anomalies over Antarctica) [cf. *Marshall*, 2003]. There is considerable interannual variability at 500 hPa, but with very similar temporal evolution in both reanalyses. The correlation between the 500 hPa time series in Figure 4 is 0.92. At 50 hPa, the picture is again different. Decadal variability dominates in the NRA data, where large changes have been noted with the introduction of satellite observations in the mid-1970s, and in 1993 where errors occurred with interpretation of Antarctic surface observations [*Marshall*, 2002]. The ERA40 data, which are more reliable than NRA in the early decades [*Marshall*, 2003], shows much less marked decadal signals. Qualitatively however, both data sets show a similar evolution in time, from positive projections in the 1960s to a period of negative projections and then back towards positive projections in recent years.

4. Summary and Discussion

[16] Comparison of daily tropospheric and stratospheric fields from NRA and ERA40 suggest that both reanalyses are most reliable over the Southern Hemisphere since the beginning of the satellite era in the late 1970s, as discussed elsewhere [*Kistler et al.*, 2001; *Marshall*, 2002, 2003].

[17] Linear trends seen during the southern summer over the last two decades in the NRA data are also seen in ERA40, at both levels examined. The magnitude of the NRA trend is larger than that for ERA40, but their form is very similar, and is consistent with recent modeling work

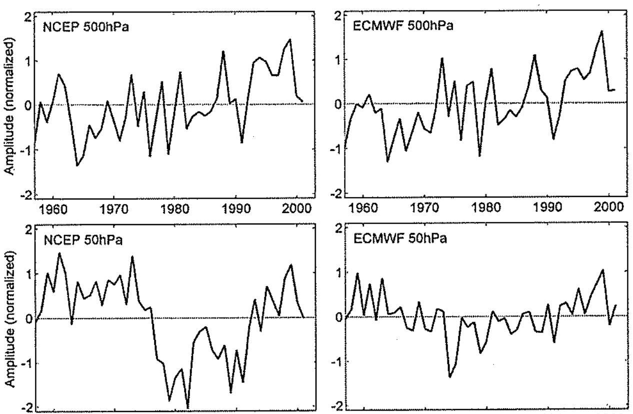

Figure 4. Pattern amplitude for the trend patterns illustrated in Figure 2. Values were calculated by projecting December–May mean height anomalies onto the DJF 1980–2001 trend patterns (Figure 2) and normalizing the resulting time series. NRA results are shown in the left panels, ERA on the right. Values for 500 hPa are shown in the top row, those for 50 hPa in the bottom row.

[*Gillett and Thompson*, 2003] showing strong forcing from Antarctic ozone depletion. The recent trend towards strengthening zonal winds dominates the full 44-year period, especially in the summer months. At 500 hPa, interannual variability in the magnitude of the trend during Dec–May is consistent between data sets, and is in broad agreement with recent observationally-based results [*Marshall*, 2003].

[18] During the first half of the record, the two reanalysis data sets do not agree strongly on the form of the trend at 500 hPa, but share some qualitative features. There is strong agreement between data sets at 50 hPa prior to 1979, showing the reverse of recent trends, with height rises over high latitudes during DJF. However, the NRA trend is at least partly related to a cold bias in the lower stratosphere over Antarctica, seen in the data-sparse period prior to the mid-1970s [*Marshall*, 2002]. The agreement between data sets suggests that ERA40 may also exhibit an early cold bias in the Antarctic stratosphere.

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J. A. Renwick, NIWA, P.O. Box 14901, Wellington, New Zealand. (j.renwick@niwa.co.nz)