On the reality, stability, and usefulness of southern hemisphere teleconnections

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A brief review is presented of published regional and hemispheric analyses of climatic data from the southern hemisphere. Besides several hemispheric analyses, regional analyses exist for southern Africa, Australia, New Zealand, and South America. These point to the importance to climatic variability of several features of the southern hemisphere atmospheric circulation, viz. the Walker Circulation or 'Southern Oscillation', the latitude of the subtropical high pressure maximum, the strength of the mid-latitude westerlies, and the eccentricity of the circumpolar flow. A new hemispheric analysis of precipitation data is used to illustrate some of the links between these features. The existence of some apparently significant correlations between climatic elements and circulation indices at lags of order 12 months are noted. These lead to a hypothesis linking anomalous circulation at high latitudes to the subsequent behaviour of the Southern Oscillation. Unfortunately there is evidence that the patterns and sequences of correlations do not remain constant with time. At best we seem unable to account for more than about one-third of the variance in Australian rainfall, even for favoured locations and seasons, in terms of its correlation with the Southern Oscillation. While relationships undoubtedly exist, some doubt as to their stability means that these relationships could be misleading as aids to long-range forecasting.

Introduction
This paper is dedicated to the memory of A.J. (Sandy) Troup who died on 10 June 1983. My desk calendar for that day bore the saying attributed to Hippocrates, 'The life so short, the craft so long to learn'. Sandy published one of the landmark papers on the Southern Oscillation back in 1965. He was a true craftsman, but we still have much to learn about this fascinating and important phenomenon which was close to his heart. His continuing contribution will be missed.

My approach in this paper is to look firstly at some evidence for hemispheric-scale climatic teleconnections which include Australian rainfall and the Southern Oscillation, then to examine the possibility of some high latitude forcing, but noting several emerging questions as to the long-term stability of the relationships. This leads to some cautionary remarks about the potential usefulness of the Southern Oscillation as a means to seasonal or longer-range prediction of Australian climatic fluctuations.

Regional and hemispheric analyses
Patterns of precipitation variations from year to year have been described on an annual or seasonal basis separately for Australia (Pittock 1975, 1978; Coughlan 1979), New Zealand (Salinger 1980a), Argentina and Chile (Pittock 1980a), and South Africa (Dyer 1975). Similar analyses of temperature variations have been described for Australia by Coughlan (1979), for New Zealand by Salinger (1980b), and for Argentina and Chile by Pittock (1980b). Such patterns have been related to indices of the large-scale atmospheric circulation, including various indices of the Southern Oscillation (Troup 1965; Wright 1975; Chen 1982), the latitude of the subtropical high pressure belt over eastern Australia (Pittock 1973), a 'Trans-Polar Index' (Pittock 1980a; Rogers and Van Loon 1982), and various zonal and meridional circulation indices in the New Zealand region (Trenberth 1976). Kidson (1975) did a global eigenvector analysis of surface pressure and precipitation, which clearly identified modes of pressure variation but not so coherent rainfall patterns. Other global-scale studies of precipitation by Stoeckelius (1981), Wright (1977) and Fleer (1981) did, however, find coherent patterns of variation which in the southern hemisphere included simultaneous anomalies over southern Africa, Australia, South America, and parts of the South Pacific.

These, and other southern hemisphere analyses of surface pressure and upper air data, notably those by Van Loon and Jenne (1972), Van Loon and Rogers (1981), and Rogers and Van Loon (1982),
leave no doubt that climatic variations on the widely separated land masses of the southern hemisphere are closely related, and indeed tied to circulation variations on a hemispheric scale.

In this paper a hemispheric eigenvector analysis of mid-latitude annual precipitation data is presented and used to illustrate some of the links between these regional variations. Eigenvector analysis arrives at a set of spatial patterns (eigenvectors of the correlation matrix) that are mutually uncorrelated in space, with the scalar amplitudes of the various patterns varying but mutually uncorrelated in time. These patterns constitute the most economical representation of the original array of data in that a linear combination of the patterns accounts in diminishing order of importance for the maximum possible percentage of the total variance (Grimmer 1963; Barry and Perry 1973).

Other forms of factor analysis, such as rotated principal components (see e.g. Mardia et al. 1979; Dyer 1975 and Salinger 1980a) could be used, and would be desirable if the empirical orthogonal functions did not have obvious physical significance. In the present case rotation does not seem to be necessary.

Annual precipitation data for the years 1931-60 were selected from larger data sets for Australia, Argentina and Chile, New Zealand, and South Africa described by Pittock (1975), Pittock (1980a), Salinger (1980a) and Dyer (1975) respectively. Twenty-five districts were selected from Australia, 17 stations from Argentina, 8 from Chile, 15 from New Zealand, and 25 from South Africa on the basis of good geographical coverage within each land mass and a roughly equal representation of the three major land masses. Locations are indicated on Figs 1 and 2.

An eigenvector analysis of the correlation matrix was performed on the University of Arizona's CYBER 175 computer using the program PRINCY developed at the Laboratory of Tree Ring Research. The analysis gives a fairly even distribution of explained variance between the first few eigenvectors, with 14 eigenvectors needed to account for 80 per cent of the total variance. The first two eigenvectors are shown in Figs 1 and 2. These are both statistically significant according to the usual criteria (e.g. Anderson 1963), although the first two eigenvectors explain only 11.6 and 10.1 per cent of the total variance respectively.

According to a recent study of the eigenvector

Fig. 1 First eigenvector of annual rainfall data, 1931-60, from 90 districts or stations as indicated by triangles. This pattern accounts for 11.6% of the total variance and the amplitude time series correlates at $r = +0.59$ with the Southern Oscillation Index, $S_t$, (chance probability less than 0.1%).
Fig. 2 Second eigenvector of annual rainfall as in Fig. 1. This pattern accounts for 10.1% of the total variance and the amplitude time series correlates at \( r = -0.58 \) with the Trans-Polar Index, TPI, (chance probability less than 0.1%).

Analysis technique (North et al. 1982), eigenvectors having eigenvalues with small separation may be confused or mixed by random variation and may not be reproducible in independent data. North et al. suggest a separation criterion that is not met in this case. However, as we shall see below, eigenvectors 1 and 2 do in fact closely resemble patterns derived from regional analyses, and have amplitude time series that show highly significant correlations with the expected indices of the general circulation. We are therefore inclined to believe that they have physical significance.

Eigenvector 1 shows strong coherence between anomalies in eastern Australia around 25-35°S and South Africa in similar latitudes, with an opposite anomaly in the South Island of New Zealand. The pattern does not account for much of the variance in Argentina and Chile.

Eigenvector 2 shows anomalies of opposite sign in the northeast relative to the southwest of Australia and New Zealand, but a reversal in the spatial phase of this pattern in South Africa and Argentina/Chile.

Correlation coefficients between the time series of amplitudes \( a_1 \) and \( a_2 \) of the first two eigenvectors and the various hemispheric and regional-scale circulation indices mentioned above are shown in Table 1.

\( S_i \), the simplified Southern Oscillation index first defined by A. J. Troup, is the mean sea level pressure anomaly difference Papeete minus Darwin, normalised for each calendar month to a standard deviation equal to ten. While this index has been used extensively, its values have not been published, and it differs from the unnormalised values recently published by Parker (1983). Values of \( S_i \) are available from the present author.

TPI is defined (Pitock 1980a) as the pressure anomaly at Hobart (43°S, 147°E) minus that at Stanley (52°S, 58°W), \( L_{AUS} \) is the latitude of the surface subtropical high pressure maximum over eastern Australia (Pitock 1973), \( L_{SA} \) is a similar index for the west coast of South America (Pitock 1980a) and \( M_1 \) and \( Z_1 \) are meridional and zonal circulation indices in the New Zealand region (Trenberth 1976). \( M_1 \) is in fact the MSL pressure difference Hobart minus Chatham Is. (46°S, 177°W), and \( Z_1 \) is the MSL pressure difference Auckland (37°S, 175°E) minus Christchurch (44°S, 173°E).
Table 1. Correlations between hemispheric precipitation eigenvectors \(a_1\) and \(a_2\) and the circulation indices \(S_1\), TPI, \(L_{\text{AUS}}\), \(M_1\), \(Z_1\), and \(L_{\text{SA}}\). Figures in brackets are the number of data pairs. Bold (italic) correlation coefficients are significant at the 99% (95%) confidence level.

<table>
<thead>
<tr>
<th></th>
<th>(S_1)</th>
<th>TPI</th>
<th>(L_{\text{AUS}})</th>
<th>(M_1)</th>
<th>(Z_1)</th>
<th>(L_{\text{SA}})</th>
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<tbody>
<tr>
<td>(a_1)</td>
<td>+0.60</td>
<td>-0.30</td>
<td>+0.37</td>
<td>-0.60</td>
<td>-0.33</td>
<td>-0.14</td>
</tr>
<tr>
<td></td>
<td>(28)</td>
<td>(30)</td>
<td>(20)</td>
<td>(30)</td>
<td>(30)</td>
<td>(20)</td>
</tr>
<tr>
<td>(a_2)</td>
<td>-0.18</td>
<td>-0.57</td>
<td>-0.69</td>
<td>-0.38</td>
<td>0.27</td>
<td>+0.41</td>
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<td>(28)</td>
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As \(S_1\) and TPI are essentially hemispheric-scale indices it is not too surprising that they correlate significantly with hemispheric-scale eigenvector pattern amplitudes. The other indices are essentially regional in scale, so that significant correlations with these indices imply that these regional indices are themselves related to hemispheric-scale circulation variations. Table 2 tests this by showing correlations found between the regional circulation indices and \(S_1\) or TPI.

Tables 1 and 2 are consistent. For example in Table 1, \(a_2\) has significant negative correlations with both TPI and \(L_{\text{AUS}}\), while Table 2 shows that TPI and \(L_{\text{AUS}}\) are positively correlated. The nearly significant positive correlation between \(a_1\) and \(L_{\text{SA}}\) is consistent with a direct negative correlation of \(-0.41\) between \(L_{\text{AUS}}\) and \(L_{\text{SA}}\) (nearly significant with 20 years data at the 95 per cent confidence level).

Confidence levels in Tables 1 and 2 have been given assuming negligible autocorrelations in the time series of annual data. In fact only \(S_1\) has significant autocorrelations. Allowance for these autocorrelations (Quenouille 1952) does not affect the quoted levels of significance.

### Discussion

The hemispheric eigenvectors in Figs 1 and 2 are in good agreement with the results of the various regional analyses. For Australia there is a close resemblance to the first and second eigenvectors, respectively, found by Pittock (1975, 1978) and Coughlan (1979), which those authors found to be related to \(S_1\) and \(L_{\text{AUS}}\) respectively.

Similarly, the first and second unrotated eigenvectors of South African rainfall found by Dyer (1975) closely resemble the corresponding sections of eigenvectors 1 and 2 of the present analysis. Subsequent to his eigenvector analysis, Dyer (1979) has related rainfall variations along the coast of Natal to \(L_{\text{AUS}}\).

Salinger (1980a) has mapped correlations of New Zealand precipitation with Trenberth’s zonal and meridional indices \(Z_1\) and \(M_1\), and these are broadly consistent with the present results. Salinger (1982) has also correlated New Zealand precipitation with \(S_1\), finding a strong negative correlation in the southeast and a strong positive correlation in the northeast similar to Fig. 1.

The regional eigenvector and correlation analyses of Argentine and Chilean precipitation of Pittock (1980a) showed some significant influence of \(S_1\) especially in northern Chile. This is not supported by the result presented here in Fig. 1, but this may be because in the hemispheric analysis eigenvector 1 is dominated by strong patterns in Australia and South Africa. Correlations of South American precipitation with the Southern Oscillation are stronger nearer to the equator, according to Wright (1977) and Stoeckenuis (1981). The second eigenvector of the regional analysis for Argentina and Chile in Pittock (1980a) correlates strongly with TPI and is in good agreement with the pattern in the present Fig. 2.

The physical significance of TPI and its relationship to \(L_{\text{AUS}}\) deserves further comment. TPI is essentially an index of wave number 1, and may fluctuate as a result of either an intensification or weakening in the amplitude of wave number 1 or a spatial phase shift, or some combination of these. It represents a fluctuating eccentricity of the polar vortex about the South Pole, such that when the vortex is displaced towards the South American-South Atlantic sector relative to its normal position TPI is more positive, and TPI is more negative when the anomaly is displaced towards the Australian-New Zealand sector. It was suggested by the fourth eigenvector of southern hemisphere MSL pressure given by Kidson, and it was confirmed in importance, at least for the southern summer, by the analysis of Rogers and Van Loon (1982). The annual mean MSL pressure at Hobart and Stanley are correlated at \(r = -0.68\) for the years 1941-60, which is significant at the 99.9 per cent level.

Clearly when TPI is positive the westerlies will be further south in the Australian and New Zealand sector, \(L_{\text{AUS}}\) will be larger and the zonal index \(Z_1\) will be weaker. Synoptic conditions over Australia and New Zealand will then give less precipitation in

Table 2. Correlation coefficients between the various regional circulation indices and \(S_1\) or TPI. Details as in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>(L_{\text{AUS}})</th>
<th>(M_1)</th>
<th>(Z_1)</th>
<th>(L_{\text{SA}})</th>
</tr>
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<tbody>
<tr>
<td>(S_1)</td>
<td>+0.29</td>
<td>-0.41</td>
<td>-0.50</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>(32)</td>
<td>(28)</td>
<td>(28)</td>
<td>(22)</td>
</tr>
<tr>
<td>TPI</td>
<td>+0.68</td>
<td>+0.38</td>
<td>-0.38</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td>(20)</td>
<td>(30)</td>
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the southwest of both countries, and more in the
northeast as seen in Fig. 1. The opposite is the case
for South Africa and Argentina/Chile.

Possible high latitude forcing of the
Southern Oscillation

The possible influence of changes in the westerlies
in the 40-60°S latitude zone of the South Pacific on
the Southern Oscillation has been touched upon by
Newell et al. (1981). This could be accomplished by
forcing of the Antarctic Circumpolar Current by
variable zonal wind stress, as demonstrated by Wear
and Baker (1980), and subsequent propagation
northward along the South American coast of sea
surface temperature anomalies by the Peru Current.
This would introduce a lag of the order of 12 months
if current speeds of about 0.2 ms⁻¹, which are
typical (Defant 1961), are applicable.

Data known to this author are at present rather
inadequate to thoroughly test this possibility, but
some significant pointers are available. Trenberth's
second zonal index Z₂, which is the MSV pressure
anomaly difference Christchurch (43.5°S) minus
Campbell Island (52.5°S), is positively correlated
with TPI at r = +0.57 with 20 years data (significant
at the 99 per cent level). Furthermore, the mean
annual sea surface temperature series for Puerto
Chicama, Peru (8°S, 79°E) (Doberitz 1967) correlates
at r = -0.49 at a lag of one year behind
TPI for the years 1931-60. This is significant at the
99 per cent confidence level. At zero lag r = -0.20,
which is not significant.

This is consistent with Trenberth's (1975b)
observation that Lₐᵤₛ is significantly correlated
with Sₘ at R = +0.48 when Lₐᵤₛ leads Sₘ by 12
months, and with a correlation of r = +0.34
between TPI and Sₘ when TPI leads by 12 months
(data 1933-60, significance 90 per cent). Such lagged
correlations help to explain the otherwise very odd
findings that Lₐᵤₛ is a useful forward predictor of
rainfall in Mauritius (Dennett 1978) and southern
Africa (Dyer 1979).

In view of the fact that two quasi-periodic
influences could be operating viz. the quasi-biennial
oscillation (e.g. see Trenberth 1975a), and the 3 to
4-year characteristic time-scale of the Southern
Oscillation itself, it is necessary to ask if an apparent
lead of TPI relative to Sₘ or Puerto Chicama sea
surface temperature (SST) could in fact be a lag
relative to an earlier cycle of Sₘ or the SST. With
this in mind, correlations have been calculated for
lags between -3 and +3 years (see Table 3). These
are not consistent with a quasi-biennial influence.
The SST does show a marginally significant
correlation with TPI when leading TPI by 3 years,
but this is considerably weaker than when it lags TPI
by one year. On the other hand, Sₘ does show an
equally significant correlation with TPI, but of
opposite sign, when leading TPI by one year. This
is consistent with a quasi-periodic influence of period
about 4 years. As a correlation of nearly equal
magnitude occurs when Sₘ lags TPI by 3 years, on
balance these lagged correlations favour TPI leading
Sₘ by one year as the primary relationship.

If such lagged correlations are indeed found to be
significant with more extensive data sets they will
support the existence of a causal relationship between
variations in the displacement of the high latitude
southern circumpolar flow and the Southern
Oscillation. They will also open up the possibility of
statistically significant and possibly useful seasonal
forecasting capability in those mid and low-latitude
regions affected by the Southern Oscillation.

How stable are these relationships?

Clearly the usefulness of the hemispheric-scale
teleconnections described above, and more
particularly of the apparent lagged relationships as
aids to seasonal or longer-term forecasting, is
dependent on the stability of the relationships.

Pitcock (1975) found almost identical results in the
eigenvector analysis of Australian district rainfall
data for the two intervals 1913-40 and 1941-70.
Moreover he found that the pattern of correlation
between Australian rainfall and Lamb and Johnson's
(1966) July L values for 120-150°E for 1913-1963
was practically identical to that using Lₐᵤₛ for
1941-1970.

There is also an abundant literature testifying to
the reality and general consistency of the El Nino-
Southern Oscillation (ENSO) phenomenon and its
teleconnections over data intervals as long as 100
years (e.g. see Angell 1981; Julian and Chervin 1978;
Newell, Selkirk and Ebisuzaki 1982 and Quinn et al.
1978). Moreover Salinger (1982) has presented
evidence suggesting that the overall precipitation
pattern for New Zealand during the period of
maximum Holocene warming some 8000 to 10 000
years ago was consistent with that caused by a more
dominantly positive Southern Oscillation index.
In 1981 Nicholls and Woodcock re-examined one
lagged relationship involving the Southern
Oscillation that was proposed in 1929 by Quayle on
the basis of 45 years of data.

| Table 3. Correlations between annual values of TPI and of sea surface temperature (SST) at Puerto Chicama,
Peru (8°S, 79°E), and between TPI and Sₘ, for lags between -3 and +3 years. Data are for 1931-60
in the cases of TPI and SST, and 1933-60 in the case of Sₘ. Confidence levels as in Table 1. |
<table>
<thead>
<tr>
<th>TPI lags</th>
<th>SST lags</th>
<th>Sₘ lags</th>
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<tbody>
<tr>
<td>Lag</td>
<td>-3</td>
<td>-2</td>
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<tr>
<td>TPI leads</td>
<td></td>
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<tr>
<td></td>
<td>-0.23</td>
<td>+0.18</td>
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<td></td>
<td>+0.21</td>
<td>-0.10</td>
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</table>
Quayle had suggested that anomalies of two-monthly rainfall averaged over ten stations in northern Victoria could be predicted during winter and spring from Darwin pressure anomalies for the previous two-month periods. Lag correlations found by Quayle using 1884–1928 data were in the range –0.39 to –0.79 for rainfalls in the June–July to October–November periods. Nicholls and Woodcock (1981) found that these relationships held up quite well on independent data, with corresponding lagged correlations for the interval 1952–1978 ranging from –0.40 to –0.59. In both data samples the lagged correlations were significant at better than the 95 per cent confidence level, and in several cases better than the 0.1 per cent level. There was, however, an interval in the 1930s and 1940s during which the lagged correlations were much weaker, and indeed changed sign, indicating some considerable degree of fluctuation in the relationship (Nicholls, personal communication).

Overall, the evidence leaves little doubt that the broad pattern of teleconnections discussed above is an important and continuing feature of world climate. Given that other forcing functions and constraints operate on the climate system (as evidenced by the variance in climatic parameters not accounted for by the teleconnections described above), it is not surprising that the influence of particular teleconnection mechanisms waxes and wanes from time to time at particular locations. Even if the unexplained variance is simply due to statistical fluctuations or stochastic noise in the climatic system, variations in the local spatial patterns of correlation and in the lagged relationships are to be expected. Indeed, with relatively short data sets such as that used to infer possible high latitude forcing of the Southern Oscillation above, some apparent relationships may turn out to be spurious.

The high latitude connection was examined in an independent study by Pando (1976) who found that sea surface temperatures off the Peruvian coast for the years 1953–75 were correlated with an index of the westerlies based on sea level pressure at four stations near New Zealand between 45°S and 55°S, with the westerlies leading by a little over a year. However, Ramage (1982) tested a similar (but not identical) relationship by correlating January Puerto Chicama sea surface temperature data from 1925–81 with the October Wellington (41°S) — Dunedin (46°S) MSL pressure difference 15 months earlier. Using 15-year running correlations Ramage found these varied from negative values as large as –0.6 prior to 1963 to positive correlations exceeding +0.5 in more recent years.

Another observation, by McBride and Nicholls (1983), suggests that the pattern of correlations between Australian rainfall and the Southern Oscillation migrated westward across Australia between the intervals 1933–53 and 1954–74.

The very intense El Nino event and highly negative Southern Oscillation index of 1982 provides another partially anomalous case, since it did not behave in the ‘usual’ manner. According to Philander (1983a) typical ENSO events start as modest warm sea surface temperature anomalies off the coast of Ecuador and Peru during February and March. These then expand westward until the entire tropical Pacific Ocean is affected some six months later. The 1982 event, however, began with unusually warm surface waters in the western and central Pacific (Philander 1983a, b). Indeed the sequence of events in 1981 led one prominent researcher in October 1981 to predict quite erroneously ‘that no moderate or strong El Nino will occur in 1982’ (Wyrtki 1981). Despite this anomalous behaviour, the 1982 ENSO event was accompanied by most of the expected teleconnections such as drought in eastern Australia and southern Africa, and flood rains in Peru.

Clearly there is still a great deal we do not understand about El Nino and the Southern Oscillation. We should not expect that such a complex and global-scale phenomenon would always behave in a similar manner. We must be aware that from year to year and decade to decade average climatic conditions, for example north-south and east-west sea and land surface temperature gradients, may differ considerably. For example, an average hemispheric or global surface warming such as we have experienced this century (Folland and Kentes 1982; Paltridge and Woodruff 1981) involves changes in the average north-south temperature gradient which will affect the preferred wavelength for stationary Rossby waves (Pittock 1983). Moreover, the different heat capacities of the ocean and land surfaces will lead to transient effects such as local reversals in north-south or east-west temperature gradients between oceanic and continental areas (Thompson and Schneider 1982; Pittock 1983). Warming and cooling epochs may therefore behave differently.

Conclusions

We may summarise by saying that:

- there is strong evidence for the reality of a connection between rainfall in Australia and the ENSO phenomenon;
- other circulation mechanisms also play a major role in determining Australian rainfall;
- there is some evidence that the ENSO phenomenon is influenced by the high-latitude circulation of the southern hemisphere;
- nevertheless, there is evidence that at least some of the patterns and sequences of correlations do not remain constant with time.

All of this leaves us in an unsatisfactory position with regard to the practical application of our knowledge of the ENSO phenomenon in relation to Australian rainfall. While there appear to be statistically significant relationships, correlations hardly ever exceed 0.6 and even these may wax and wane from decade to decade. Thus at best we may be able to account for about one-third of the variance...
in Australian rainfall in favoured locations and seasons. While doubt exists as to the stability of at least some of these relationships even this knowledge may prove to be misleading as a forecasting tool. This could be even more the case if we are indeed moving into an era of historically unprecedented climatic change, due to global warming by CO₂ and other infrared absorbers (Tucker 1981; Pittock 1983).

My recommendation is that we put more effort into understanding the historical record that we have, including possible long-term variation, and into gathering key data. More effort should go into key observations and data series at middle and high latitudes than is envisaged, e.g. in the US El Nino and Southern Oscillation planning document (Climate Research Committee 1983). These should include sea surface temperatures, and measures of the strength of the Antarctic Circumpolar Current as suggested by Wearn and Baker (1980).

Indices of the mid and high-latitude westerlies, and measures of the ocean surface wind stress would also be valuable, and attention should be paid to possible triggering mechanisms originating in mid-latitudes.

Acknowledgments

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References


