in stratified atmospheres. Table 1 illustrates the failure of the theory to account for the observed properties of both the integral and spectral correlation coefficients for momentum transfer (but not heat transfer). This is most pronounced in moderate instabilities where the dependence upon the wind speed apparently relates to the existence of different types of larger scale circulations in the atmospheric boundary layer (Haugen et al. 1971). It would seem that, for momentum transfer in unstable conditions, transfer efficiency will be high so long as the wind speed is high (say greater than 5m/s at 5m). In contrast, the heat transfer efficiency remains relatively high irrespective of the value of the wind speed, even increasing with increasing instability.

The dependence of the correlation coefficients upon the wind speed in unstable conditions emphasises the recent remarks made by Busch (1973): "that some representation of the simple implications of the Monin-Oboukhov similarity theory is necessary to represent the data, and this implies that the strict dictates of the hypotheses probably must also be relaxed to fit better the actual situations”.

REFERENCES

Smith, S. D. 1970 'Spectra and cospectra of turbulence over water,' Ibid., 96, pp. 138-143.

Division of Atmospheric Physics,
C.S.I.R.O.,
Station Street,
Aspendale, Victoria 3195,
Australia.
12 June 1974

COMMENT ON THE PAPER BY K. E. TRENBERTH 'A QUASI-BIENNIAL STANDING WAVE IN THE SOUTHERN HEMISPHERE AND INTERRELATIONS WITH SEA SURFACE TEMPERATURE'*

By A. B. PITTOCK

Dr. Trenberth’s analysis is both valid and useful in so far as it refers to the 13 years’ data 1959-1972 inclusive, and to the mean behaviour of the quasi-biennial oscillation (QBO) during this time. However, serious doubts must be raised about the general representativeness of this data period as a sample from which to derive a description either of the long-term mean behaviour of the QBO or of the general significance of the QBO in the mid-latitude general circulation.

* Pages 53-74 of this issue.
The Australian total ozone data series, my own L-index series, and upper air temperature data (Pittock 1973) all show a very marked QBO in middle latitudes in the years 1955–1963, and there is only a weaker QBO in evidence in total ozone since 1969 (Kulkarni, personal communication). The QBO was not evident in these parameters prior to 1955 (where such data is available) nor in the years 1964–1969. I did earlier report transient QBO oscillations in various Australian rainfall district data (Pittock 1971), but an as yet unpublished EOF analysis of annual district mean rainfall data for all Australian rainfall districts since 1913 shows no persistent QBO of any appreciable amplitude at least in the first three patterns. Even in the equatorial stratosphere, the amplitude and 'period' of the QBO is now known to be subject to very large variations (McInturff and Miller 1972).

Subject to the admitted limitations in data quality, Trenberth's EOF patterns must therefore be regarded as a valid description of the 1959–1972 data sample but not necessarily as an exact or representative description of the patterns which would derive from a longer data series. For this reason and because the statistical significance of correlations is greatly influenced by serial correlations such as those involved in the QBO over the data period, the relationship found between my L-index, or the Southern Oscillation Index $S_I$ (Troup 1965), and Trenberth's time series of pattern amplitudes (eigenvalues) must be regarded as tentative and not necessarily representative.

While EOFs are constrained by their mathematical derivation to be mutually orthogonal, the physical processes which they represent are not, so we should not necessarily expect mutually exclusive relations between the P1 and P2 patterns on the one hand and $S_I$ and L on the other. However, $S_I$ and L are not significantly correlated, and P1 is significantly correlated with L but not with $S_I$. It would thus be nearer physically if P2 were significantly correlated with $S_I$ but not with L. In fact P2 is significantly correlated with both $S_I$ and L. Taking somewhat the opposite view to Trenberth, I therefore favour an interpretation in which the P1 pattern is seen as an approximation to a zonal mean pattern such as I associate with the L-index, and the P2 pattern as an approximation to a standing wave (or 'blocking') pattern normally associated with $S_I$. According to this interpretation the orthogonal P1 and P2 eigenvectors are probably rotated slightly with respect to those one would obtain from a more representative set of data, thereby causing P2 to be partially correlated with L.

Of course there is no fundamental reason why L should be a purely zonal-mean index. The approximation of L to such a zonal-mean is in fact due to the fortuitous location of the east coast of Australia (where it was determined) close to a nodal line of the southern oscillation. This was discussed by Pittock (1974) and is confirmed by recent global EOF analyses by Dr. J. W. Kidson which show the characteristic southern oscillation anomaly pattern in the eastern Pacific extending south-westward into the Australian sector of the Southern Ocean at about latitude 60°S with the nodal line passing through Bass Strait (Kidson, and Trenberth, private communications).

In conclusion, Trenberth has clearly demonstrated the value of EOF and associated cross-spectral analyses, and it is to be hoped that these will be applied to a fuller discussion of the role of the so-called southern oscillation which seems to me to be fundamental. My rainfall analyses indicate that the standing wave pattern of $S_I$ is the dominant influence on Australian climatic variation. Understanding of the variations in the amplitude and position of standing planetary-scale waves would seem to be basic to an understanding of climatic change. My other main point is to suggest that the more or less transient quasi-periodic oscillations with 'periods' of about 2–4 years which are commonly observed are probably explicable in terms of the characteristic time and space scales of various atmosphere/ocean feed-back processes. These 'periodicities' may well provide clues to the processes, but it is the processes themselves which are fundamental. There is some danger of placing too much importance on periodicities as such.

REFERENCES

McInturff, R. M. and Miller, A. J.

Pittock, A. B.


CORRESPONDENCE AND NOTES


Division of Atmospheric Physics,
C.S.I.R.O.,
P.O. Box 77,
Mordialloc, Vic. 3095,
Australia.
21 August 1974

---

REPLY

By K. E. TRENBERTH

My paper investigated the 'regimes' that were found to persist in pressure patterns, by seeking relationships with SST variations. The discovery of quasi-biennial variations in the regimes was somewhat incidental, and if the aim had been to determine the form of a QBO, rather different techniques would have been preferred. The problem of obtaining a long series of data is always present, especially in the Southern Hemisphere (S.H.). Establishing EOF patterns may enable this problem to be circumvented by treating them as indices represented by values at the 'centres of action', in the manner of the Southern Oscillation index.

Kidson (1974a, 1974b) has performed separate EOF analyses of the Northern Hemisphere, S.H., Tropical belt, and entire globe for the 1951–1960 period. The analysis of S.H. SLP anomalies suffered from a lack of Antarctic data in early years; however, results in the Australasian area lend support to the stability of the main features shown by P1 and P2 in my paper (Kidson private communication). The first two components essentially represent variations in the zonal flow and wavenumber 1, which together would correspond to P1. The third component corresponds to P2 and its time series shows the beginnings of the QBO after 1955, but not prior to then.

Rainfall is an almost discontinuous parameter which depends on the source of moisture, orography, and other factors, and may not be correlated with pressure departures. Rainfall departures from normal are therefore much less coherent than other meteorological parameters and EOF patterns tend to represent variations over limited regions (Kidson 1974a). Therefore Pittock's rainfall results are not surprising.

Although relations of the QBO with the L-index and the strength of the Hadley and Walker Cells were discussed, Pittock has criticized the absence of discussion with $S_I$. Pittock (private communication) has since supplied me with $S_I$ values which have been smoothed in the same way as data used in this study. Results of spectral and cross-spectral calculations are shown in Fig. 1. For this 14-year period, $S_I$ did not reveal a significant periodicity. P1 and $S_I$ are significantly coherent for periods of 4 to 9 years with $P_I$ leading $S_I$ by about 12 months. P2 and $S_I$ are most significantly coherent for periods from 22 to 36 months with $S_I$ leading by about one month. $L$ and $S_I$ were not significantly coherent, but nevertheless exhibited a correlation coefficient $r = 0.48$ at a lag of 12 months with $L$ leading $S_I$. Other statistically significant coefficients are shown in Table 1. All correlation coefficients shown, except $P2$ and $S_I$ at 12 months lag, appear to be significant at the 5% level, where the significance test was applied after reducing the effective number of observations by a factor of 2.5 to 3 to allow for the observed persistence in $P1$, $P2$, $S_I$, and $L$ (autocorrelation coefficients range from 0.36 to 0.49).

An interpretation of these results in physical terms is now given. The Southern Oscillation affects substantial parts of both hemispheres but has centres of action in the tropics over Indonesia and the Eastern Pacific with little influence poleward of latitude 40° (Troup 1965). In contrast, $P1$ and $P2$ have their centres of action south of 40°S and clearly represent mid-latitude disturbances. Based upon the power spectra and the above results, $L$ and $S_I$ can be interpreted to be mixed indices. For example, $S_I$ then consists of quasi-biennial fluctuations associated with $P2$ variations and the
Figure 1. Normalized power spectrum and red noise spectrum for $S_T$ and cross-spectra of $P_1 - S_T$ and $P_2 - S_T$ (squared coherency and phase spectra).

**TABLE 1.** Correlation coefficients between Index 1 and Index 2, with Index 1 leading. A dash indicates lack of significance.

<table>
<thead>
<tr>
<th>Index 1</th>
<th>Index 2</th>
<th>Zero lag</th>
<th>12 mo. lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$P_1$</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>$P_2$</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>$P_2$</td>
<td>$S_T$</td>
<td>0.45</td>
<td>-0.36</td>
</tr>
<tr>
<td>$P_1$</td>
<td>$S_T$</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td>$L$</td>
<td>$S_T$</td>
<td>-</td>
<td>0.48</td>
</tr>
</tbody>
</table>

QBO, as well as longer term fluctuations associated with $P_1$ but lagging by 12 months or so. Air–sea interaction provides a possible physical mechanism for the lag relation. When $P_1$ is positive, the easterlies are stronger than normal (or westerlies weaker) in the 30–40°S belt and the westerlies are stronger than normal south of 50°S. Therefore the north Tasman SST values increase (Figs. 10a and 11). The west wind drift or southern ocean current is also enhanced, which in turn supplies cold water to the Humboldt–Peru current complex off the west coast of South America. This influx of cold water one year later into the region of the semipermanent anticyclone that lies near one centre of the Southern Oscillation, combined with the warming in the west Pacific–Tasman Sea area, triggers a change in $S_T$. The reverse also applies. Clearly more data are needed to establish such lag relationships, and the mechanism is speculation at this point. Nevertheless, the major
variations of $P_1$ (see Figs. 6 and 8) occur primarily in the 3 to 7 year range, and for this period were all followed by changes in $S_7$. I also interpret $L$ as consisting of long-term variations associated with $P_1$ and quasi-biennial variations associated with $P_2$. The lack of significance of the correlation between $L$ and $S_7$ at zero lag therefore results from the interference and cancelling effects of the positive correlation of $L$ with $P_1$ and negative correlation of $L$ with $P_2$. However, at 12 months lag, these effects are additive.

Although Pittock's interpretation is the reverse of this, it appears that the above is in fact 'neater physically' by sorting the main variations into quasi-biennial and longer term periodicities. The latter may be related to air-sea interaction effects. The cause of the QBO is unknown. The positive correlation of $P_2$ with $S_7$, as noted in section 8, implies that when $S_7$ is positive (pressures low over Indonesia, high over the East Pacific), so that the Hadley cell is weak and the Walker circulation is strong, then the mid-latitude westerlies are weak and blocking is prevalent south-east of New Zealand ($P_2$ positive). The long-term mean behaviour of the QBO, as noted by Dr. Pittock, is apparently one where it strongly manifests itself for periods of a decade or so, and may die out at times, but there is ample evidence to suggest that it has been present in the near and distant past, over most of the globe, and throughout the troposphere and the stratosphere.

A major conclusion of my and Dr. Pittock's work seems to be that more research is required.

REFERENCES


New Zealand Meteorological Service, P.O. Box 722, Wellington, New Zealand. 30 August 1974

DISCUSSION OF MASON-AND JONAS' MODEL OF DROPLET GROWTH IN CUMULUS CLOUDS

By J. WARNER

1. INTRODUCTION

The principles underlying the evolution of cloud droplet spectra and the formation of precipitation in warm clouds are well known. It is also generally recognized that these processes will be affected by mixing between a growing cloud and its environment; further, the nature of the changes resulting from the mixing process is well understood. This being the case, a model formulated to describe in quantitative terms the process of droplet development and rain formation is only of value to the extent that one can have confidence in the soundness of the dynamics and thermodynamics of the model itself. The model described by Mason and Jonas (1974) and Jonas and Mason (1974) (hereinafter I and II) inspires no confidence in this respect; further, the quantitative nature of the droplet spectra predicted from it are likely to be valueless. In what follows I would like to look at these predictions in some detail and examine their significance in terms of both the dynamics and thermodynamics of the model and of its microphysics.

2. DYNAMICS AND THERMODYNAMICS

In I a spherical thermal of known initial size, temperature excess and upward velocity is postulated; it rises through essentially non-turbulent surroundings, loses its buoyancy as a result of mixing,