# Tropical-Extratropical Interactions in the Australian Region

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ABSTRACT

The months of October 1971 and 1972 were, respectively, months of heavy and light rainfall over much of Indonesia and New Guinea. The two months also showed considerable differences in the atmospheric circulation in the higher latitudes of the Australian region, with the wetter month (1971) exhibiting stronger westerlies between 30° and 45°S and weaker tropospheric westerlies poleward of 45°S. These changes are similar to those observed in the eastern Pacific during periods of heavy or light equatorial rainfall. Examination of 14 years of data in the Australian region suggests the presence of 1) significant coherence between tropical rainfall and the strength of the subtropical westerlies for periodicities greater than six months with no apparent lag, and 2) a significant out-of-phase relationship between tropical rainfall and high-latitude westerlies at periods greater than 24 months, the latter lagging the former by several months. The relevance of these results to tropical-extratropical interactions and numerical modeling is discussed.

## 1. Introduction

In recent years, increasing attention has been focussed on the interaction between equatorial rainfall and the atmospheric circulation of the subtropics and extratropics. In particular, many observational case studies have been performed with the intention of testing Bjerknes' (1966) hypothesis that increases in latent heat release due to anomalously heavy equatorial rainfall will cause the meridionally circulating Hadley cell to accelerate, resulting in increased export of absolute angular momentum from tropical latitudes and thus leading to a strengthening of the zonal westerlies in the longitudes of the equatorial rainfall anomaly. Such studies have been concentrated in the eastern Pacific where Bjerknes (1966, 1969, 1972), Krueger and Winston (1974, 1975) and Krueger and Gray (1969) have all shown that periods of abnormally heavy equatorial rainfall are also times of increased strength of the zonal westerlies further poleward.

Studies of tropical-extratropical interactions in the western Pacific have been rare. Ramage (1968) compared two Januaries with widely differing rainfalls in the Indonesia-New Guinea area and concluded that the increased latent heat release in the wetter month probably helped maintain the more intense subtropical jet stream observed in that month over the western and central North Pacific. In the Australian region, recent studies of meridional interactions between the tropics and extratropics have included those of Pittock (1973) and Trenberth (1975, 1976). However, explicit and conclusive testing of the applicability of Bjerknes' hypothesis to this area has not yet been undertaken. This is somewhat surprising given the unique positioning of a continental land mass with a relatively good data network stretching from tropical to middle latitudes in the longitudes of the "maritime continent" of Indonesia and New Guinea where the largest portion of the heat exported from the equatorial regions is generated (Ramage, 1968). Hence the primary objective of this study is to partially fill this void by investigating the interrelationship of rainfall in the Indonesia-New Guinea region and the tropospheric circulation in the Australian region and to compare the observed behavior with the eastern Pacific studies noted above. In the first instance an examination is made of the differences in some of the parameters of the circulation observed between a month associated with drought in Indonesia and New Guinea and a month of abnormally heavy rainfall in this area. The limited "historical" record is then examined to determine whether such changes are systematic.

## 2. The atmospheric circulation of October 1971 and 1972

During the period June to October 1972 severe drought occurred over Indonesia and New Guinea (WMO, 1973; Staff Members, 1972). By comparison, during the previous Southern Hemisphere winter of 1971 this region received copious rainfall with severe flooding occurring in Indonesia (WMO., 1972) and record rainfall in many areas in New Guinea (Staff Members, 1972). The change between the two periods can be seen by comparing the rainfall for the months of October 1971 and 1972. Rainfall totals for these months at several stations in the region are presented in Table 1 and reveal that considerably more rainfall fell over much of this region in October 1971 than in October 1972. It could be expected, from Bjerknes' (1966) hypothesis, that the higher latitude, upper tropospheric circulation in the Australian region should exhibit significant differences between the two months.

In the following discussion, mean monthly analyses for the two months, produced by the operational numerical analysis system of the Australian Bureau of Meteorology are compared. Two factors associated with these analyses require that some caution be applied in the interpretation of any differences observed between the two months. First, the analysis system changed somewhat during the intermediate 12 months and second, the area south and west of the Australian continent is virtually void of conventional data. In this region the analysis system gives considerable weight to subjective satellite cloud picture interpretation and thus the accuracy of the analyses is somewhat suspect. However, gross differences over the continent can be confidently treated as being free of analysis error and only the smaller differences south and west of the Australian continent need more cautious interpretation.

The difference between the monthly mean 200 mb geopotential heights of October 1971 and 1972 over the Australian region is shown in Fig. 1. Two major differences between the two months are revealed by this diagram: first, a decrease in 200 mb height in the subtropics from 1971 to 1972, centered about latitude 25°S and second, a zonally oriented region of increased heights in the mid-latitudes centered on latitude 45°S.

The differences in the troposphere associated with these 200 mb changes have been investigated using meridional profiles of tropospheric temperatures and geopotential heights. The essentially zonal alignment of the changes from October 1971 to 1972 (e.g., Fig. 1) ensures that meridional profiles at a particular longitude can be assumed to realistically represent changes occurring throughout much of the region considered.

TABLE 1. Rainfall (mm) at selected stations for October 1971 and 1972.

| | | | Rainfall | |
|---|---|---|---|---|
| | Latitude | Longitude | October 1971 | October 1972 |
| Singapore | 01°22′N | 103°55′E | 190 | 84 |
| Surigao | 09°48′N | 125°30′E | 628 | 148 |
| Zamboanga | 06°54′N | 122°04′E | 394 | 259 |
| Cebu | 10°20′N | 123°54′E | 295 | 100 |
| Dili | 08°34′S | 125°34′E | 28 | 0 |
| Madang | 05°13′S | 145°48′E | 590 | 92 |
| Lae | 06°44′S | 147°00′E | 538 | 212 |
| Port Moresby | 09°26′S | 147°13′E | 25 | 5 |
| Koror | 07°20′N | 134°29′E | 498 | 250 |
| Yap | 09°29′N | 138°05′E | 385 | 143 |
| Momote | 02°04′S | 147°26′E | 200 | 97 |

Two meridional profiles showing the heights of the 200 and 1000 mb surfaces and the 1000-500 mb and 500-200 mb thicknesses, at longitudes 115° and 150°E, for the two months are shown in Fig. 2. Poleward of about 35°S the two profiles are very similar confirming the essentially zonal character of the changes noted above. Both profiles show an increase in 200 mb heights from 1971 to 1972 centered about latitude 45°S, and reveal that this is due to both higher tropospheric temperatures and to increases in the height of the 1000 mb surface.

Equatorward of 35°S the profile at 150°E reveals that fairly small changes occurred from 1971 to 1972. However, at 115°E, through the region of the greatest changes evident in Fig. 1, considerably lower temperatures (centered on about latitude 25–30°S) occurred in the upper troposphere in 1972 associated with a de-

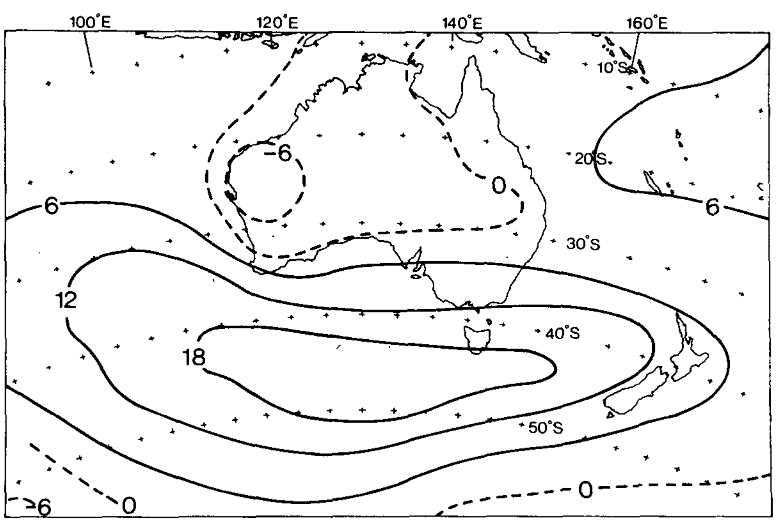


FIG. 1. Change in monthly mean 200 mb geopotential height (dam), October 1972 minus October 1971.

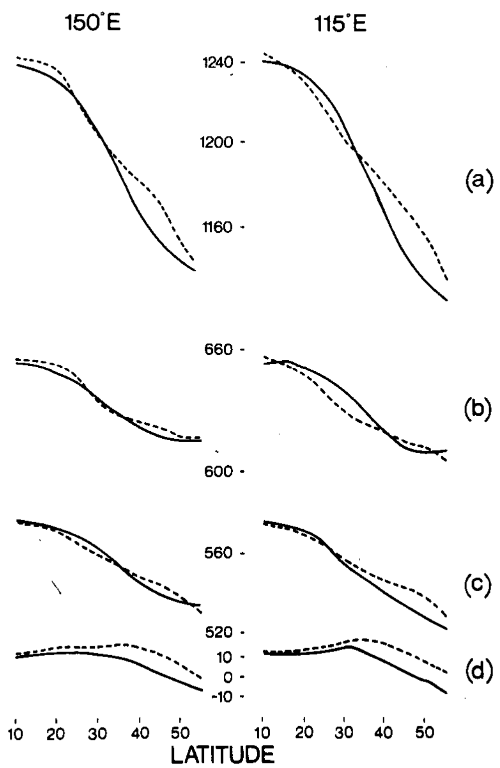


FIG. 2. Meridional profiles of monthly mean height and thickness (dam) at 150°E and 115°E. Solid line is October 1971, broken line is October 1972. (a) 200 mb geopotential height, (b) 500–200 mb thickness, (c) 1000–500 mb thickness, (d) 1000 mb geopotential height.

crease in 200 mb heights in this region (Figs. 1 and 2). This decrease in upper tropospheric temperature is also evident in Fig. 3 which shows meridional cross sections of the changes in temperature from 1971 to 1972 along longitudes 130° and 115°E.

The concomitant changes in wind speed are illustrated in Fig. 4 which shows cross sections of the mean wind speed along 150°E for the two months and also the change from 1971 to 1972. South of about latitude 30°S the wind direction is almost zonal and thus Fig. 4c can be assumed to show the changes in the strength of the westerlies. It is clear that the westerlies between 28° and 45°S were weaker throughout the troposphere during 1972, while the westerlies in higher latitudes (poleward of 45°S) were stronger.

These circulation changes from October 1971 to 1972 closely resemble the differences in the circulation over the eastern North Pacific between periods of heavy equatorial rainfall and periods of low rainfall (e.g., Bjerknes, 1966, 1969, 1972; Krueger and Winston, 1974, 1975; Rowntree, 1972; Krueger and Gray, 1969). This suggests that the interrelation of tropical rainfall and meteorological events further poleward, in the Australian region, is similar to that observed in the aforementioned studies of other regions. However, this tentative conclusion can be valid only if an examination of data from previous years indicates that the higher latitude differences between "wet" and "dry" months are systematic. Cross-spectral and correlation analyses have been used to investigate this and also to study the relative timing of the various observed fluctuations in an attempt to determine the mechanistic nature of this tropical-extratropical interaction.

## 3. Cross-spectral analysis

The temporal and spatial variability of rainfall in the Indonesian-New Guinea region makes the task of selecting a single parameter to describe the large-scale rainfall variations difficult. However, it is known (e.g., Kidson, 1975) that rainfall in this area is related to surface pressure, heavy rainfall periods generally coinciding with lower pressure. Surface pressure at Darwin (12°S, 131°E) has therefore been used in cross-spectral analyses with parameters representing the fluctuations in the circulation further poleward. The close association of many of the circulation differences noted in the previous section means that considerable information can be gained from examination of a few parameters. Those selected for cross-spectral analysis

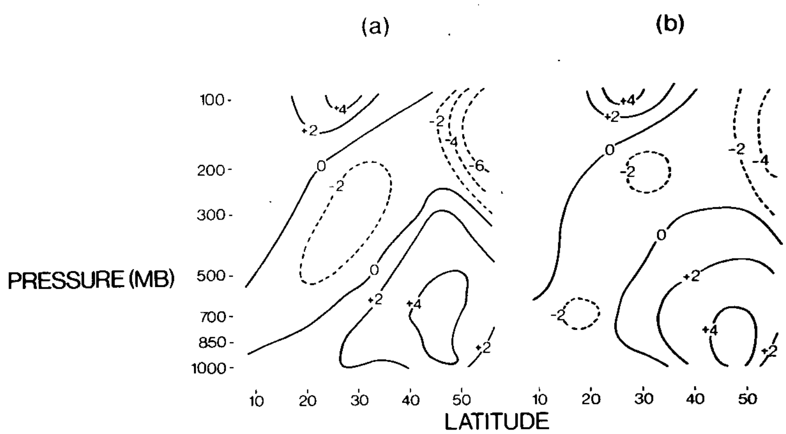


FIG. 3. Change in monthly mean temperature (K), October 1972 minus October 1971 for longitude 115°E, (a) and longitude 130°E (b).

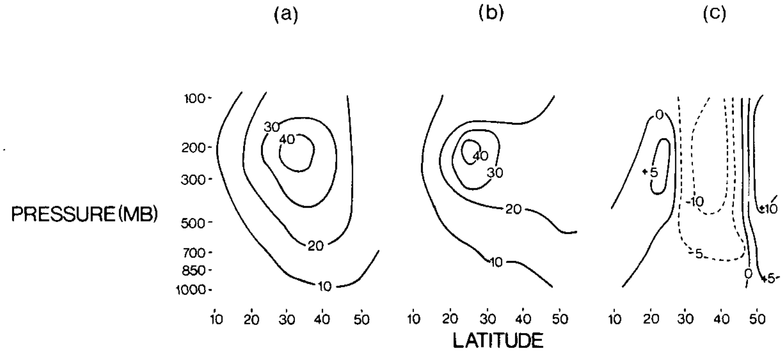


FIG. 4. Monthly mean wind speed (m s$^{-1}$) for (a) October 1971, (b) October 1972 and (c) October 1972 minus October 1971. Longitude 150°E.

with the Darwin data were the strength of the subtropical and higher latitude, upper tropospheric westerlies and surface pressure in the mid-latitudes. The parameters used to describe these are 200 mb zonal wind speed at Williamtown (33°S, 152°E), 300 mb zonal wind speed at Macquarie Island (55°S, 159°E) and surface pressure at Hobart (43°S, 147°E). The somewhat fragmentary nature of the Macquarie Island record has restricted its study to the period since 1964 and enforced the use of 300 mb winds rather than 200 mb. Data for 1960–73 have been used for all the other parameters. For each parameter several months with very few observations have been replaced by long-term means. Data are available prior to 1960 but their use could introduce uncertainties due to instrument or timing changes, incomplete or inhomogeneous records or the presence of long-term trends in the series.

Twelve-month running means of the time series of the four parameters are shown in Figs. 5 and 6. These diagrams illustrate the existence of fluctuations with rather long periods in each parameter and reveal the relationships that exist between them. It can be seen that periods of abnormally high Darwin pressure approximately coincide with periods of strong Macquarie Island zonal wind, weak Williamtown zonal wind and high surface pressure at Hobart.

Spectral and cross-spectral analyses of monthly anomalies of these parameters were performed using a procedure given by Jenkins and Watts (1968) which makes use of the Tukey window. Spectral analyses revealed considerable power in periods >18 months for each parameter. Cross spectra between Darwin pressure and the other three parameters are shown in Figs. 7–9. The 95% confidence limits of the squared coherence are listed in Table 2 for the maximum squared

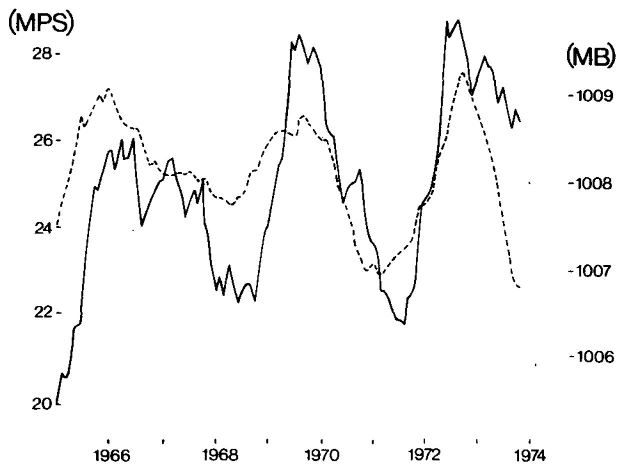


FIG. 5. Twelve-month running means of Macquarie Island 300 mb west-east zonal wind (solid line) and Darwin surface pressure (broken line).

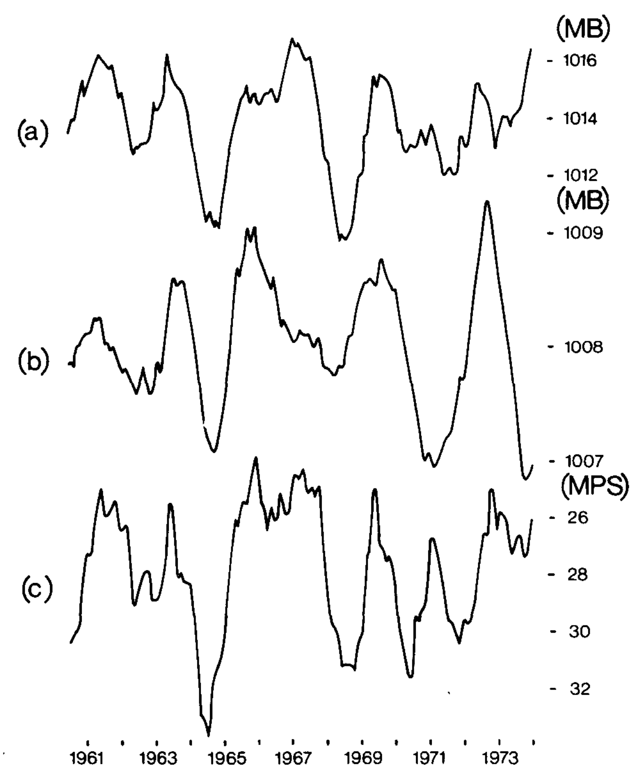


FIG. 6. Twelve-month running means of (a) Hobart surface pressure, (b) Darwin pressure and (c) Williamtown 200 mb west-east zonal wind speed (scale reversed).

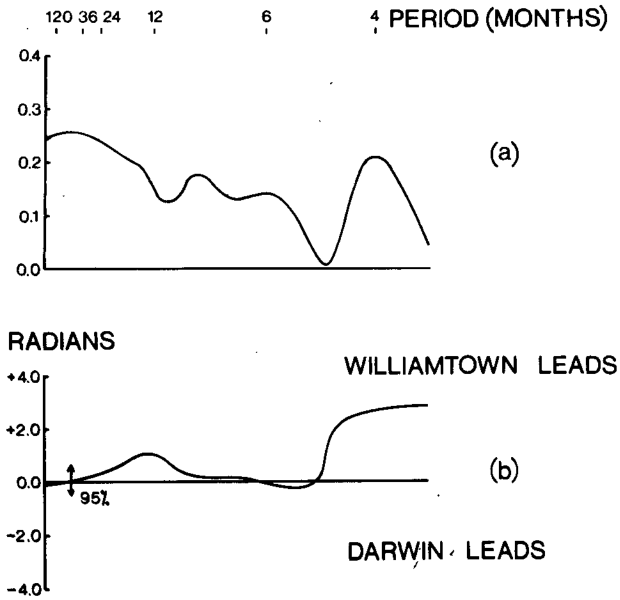


FIG. 7. Cross spectrum. (a) squared coherency and (b) phase spectrum for time series of 200 mb east-west zonal wind at Williamtown and Darwin surface pressure.

coherence observed in each analysis. For the phase spectra the 95% confidence limits are plotted on Figs. 7–9 at the period of maximum coherence.

Cross-spectral analyses of Darwin pressure with Williamtown east-west zonal wind and Hobart surface pressure are shown in Figs. 7 and 8. Both figures reveal that significant coherence exists between the parameters at the longer periods, reaching a maximum at approximately 48 months. The events at Darwin and Williamtown operate in phase at this periodicity

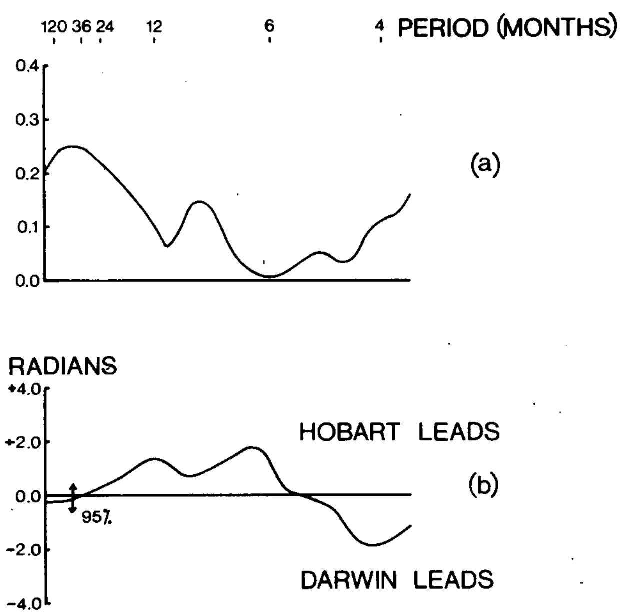


FIG. 8. As in Fig. 7 but for surface pressure at Hobart and at Darwin.

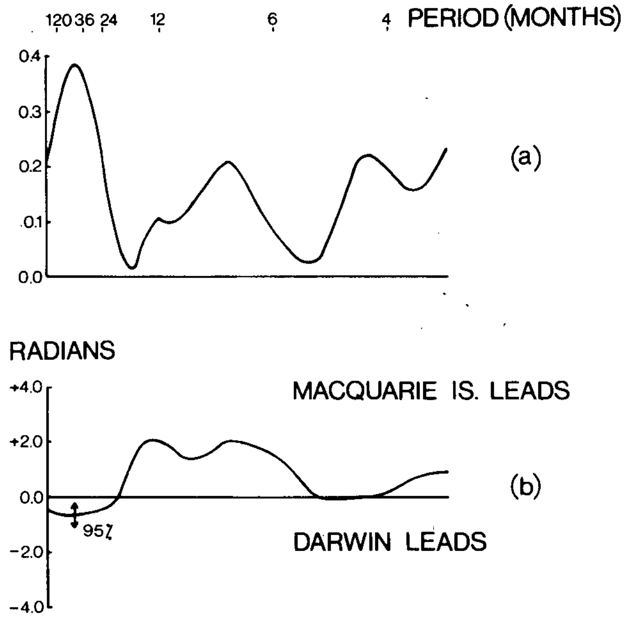


FIG. 9. As in Fig. 7 but for 300 mb west-east zonal wind at Macquarie Island and Darwin surface pressure.

indicating that strong westerlies occur at Williamtown during periods of low pressure (i.e., heavy rainfall) in the tropics. No consistent lag exists between the two parameters. Darwin and Hobart operate in phase (Fig. 8) although in this case there is slight evidence of a small lead (about one month) by Darwin. The cross-spectral analysis of monthly anomalies of Darwin station-level pressure and Macquarie Island 300 mb west–east zonal wind is shown in Fig. 9. A significant peak in the coherence occurs at a period of approximately 48 months. The phase spectrum shows that events at Darwin lead those at Macquarie Island by about 5 months. This lag is confirmed by calculation of correlation coefficients between 12-month running means of the two time series at various lags. The largest coefficient found was +0.85 with Darwin leading by 4 months.

A major problem with the analysis performed above is the extent to which single-station wind reports adequately represent, for instance, the strength of the subtropical westerlies. This problem was examined by correlating the annual mean surface pressure at Darwin with the annual mean differences between the 200 mb geopotential height at several station pairs located near

TABLE 2. Confidence levels of maximum coherences.*

| Station pair | $M$ | $C$ |
|---|---|---|
| Darwin-Macquarie Is. | 0.38 | 0.05–0.70 |
| Darwin-Williamtown | 0.26 | 0.02–0.56 |
| Darwin-Hobart | 0.25 | 0.02–0.56 |

* $M$ is the maximum squared coherence, $C$ the 95% confidence limits on the maximum squared coherence.

longitude 150°E for the years 1960–73. Correlation coefficients of +0.661 and −0.568 were found between Darwin pressure and the Hobart-Macquarie Island and Williamtown-Hobart differences, respectively, confirming the scheme of strengthened subtropical (30–40°S) westerlies and weakened mid-latitude (40–55°S) westerlies during periods of low Darwin pressure revealed by the cross-spectral analysis of the single-station winds. Similar behavior occurred at the 500 mb level. No appreciable correlation existed between Darwin pressure and height differences between Williamtown and stations further equatorward, indicating that the correlations between the height difference between Williamtown and Hobart and Darwin pressure represent primarily *in situ* fluctuations in the strength of the subtropical westerlies rather than latitudinal shifts of the subtropical jet.

The present study has concentrated on events in the middle and upper troposphere because the behavior observed at the surface can be readily deduced from previously published work. Trenberth (1975) performed an empirical orthogonal function analysis on monthly mean sea level pressure anomalies in the Australian area. One component of this analysis (*P*2) possessed considerable power on the time scale considered in the present study. A positive coefficient of this component represents stronger than normal surface westerlies over the Australian continent, equatorward of 45°S, and weaker than normal surface westerlies poleward of 45°S, in Australian longitudes. Using 38 years of data, Trenberth (1976) found that highly significant coherence exists between *P*2 and Darwin surface pressure, on a time scale of about 30–52 months, indicating that periods of low Darwin pressure approximately coincided with increased surface westerlies equatorward of 45°S with weaker westerlies poleward of this latitude. A tendency for *P*2 to lag behind Darwin pressure by about 4 months was also found by Trenberth (1976). The similarity of this surface behavior deduced from Trenberth's results and the middle and upper tropospheric behavior found in the present study suggests that Trenberth's results might apply throughout the troposphere. Thus the scheme of variations in circulation observed in the present study has most likely occurred systematically throughout the period of Trenberth's study (38 years) and is not simply the result of the small data sample employed.

## 4. Discussion

The association between periods of low Darwin pressure (i.e., heavy rainfall in the Indonesia-New Guinea region) and strong subtropical westerlies is in accord with the behavior in the eastern Pacific (e.g., Bjerknes 1966). Since rainfall variations in the east and west equatorial Pacific are negatively correlated (Nicholls, 1973; Kidson, 1975), the present results suggest that the variations in the subtropical westerlies in the two regions would also be negatively correlated. If so, there may well be no change in the zonally averaged circulation, i.e., the interrelation of equatorial rainfall and the subtropical westerlies may be reflected entirely as changes in the large-scale eddies.

If fluctuations in equatorial rainfall force variations in the atmospheric circulation further poleward (or vice-versa), there is no apparent reason why such behavior should not operate at all periodicities and therefore the relationships revealed in Figs. 7 to 9 should be consistent over a wide range of periods. In fact Fig. 7 reveals that, over the range of periods covered by the analysis, this does occur. For periods > six months considerable coherence exists between the two series and the phase remains approximately constant apart from the small peak at about 12 months. This suggests that a relatively simple form of interaction, such as forcing by equatorial latent heat release, might take place between the tropics and subtropics. However, the reason for the occurrence of a maximum coherence at periods >24 months is not clear. This effect is presumably related to the Southern Oscillation (Troup, 1965) since Darwin pressure has often been used as an index of the Southern Oscillation, and because the Oscillation in general operates on time scales greater than two years (Trenberth 1976).

The cross-spectral analysis of Fig. 9 differs considerably from that of Fig. 7. In this case the maximum coherence is concentrated in periodicities >24 months and drops sharply to a minimum at about 18 months. Another maximum occurs at about 9 months but at this periodicity the higher latitudes lead the tropics. Such a variation of coherence and phase with varying periodicity is difficult to explain by a simple forcing mechanism of tropical-extratropical interaction. Apparently a much more complicated mechanism operates.

Irrespective of the mechanism of these interactions the results of this and earlier studies have obvious relevance to numerical simulations of the general circulation. Rowntree (1972, 1976) showed that the subtropical and extratropical circulation in general circulation numerical models react markedly to fluctuations in the models' tropical latent heat release. This implies that correct specification of the longitudinal variation in tropical rainfall is a necessary requirement for proper numerical simulation of the subtropics and extratropics. In particular, the heavily smoothed orography used by general circulation models will result in incorrectly specified latent heat release in the Indonesian Archipelago where the massive island orography considerably assists in the development of strong convective activity (Ramage, 1968). The underestimation of latent heat release that the use of smoothed orography would presumably cause should, from the results of the present study, result in model subtropical westerlies somewhat weaker than normal whereas the higher latitude westerlies would be anomalously strong in Australian longitudes.

## 5. Conclusions

This investigation has provided evidence that, in general, differences in the atmospheric circulation of the Australian region from a period of above-normal to a period of below-normal rainfall in the Indonesia–New Guinea region were similar to those observed in other areas, notably the eastern Pacific, and also in numerical model experiments. The changes observed during the period of increased equatorial rainfall include stronger subtropical westerlies, and a decrease in the strength of the westerlies further poleward. Examination of recent historical data for the Australian region revealed that this scheme of variations appears to be a systematic phenomenon operating at periodicities greater than two years and that these effects are probably related to the behavior of the large-scale eddies.

The cross-spectral analyses performed in this study provide several clues to the nature of tropical-extratropical interactions. First, the interactions observed between the tropics and the subtropical westerlies were very similar throughout a large range of periodicities, suggesting that a simple forcing mechanism might explain the interaction. No discernible lag was found between the tropics and subtropics, indicating that the reaction to such forcing was extremely rapid. The relationship between the tropics and extratropics (poleward of 40°S) was more complicated with the coherence and phase varying considerably with periodicity. This suggests that a more complex mechanism is required to explain the tropical-extratropical interaction. However, at the periodicity of maximum coherence (~48 months) the tropics lead the fluctuations in the extratropical circulation.

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