The Southern Oscillation. Part III: Associations with the Trades and with the Trough in the Westerlies of the South Pacific Ocean

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ABSTRACT

Differences of sea-level pressure between pairs of stations in the South Pacific Ocean are used to examine the trades and the trough in the westerlies during the development of the phase of the Southern Oscillation when pressures fall over the tropical Pacific, equatorial waters warm, and rainfall increases in many otherwise dry places. It is demonstrated that this phase is characterized by an appreciable enhancement of the annual cycle of the trades and the trough compared to the year before. The warm event of 1982 followed this pattern closely.

1. Introduction

Our knowledge of the Southern Oscillation (SO) has expanded at a considerable rate during the last decade, but there are regions where its features are not well known, either owing to the short period of observations or to a lack of observations. The southern oceans suffer these shortcomings and an analysis of the SO there can be made only by means of the comparatively short records at isolated islands. The daily synoptic analyses of sea-level pressure (SLP) over the Southern Hemisphere must be used judiciously, and mainly to confirm and extend the analyses of station data.

This paper deals principally with the South Pacific Ocean and with station data, and the results are not necessarily valid beyond the areas where the stations are located. Means of three months are used throughout, except for Fig. 3, so SLP in June is the mean of May, June, and July (MJJ), etc. The term LOW/WET (LW) describes the phase of the SO which often is called El Niño by others. El Niño is a local phenomenon, a warm ocean current which flows south along the coast of Ecuador as part of the seasonal cycle, and the term should not be used to describe the phase of an oscillation which affects vast areas of the earth. LOW in LOW/WET refers to SLP in the subtropical ridge of the South Pacific Ocean, and WET to the usually heavy rains near the equator in the Pacific and on the Peruvian coast during a LW. The term is from van Loon and Madden (1981), who describe the response of SLP and surface air temperature to the SO in this extreme, and it is identical to the term WARM EVENT or WARM EPISODE, as defined and used by Horel and Wallace (1981) and Rasmusson and Carpenter (1982).

The emphasis in this paper is on SLP gradients in southern temperate latitudes during a LW and the year before. The pressure gradients are used to substitute for geostrophic wind to demonstrate that most LWs during the last 50 years were distinguished by an enhanced annual cycle both in the easterlies between 15 and 30°S over the mid-Pacific Ocean, and in the trough in the westerlies of that ocean. In addition, a limited comparison is made of the 1982 LW with other LWs.

2. Defining a LOW/WET

Three criteria are necessary to define a LW: sea-surface temperature (SST) in the equatorial Pacific Ocean, sea-level pressure at one or more key stations, and rainfall at equatorial islands in the dry zone. A combination of these three criteria was used to obtain the list of years in Table 1. Year zero in this table is the year in which the positive SST anomaly develops, such as 1957, 1972, and 1982 in the best known recent LWs. Some would add, and others subtract years from the list because it is often impossible to avoid ambiguity. Rasmusson and Carpenter (1983), for example, include 1932 in their Table 2, but Rasmusson and Wallace (1983) omit 1932 and include 1963, which is omitted in Rasmusson and Carpenter (1983) and only selectively used in Rasmusson and Carpenter (1982). This paper perhaps errs on the conservative side because both years are included even if they are weak LWs. Some of the events in Table 2, such as 1904–05, 1913–14, 1918–19, 1939–41, 1957–58 and 1976–77, lasted more than a year; but that does not concern this study which deals only with year$_0$ and the preceding year.

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TABLE 1. LOW/WETS (Warm Events) in the twentieth century. Only years zero are included.

1902	1918	1932	1957	1972
1904	1923	1939	1963	1976
1911	1925	1951	1965	1982
1913	1930	1953	1969	

Dr. J. Fletcher kindly provided two time series of SST from the Pacific. One series begins in 1861 and ends in 1982, and has seasonal anomalies for a belt between 5°N and 5°S. The other series has monthly anomalies separately for 0 to 10°N and 0 to 10°S, and runs from 1861 to 1960. They are as yet unpublished, but are available on request from Dr. J. Fletcher at CIRES/NOAA, Boulder, Colorado.

The rainfall data used are from Taylor (1973) and Meisner (1976). The latter's Line Islands precipitation index is reproduced by Reiter (1978) as his Fig. 6. Three-monthly SLP data for Darwin covers the whole period, and from 1935 Tahiti's pressure was used too. The list of years in Table 1 differs a little from that in van Loon and Madden (1981) because the years of weak LW, 1923 and 1932, have been added, and 1951 and 1953 have been substituted for 1952 which in the previous paper we regarded as the peak of a three-year event.

Figures 1 and 2 are examples of the diagrams used to arrive at a definition of a LW. Fanning Island (Fig. 1), with an annual rainfall of 2086 mm (Taylor, 1973), gets its heaviest rain in April–May–June (833 mm), and the lightest rain in September–October–November (132 mm). Figure 1 contains time series of the rainfall in these two three-month periods, plus one time series for December–January–February (mean 510 mm) when the effect of a LW on the circulation over the Northern Hemisphere is most evident. In a station with a reliable wet season it makes little sense to search for abnormal rainfall in the wet season. In the dry season, the anomalies stand up above the scant amounts that fall in most years, and they are easy to see in Fig. 1 even in December–January–February at the end of year$_0$.

Only the choice of 1932 as a year$_0$ is not supported by Fig. 1, but in this instance there was a marked El Niño on the Peruvian coast (Rasmusson and Carpenter, 1982; their Fig. 11), a somewhat above normal equatorial SST, and the rainfall west of Fanning was heavy. Nauru at 0°30′S 167°E, for instance, had 2662 mm during the first eight months of the year whereas the 65-year average for the same months is 1413 mm. In 1927–28, on the other hand, the rainfall at Fanning was heavy in January and February of 1928 (Fig. 1, December–January–February), but there was no El Niño and the equatorial SST was slightly below normal, so this year was not included as a year$_0$.

Figure 2 shows the mean SLP at Darwin and the rain at Fanning for December–January–February. The pressure has a clear peak in 1927–28, but was low in 1932–33. Earlier in the year, it had been low in 1927 and high in 1932. Such years are thus on the borderline, but they are few and their inclusion or exclusion will not seriously affect the results of this study.

3. The seasonal changes of the trades and the trough

This section outlines the seasonal changes of the westerly trough in the South Pacific Ocean and the trades between about 30 and 15°S, and shows that the amplitude of these seasonal changes is associated with the Southern Oscillation. The annual cycle of the SLP south of 30°S and between 150°W and New Zealand is dominated by a half-yearly wave which between 30 and 60°S reaches its maxima in March and September (see, e.g., van Loon, 1967, 1972). The mean pressure in temperate latitudes therefore falls from March to June (Fig. 3, which also contains the locations of the stations used below), by as much as 10 mb east of New Zealand, about 7 mb of which are accounted for by the half-yearly oscillation. Over Tasmania the yearly wave dominates the seasonal changes, its maximum in the southern winter being associated with the heating and cooling of Australia. As a result the trough in the westerlies amplifies from March to June, reaching its farthest northward extent of the year in May–June–July (Fig. 4), and greatly weakening the subtropical ridge. The difference Hobart minus Chatham (1930–80) is negative through most of the year (Fig. 5, standard deviations in Table 2), and because these stations are at almost the same latitude this means that the meridional component of the geostrophic wind during this period is northerly. However, from April to July the SLP difference changes sign and the mean geostrophic wind is then southerly. This is obviously not the *best* measure of the trough, but it is the best one available given the way the points of observation are distributed. Note, however, that on the average the pressure difference between the two stations does span

TABLE 2. Standard deviations (mb) of the three-month running differences in sea-level pressure between Hobart and Chatham (A) and Rapa and Tahiti (B). See Fig. 3 for locations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A (51 years)	2.7	2.1	2.4	3.1	4.0	3.8	3.4	2.8	2.8	2.9	3.2	2.9
B (29 years)	1.0	1.0	0.8	0.9	0.9	1.3	1.4	1.6	1.7	1.7	1.3	1.2

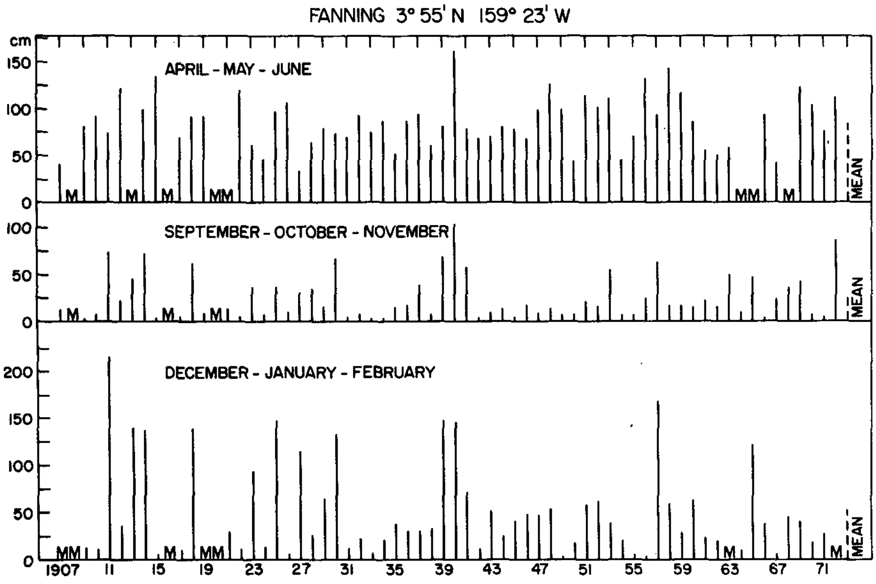

FIG. 1. Rainfall (cm) at Fanning for April–May–June, September–October–November, and December–January–February. In the latter period the year refers to December. Missing data are denoted by M (from Taylor, 1973).

nearly all the change in west–east gradient as the trough amplifies from March to June (Fig. 3).

The pressure differences Raoul minus Samoa (1940–80) and Rapa minus Tahiti (1952–80, standard deviations in Table 2) correspond to an easterly geostrophic wind, and that between Easter and Antofagasta (1942–80) to a southeasterly geostrophic wind. These sections of the trades are weakest during the months when the trough is strongest and the subtropical ridge is weakest, and strengthen as the trough contracts.

Because the subtropical ridge in the South Pacific Ocean plays an important role in the Southern Oscillation, and because the annual cycle of the ridge obviously is associated with the annual cycle in the trough in the westerlies (Fig. 5), it is logical to examine the behavior of the trough in LWs to see if the domain of the SO in this phase extends to middle latitudes. The SLP difference Hobart minus Chatham in twelve LWs and eleven years before (Fig. 6) does suggest that the trough takes part in circulation changes associated

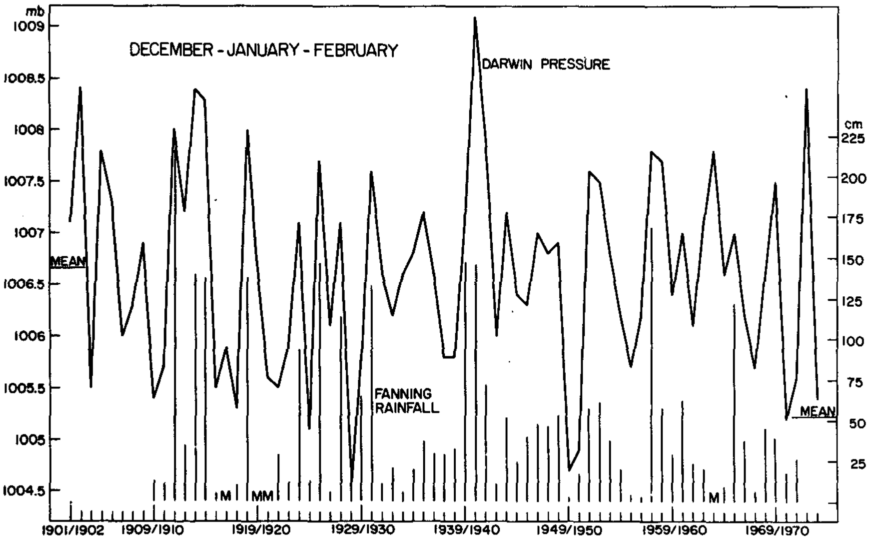

FIG. 2. Rainfall at Fanning and mean sea-level pressure at Darwin (12°30'S, 130°E) for December–January–February.

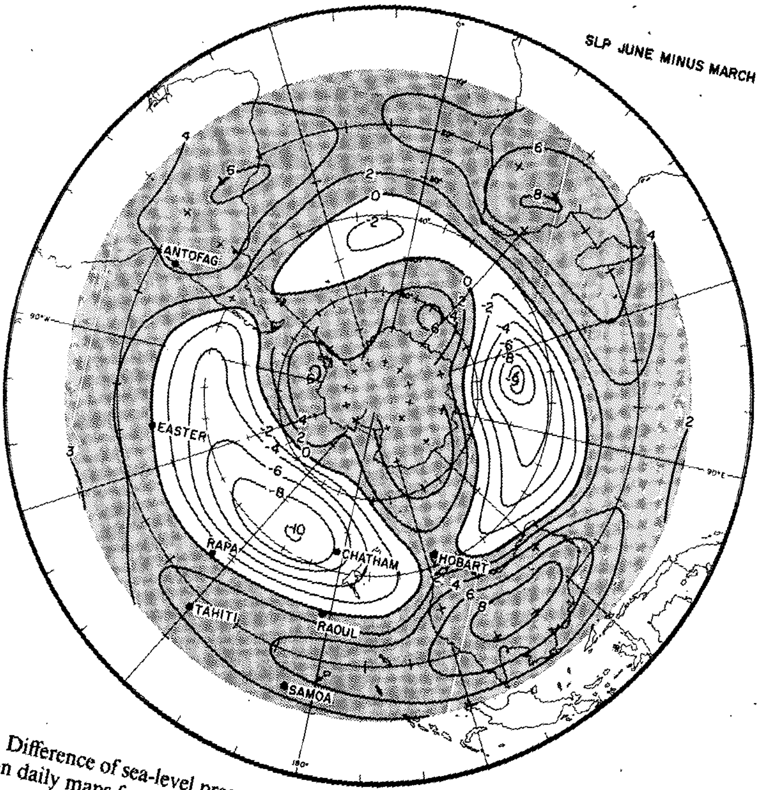

FIG. 3. Difference of sea-level pressure (mb), June minus March. Twelve-year mean is based on daily maps from South Africa and Australia. Shaded areas denote positive difference.

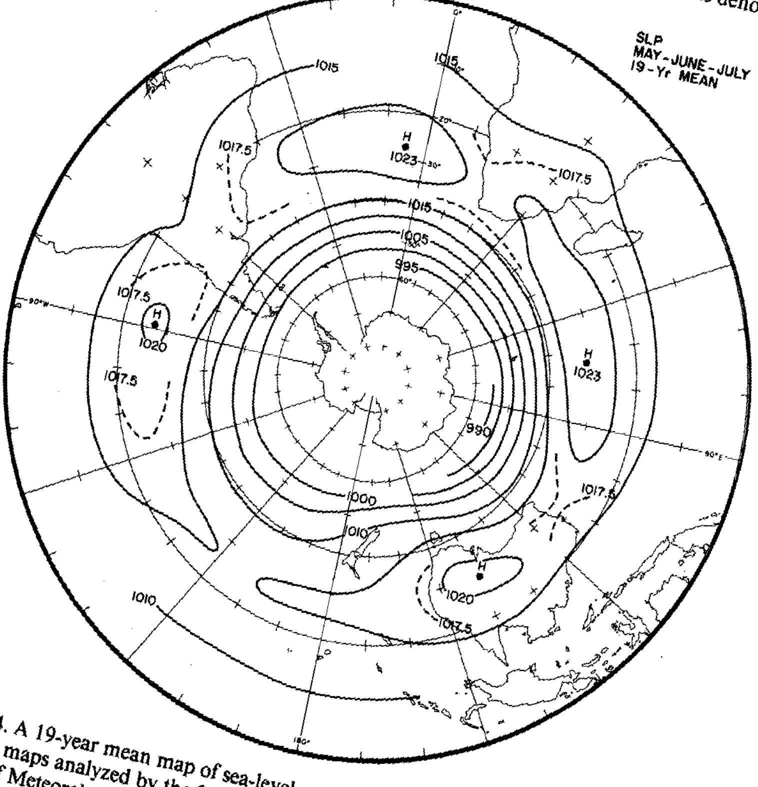

FIG. 4. A 19-year mean map of sea-level pressure in May–June–July based on daily synoptic maps analyzed by the South African Weather Bureau (1951–58), Australian Bureau of Meteorology (1972–80), and the U.S. National Meteorological Center (1981–82).

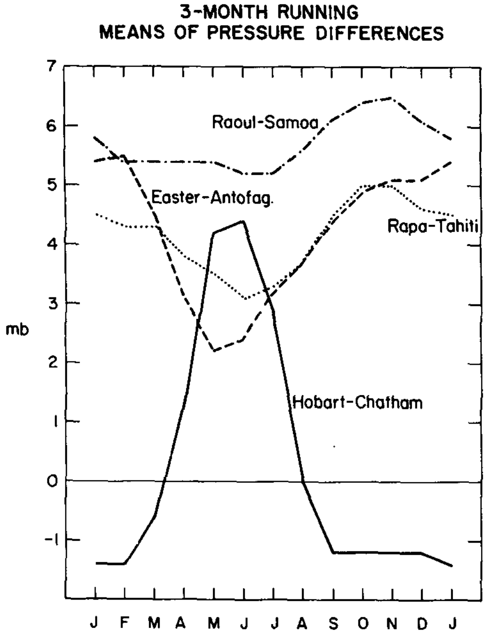

FIG. 5. Three-month running, long-term means of the annual cycle in the pressure differences Hobart minus Chatham, Raoul minus Samoa, Rapa minus Tahiti, and Easter minus Antofagasta.

with the SO. For instance, the lines in Fig. 6 between May–June–July in year$_{-1}$ and year$_0$ indicate that in nine of the eleven LWs the trough is larger than it was the year before. The two exceptions are 1951 and 1953. If the 11 years$_{-1}$, and the 12 years$_0$ are averaged (Fig. 7), it is obvious that in the mean the annual cycle of the trough is much larger in year$_0$ than in the year before. To test the statistical significance of the difference one can apply a measure which is the estimated standard deviation (ESD) for an n-year composite, given by $\sigma_{3\text{mo}}/\sqrt{n}$ for composites consisting of n years of three-month averages. The 51-year standard deviation for the May–June–July SLP difference between Hobart and Chatham is 3.8 mb, the ESD is 1.1 mb, and the average difference between May–June–July in year$_0$ and year$_{-1}$ is 5.7 mb, which then is 5.2 times the ESD. Note also that not only is the trough enhanced in year$_0$ compared to year$_{-1}$, but Hobart minus Chatham is positive for a longer period in year$_0$. Trenberth (1975) found that this change in circulation is common in the area and that it is well described by the second component in an empirical orthogonal function analysis, accounting for 26.4% of the variance. It is associated with distinct anomalies in the sea-surface temperature and with an almost two-yearly oscillation.

The Rapa–Tahiti SLP difference measures not only the strength of the trades in that region, but owing to the position of the stations it is also a gauge of the strength of the ridge and the extent of the trough. Figure 8 shows this pressure difference for the eight available LWs (Rapa's record begins in 1952), and in each of them the trades described by the pressure difference are weaker in year$_0$ than in year$_{-1}$. The contrast between the May–June–July values can be judged by the line which connects them. Note that the trades are weaker in 1953 too, which might indicate that although Hobart–Chatham showed no enhancement of the trough in 1953, the trough may have strengthened east of the area which can be measured by those two stations. The eight-year means of Rapa–Tahiti in Fig. 7 show that in this instance too, we are dealing with an amplification of the annual cycle from year$_{-1}$ to year$_0$. The difference between May–June–July in year$_0$ and year$_{-1}$ is 1.9 mb at Rapa–Tahiti, the three-month standard deviation is 1.3 mb, and the ESD for the eight-year sample is 0.45 mb, so that the 1.9 mb difference is 4.1 times the ESD.

The association between LWs and the easterly trades between Rapa and Tahiti is also found in the southeast trades between Easter and Antofagasta, although it is somewhat weaker there because the difference between May–June–July in year$_0$ and year$_{-1}$ is only three times the ESD for the eight samples. The association does not apply to the easterlies in the western part of the Pacific which are represented by the pressure difference Raoul minus Samoa. These easterlies are weakest in November–December of year$_{-1}$, and in May–June–July of year$_0$ the anomaly is almost gone, being only −0.1 mb.

4. The LOW/WET of 1982

This section compares the LW of 1982 with the long-term mean and with single events. It is obvious from Figs. 6 and 8 that 1982 (year$_0$) and 1981 (year$_{-1}$) followed the pattern outlined in Fig. 7 with respect to the trough in the westerlies and the easterly trades: the amplitude of the seasonal cycle in both was substantially larger in year$_0$ (1982) than in year$_{-1}$, and the trough lasted from May until the end of the year.

It is possible to use the surface air temperature measured at San Cristóbal in the Galápagos Islands since 1951 as an indicator of the appearance of a LW in that area. Figure 9 is a time series of three-month running means of anomalies of this air temperature; all LWs but that in 1963, which was more intense farther west (Bjerknes, 1969), stand out as strongly positive anomalies. The mean of the anomalies in the seven strong events at Galápagos is in the lower left part of Fig. 9 for year$_{-1}$ and year$_0$, and the same anomalies expressed as ESDs for seven-year samples are on the lower right. The air temperature anomalies in the mean are negative during the year before a LW and do not become positive until April in the year of the LW. Then they rise quickly to a peak that lasts from June to October, but they stay above three ESD from April–May–June until November–December–January.

The mean anomalies for the seven LWs reappear in Fig. 10a with the anomalies for 1981 and 1982. The

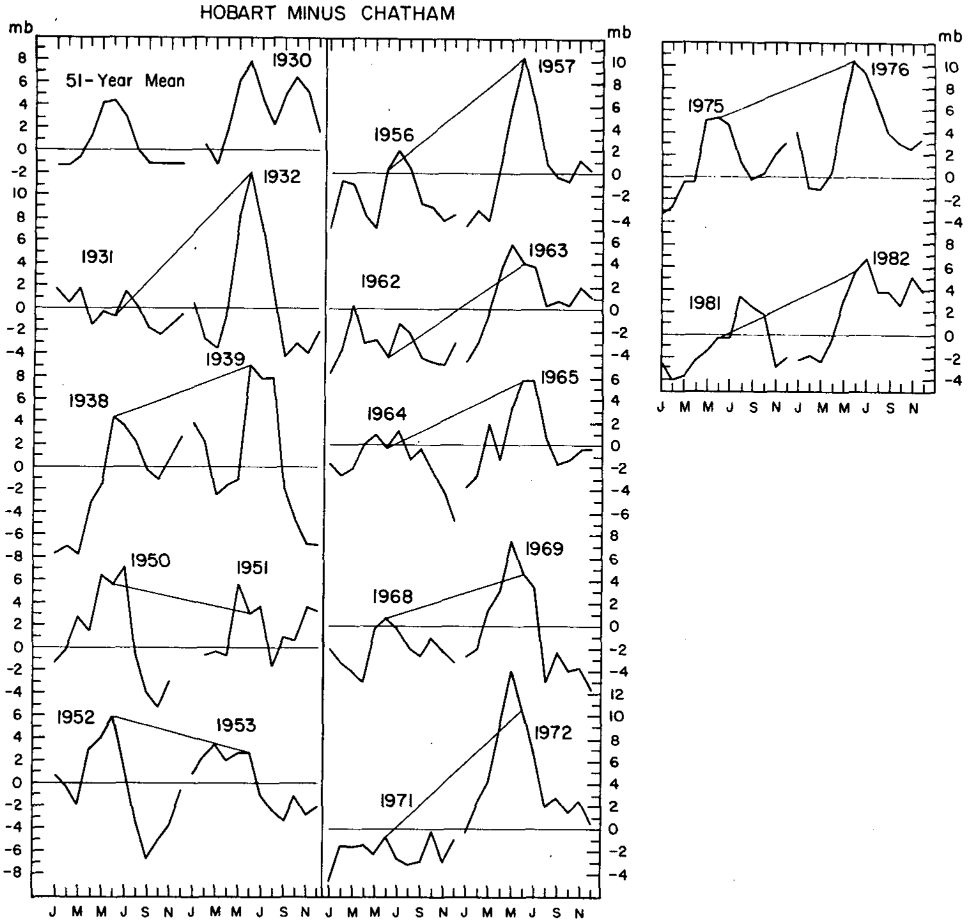

FIG. 6. Three-month running means of the pressure difference Hobart minus Chatham for 12 warm events and the 11 preceding years. The lines connect the June values. The 51-year mean is on the upper left.

development of the LW of 1982 followed the seven-year mean through 1981 until March 1982. The rise from March to April was smaller than the mean rise, and the 1982 curve stayed below the mean until September. The LW of 1982 also is drawn on Fig. 10b, and it is accompanied here by the weakest and the strongest LWs of the seven in Fig. 9. The development of the LW of 1982 followed the pattern of the two other LWs, and the amplitude of the warming in the Galápagos area was midway between those of 1953 and 1972 until the southern spring of 1982. The 1982 LOW/WET was thus not abnormal in this area, at least not during year$_{-1}$ and most of year$_0$.

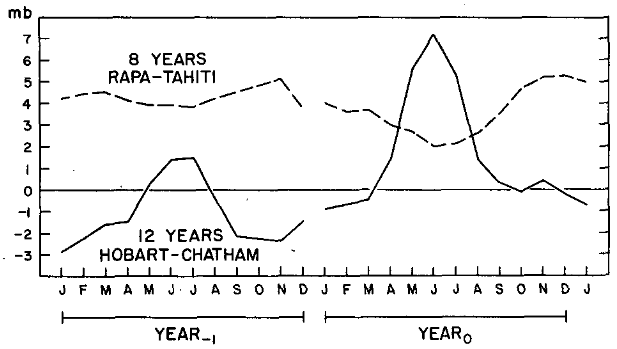

FIG. 7. Three-month running means of the 12 warm events (year$_0$) and 11 years before (year$_{-1}$) for Hobart–Chatham, and of 8 years$_0$ and 8 years$_{-1}$ for Rapa–Tahiti.

5. Conclusion

This study uses sea-level pressure at stations in the South Pacific Ocean to investigate the Southern Oscillation in the phase LOW/WET when the pressure is low in the tropical South Pacific and high over Australasia, the Pacific equatorial waters are warmer than normal, and many usually dry places experience heavy rain. The emphasis of the investigation is on the conditions in the year before the LW and through its development until it reaches its peak during the following year. The method of analysis is to use the pressure

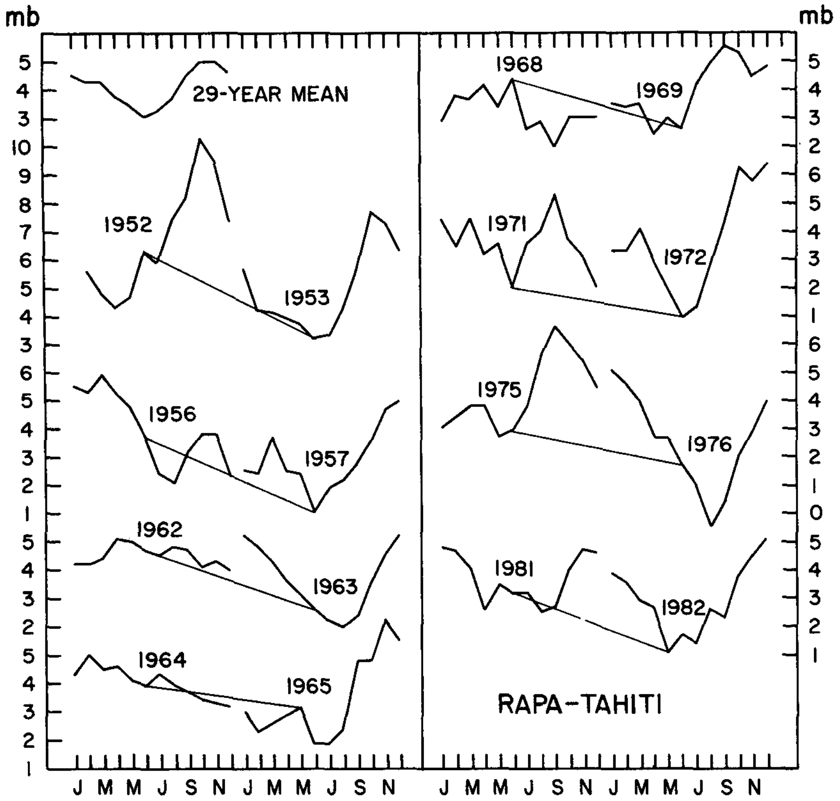

FIG. 8. As in Fig. 6, but for Rapa minus Tahiti.

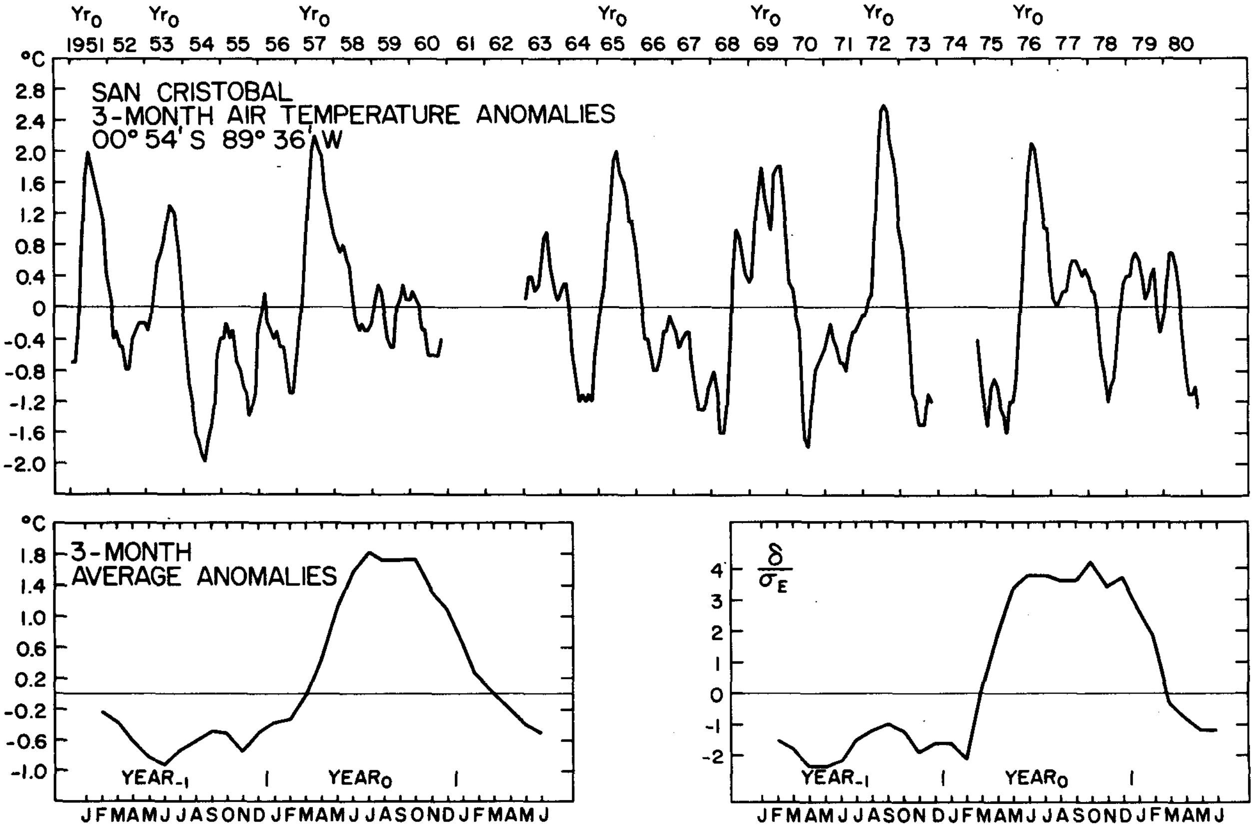

FIG. 9. Top: Three-month running mean surface air temperature anomalies at San Cristóbal, Galápagos Islands. Lower left: Running average three-month anomalies for the seven years of strongest positive deviations (year$_0$) and the year before (year$_{-1}$). Lower right: Seven-year running averge anomalies expressed in estimated standard deviations.

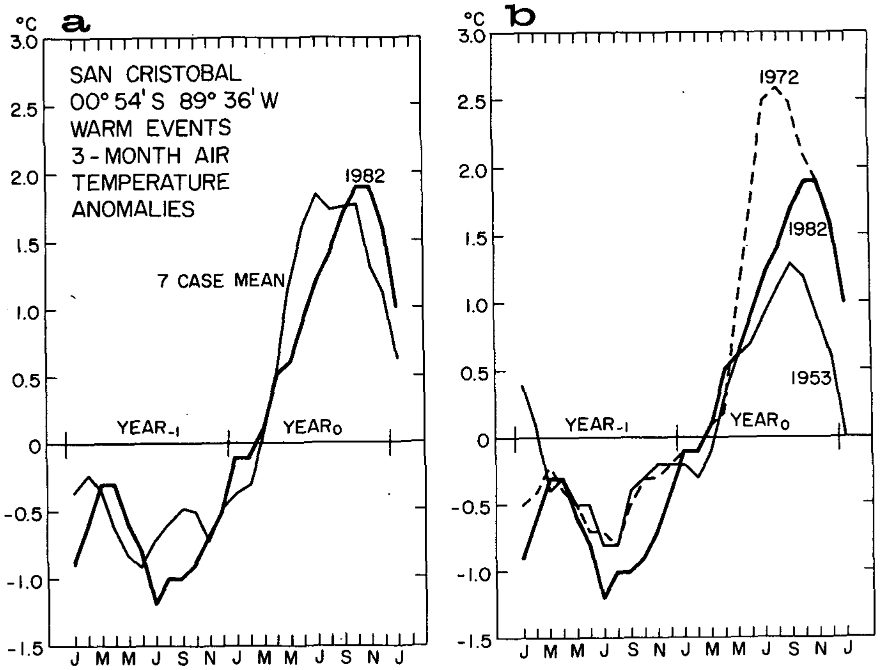

FIG. 10. (a) Three-month running average temperature anomalies for the seven strong warm events in Fig. 8 (year_0) and for the year before (year_{-1}) together with the same anomalies for 1981 and 1982. (b) Three-month running mean temperature anomalies for three years_0 (1953, 1972, 1982) and three years_{-1} (1952, 1971, 1981).

difference between stations as a measure of the trades and of the trough in the westerlies of the Pacific Ocean.

The main result is the connection which the study establishes between the trades and the Pacific trough in the westerlies during the development of a LOW/WET. Normally, the trough reaches its peak between April and July and the trades weaken at the same time. A substantial increase of this annual cycle in the trades and the trough from a year when the annual cycle was depressed is a characteristic of the development of a LOW/WET.

The development of the LOW/WET of 1982 followed this pattern. Its main departure from normal was that the trough in the westerlies stayed strong into the following southern summer after its initial enhancement in fall and winter.

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