The Southern Oscillation. Part VI: Anomalies of Sea Level Pressure on the Southern Hemisphere and of Pacific Sea Surface Temperature during the Development of a Warm Event

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ABSTRACT

The paper shows the discrete, mean three-month anomalies of sea level pressure on the Southern Hemisphere during the year before and the year of a Warm Event in the Southern Oscillation, together with associated anomalies of sea surface temperature in the South Pacific Ocean. The two sets of anomalies develop in a parallel and physically logical sequence over the South Pacific Ocean in conjunction with changes in the South Pacific Convergence Zone. Nearly all of the Southern Hemisphere responds to the Southern Oscillation, but the response is largest in the Australia–South Pacific sector. Large anomalies of sea level pressure form well ahead of any on the Northern Hemisphere, and this observation together with the conspicuous anomalies in the region of Australia and the South Pacific suggest that the origin of the Southern Oscillation must be sought in this region.

1. Introduction

In our previous paper (van Loon and Shea, 1985; referred to as vLS below) we described the anomalies in sea level pressure, sea surface temperature, and rainfall over the area between Australia and 135°W, from 15°S to 45°S, during the year before (Year$_{-1}$) and the year of (Year$_0$) Warm and Cold Events in the Southern Oscillation (SO). We demonstrated that in the winter of Year$_{-1}$ the trough in the westerlies at the surface of the South Pacific Ocean in the mean of several Warm Events fails to amplify in the latitudes north of 45°S. In contrast, the trough extends into the tropics in the same seasons of Year$_0$. Accordingly, one observes northerly anomalous winds in the tropical and subtropical tracts over the western half of the South Pacific in Year$_{-1}$ and southerly anomalous winds in Year$_0$. Consistent with these anomalous winds the temperature of the surface water and air south of 10°–15°S is above normal during the second half of Year$_{-1}$ and below normal a year later. When the South Pacific Convergence Zone (SPCZ) expands toward the south as usual in the southern spring of Year$_{-1}$, the convection in the convergence zone is enhanced over the anomalously warm water, and the sea level pressure is consequently below normal along the SPCZ. Therefore, on the north (equatorward) side of the SPCZ, the trades weaken (westerly anomalous wind) over large parts of the South Pacific Ocean. Much of what we describe above is also evident in the temperature and wind anomalies shown by Rasmusson and Carpenter (1982), and is inherent in Trenberth's (1975) analysis of the association between changes in surface pressure and temperature over the ocean surrounding New Zealand.

In the following we shall extend the analysis of the mean sequence which accompanies Warm Events to span two years on the Southern Hemisphere by means of discrete three-month anomalies of sea level pressure (SLP), beginning with February–March–April of Year$_{-1}$. We give also some examples of the concurrent anomalies of sea surface temperatures (SST) over the Pacific Ocean.

2. Data and analysis

The Years$_0$ of Warm Events are listed in Table 1 of vLS; for the Southern Hemisphere SLP, grid points are available for the events of 1951, 1953, 1957, 1972 (after April), 1976 and 1982. The data sets and objective analysis method used in the following are the same as we describe in vLS. These data are not flawless, but it is unlikely that the sequences of anomalies of large scale in space and time are seriously affected by the flaws. The logical developments and phase reversals between the same seasons of Year$_{-1}$ and Year$_0$, which the maps show, indicate that the largest scales are correctly represented in regard to sign and phase, although perhaps not always in regard to amplitude. Interested readers can find discussions of the quality of the SLP data in Swanson and Trenberth (1981).

The anomalies are all deviations from a mean without Warm and Cold Events. As we go on, we shall

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mention how many years the mean and anomalies contain in the various analyses. All seasons mentioned are the seasons of the Southern Hemisphere.

3. The sequence of sea level pressure anomalies on the Southern Hemisphere

A year before a Warm Event becomes evident as positive SST anomalies in the eastern equatorial zone of the Pacific Ocean, the mean SLP anomalies on the Southern Hemisphere, FMA_{-1} in Fig. 1a, are positive in the antarctic, negative along most of the circumference in the latitudes about 50°S, and positive northeast of New Zealand. This and the other anomaly maps are based on three-month averages which, as Trenberth (1976) points out, helps to avoid the effects of sampling through the arbitrary use of the month as a sampling period. Although we have calculated Student's t-tests for all our anomalies, we refrain from showing them because the samples are small: only four Warm Events are available in the first three seasons of $Year_{-1}$, five in the last season, and six in all of $Year_0$. The tests do show significance beyond the 95% level for most of the major anomalies we describe, but as the cases fall within a comparatively short period—the first event is in 1951 and the last in 1982—it is questionable if the tests have much meaning. It is indeed possible that the results are largely valid only for the period with which we work. There is, however, a logical sequence in the development of the anomalies and in the association between the SLP and SST anomalies for which we should like to claim physical significance.

In MJJ_{-1} (Fig. 1b)—the months when the Pacific high is weakest and the trough in the westerlies is strongest in the mean (van Loon, 1984)—the pressure is below normal over Australasia and above normal over most of the rest of the South Pacific Ocean. South of 45°S the pattern of anomalies is dominated by zonal wave 3, with ridges in the southwestern Atlantic, in the central Indian Ocean, and south of the Tasman Sea. One may also read into the pattern a stationary wave train which begins at 30°S–40°S in the central Pacific and runs through the Drake Passage and South Atlantic into the Indian Ocean between 60°E and 90°E. The anomalies have large amplitudes and cover the whole hemisphere in a coherent way. In contrast, the SLP anomalies at the same stage on the Northern Hemisphere (Fig. 2) are weak and hardly reach statistical significance outside the area where negative anomalies from Australasia reach into the Northern Hemisphere. For this anomaly map of the Northern Hemisphere there are 19 Warm Events available since 1899, north of 20°N, and nine events since 1946 between the equator and 20°N, and the mean contains 50 years north of 20°N and 23 south of 20°N during which neither Warm nor Cold Events occurred.

The arrows in Fig. 1b indicate the direction of the geostrophic anomalous wind associated with the pressure anomalies. We stress the westerly anomalies north of Australia and the northerly component in the tropics and subtropics between 130°W and Australia, north of 45°S, which we shall show later are associated with positive anomalies in the SST.

In ASO_{-1}, Fig. 1c, the clear features of MJJ_{-1} are weakening, but the anomalous wind retains a northerly component over the area between Australia and 130°W. A trough of negative values is developing between 20° and 40°S over the western Pacific, which in the following period, $ND_{-1}J_0$ in Fig. 1d, becomes an area of negative, or weak positive, anomalies along an axis on 30°S. On the north side of this area are westerly anomalies (weakened trades) across the Pacific Ocean. The pressure anomalies in Figs. 1c and d are substantiated north of 30°S by the wind anomalies in Rasmusson and Carpenter (1982, their Figs. 17 and 18). Over the rest of the hemisphere the SLP anomaly pattern is now zonal, in contrast to the winter pattern, with negative anomalies in the antarctic surrounded by positive anomalies in middle latitudes; in other words, the opposite sign of the anomalies at the beginning of the year (Fig. 1a).

Early in $Year_0$ (FMA_0 in Fig. 1e) the large negative anomaly has moved from the northern Tasman Sea (Fig. 1d) into the region northeast of New Zealand and the westerly anomalies persist over the western half of the Pacific, but the trades have become above normal over the eastern half. Note that over much of the hemisphere the anomaly pattern is almost the diametrically opposite of the one occurring 12 months earlier in Fig. 1a, with negative values in the antarctic in FMA_0 surrounded by positive ones in middle latitudes, and with the positive anomalies northeast of New Zealand in FMA_{-1} replaced by negative anomalies in FMA_0.

In MJJ_0 (Fig. 1f) these negative anomalies have moved east into the central Pacific, and Australasia is now covered by positive anomalies. The stationary wave train from the Pacific across the Atlantic into the Indian Ocean in Fig. 1b has the reverse phase in Fig. 1f, or interpreted otherwise, the wave 3 in the anomalies of middle and high latitudes has changed phase so that the ridges now lie approximately where the troughs lay 12 months earlier. The wind anomalies are now easterly in the tropics from the date line into the Indian Ocean, westerly from the date line to South America, and southerly from Australia to 140°W. The same pattern prevails in the next period, ASO_0 in Fig. 1g, although as in the previous year it is not quite so marked as in the winter months. Stronger trades now appear in the easternmost Pacific, and a separate center of positive anomalies lies between New Zealand and New Caledonia.

At the end of the two years in ND_0J_{+1} (Fig. 1h), the anomalous pattern has again changed sign from the same period 12 months earlier. The positive anomalies reach eastward from Australia and then southeastward across middle latitudes, and the SLP is above normal over the antarctic and below normal in middle lati-

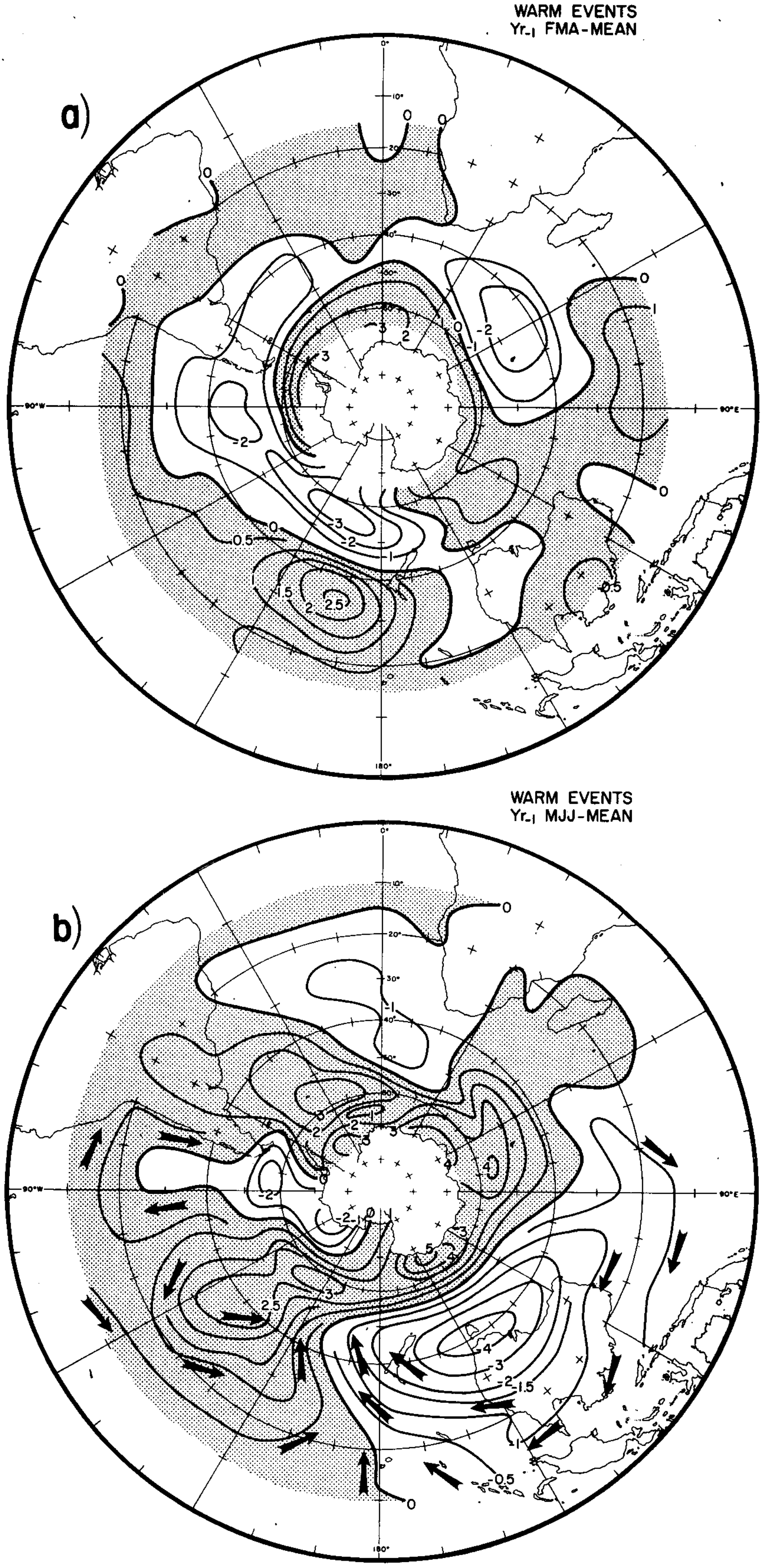
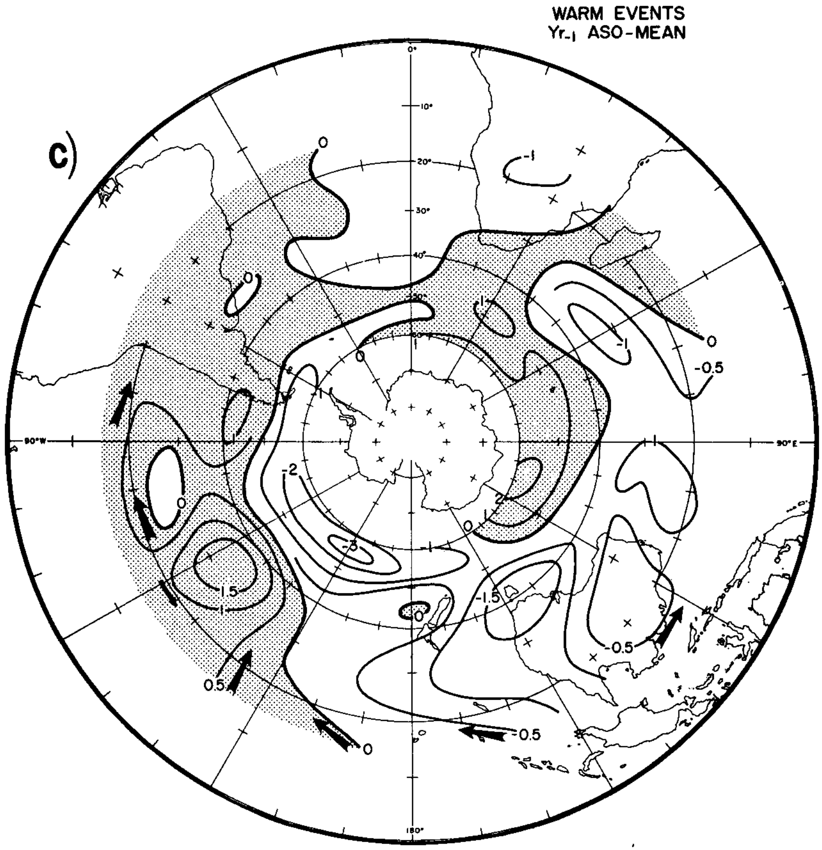


FIG. 1. The anomalies of sea level pressure (mb) associated with the year before (−1) and the year of (0) a Warm Event: (a) Feb–Mar–Apr$_{-1}$; (b) May–Jun–Jul$_{-1}$; (c) Aug–Sep–Oct$_{-1}$; (d) Nov–Dec$_{-1}$–Jan$_0$; (e) Feb–Mar–Apr$_0$; (f) May–Jun–Jul$_0$; (g) Aug–Sep–Oct$_0$; Nov–Dec$_0$–Jan$_{+1}$. The arrows indicate the direction of the geostrophic wind anomaly.



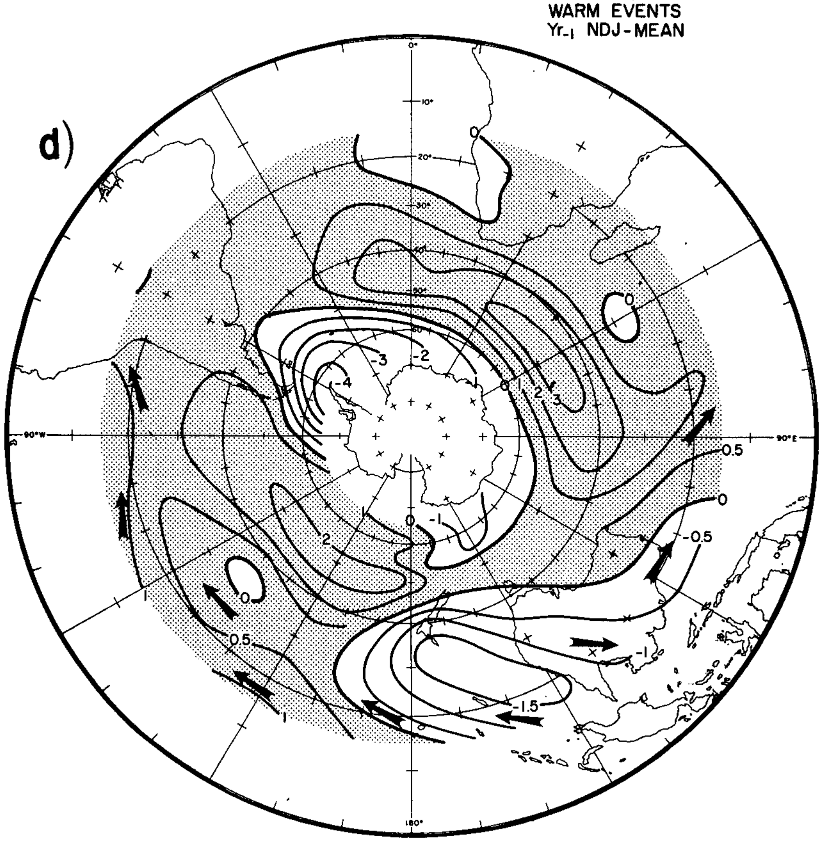
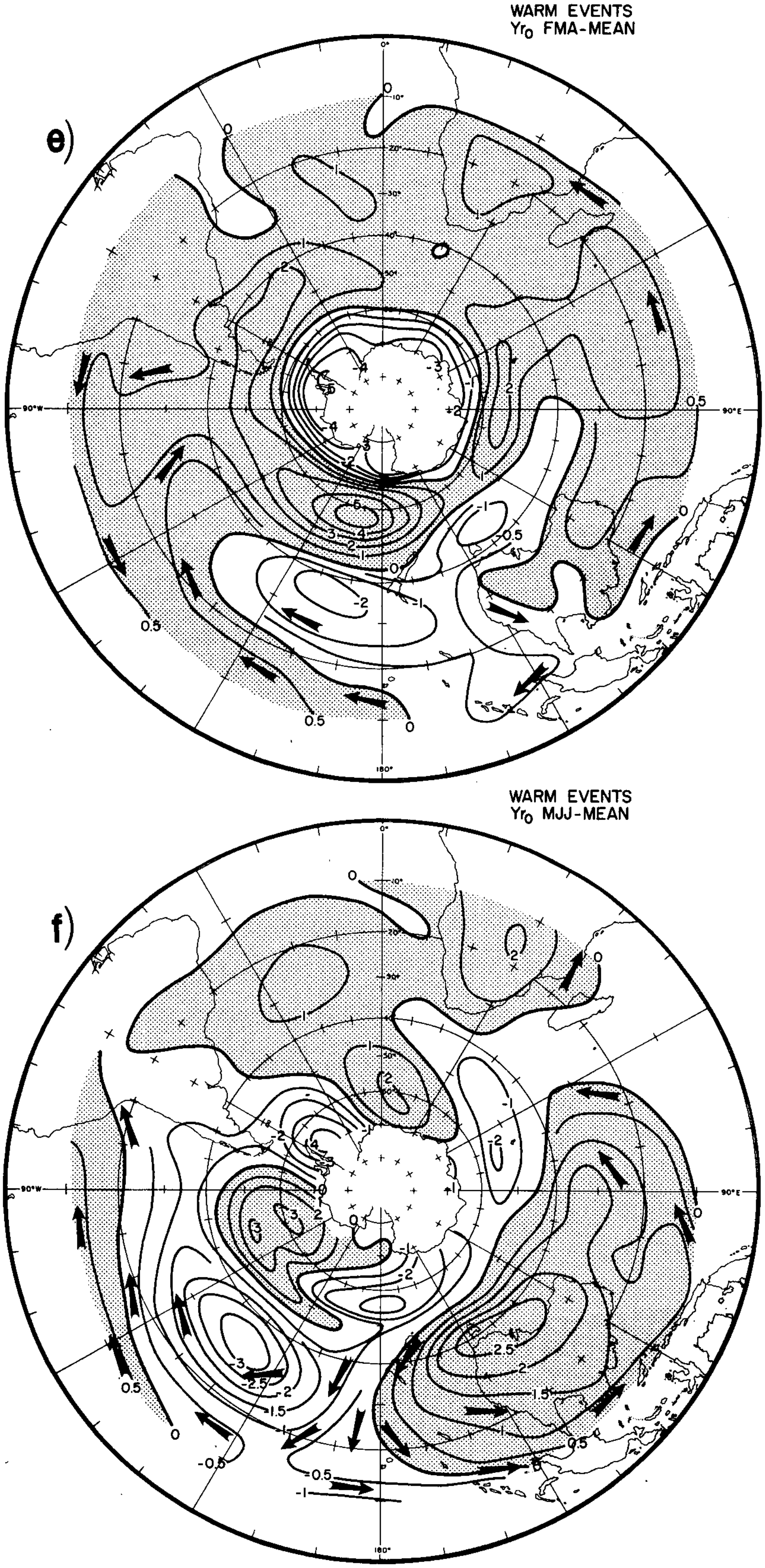


FIG. 1. (*Continued*)



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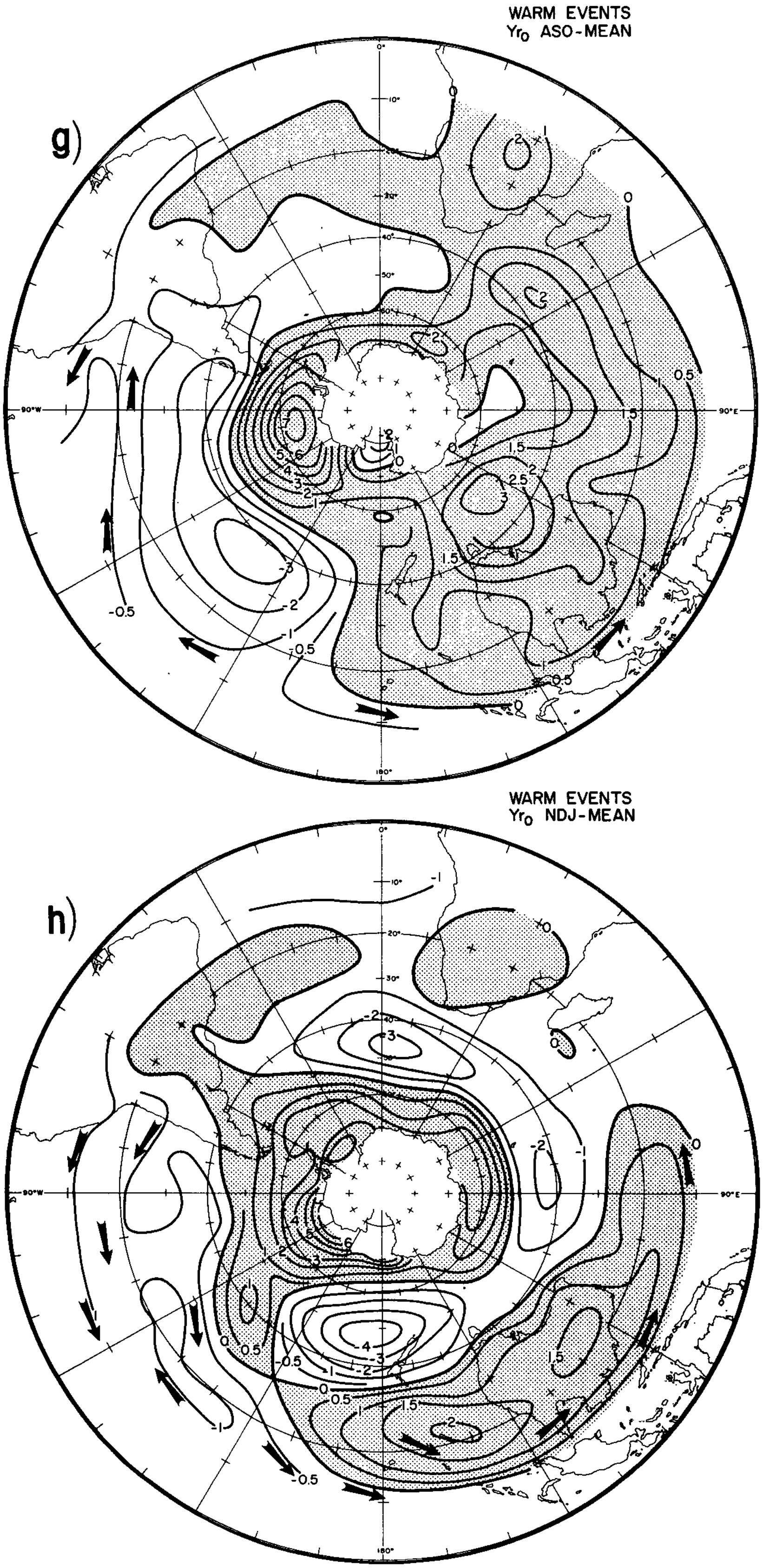


WARM EVENTS
Yr_0 ASO-MEAN

WARM EVENTS
Yr_0 NDJ-MEAN

FIG. 1. (*Continued*)

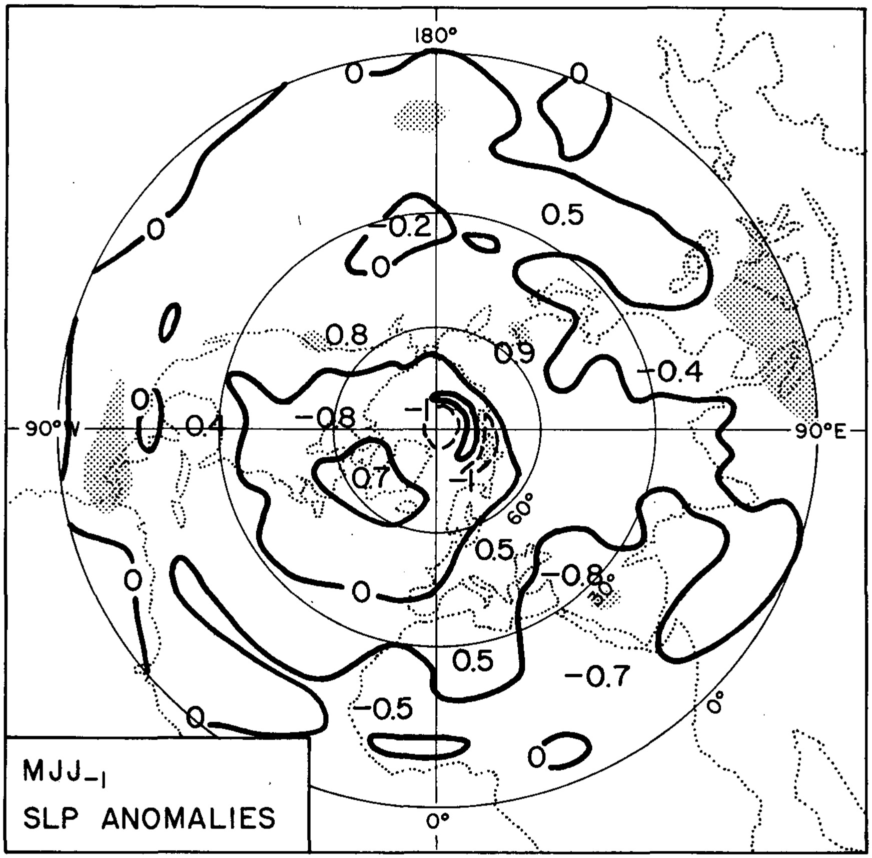


FIG. 2. As in Fig. 1b, but for the Northern Hemisphere; the areas above the 95% confidence level are shaded.

tudes. In many respects the anomalies have returned to the same sign as in FMA_{-1}, which is indicative of the strong tendency toward a biennial component found in vLS, in Trenberth (1975, 1980), and Meehl (1986). The anomalous winds in ND_0J_{+1} are easterly over most of the tropical Pacific and to the north and northwest of Australia.

We illustrate the average movements of the major negative and positive SLP anomalies in the central area of the Southern Oscillation through $Year_{-1}$ and $Year_0$ by means of Fig. 3. The dots are near the largest value of the 3-month anomalies which overlap by one month, and the number refers to the middle month: 3_{-1} thus means FMA_{-1}, 5_{-1} AMJ_{-1}, and so on to 1_{+1} which is D_0JF_{+1}. The major negative anomalies move clockwise (Fig. 3a) beginning southeast of New Zealand in FMA_{-1} and ending nearly two years later east of New Zealand. Note also the inclination for anomalies which are a year apart to be opposite each other, e.g., 1_0 and 1_{+1}; and 5_{-1}–7_{-1}–9_{-1} and 5_0–7_0–9_0. The tracks of the major positive anomalies (Fig. 3b) are positioned on either side of the negative ones. On the eastern side, the positive anomalies move irregularly southeastwards across the Pacific Ocean during $Year_{-1}$ and $Year_0$. On the west side two weak positive centers in FMA_0 and AMJ_0 merge in winter to a strong anomaly near Tasmania which then splits into two, one of which moves southwestward (not shown) and the other moves into the area north of the Tasman Sea. Evidently, *the major SLP anomalies arise and move within the core area of the SO on the Southern Hemisphere;* that is, Australia and the South Pacific Ocean.

With so few events entering the composite patterns, it is natural to be concerned about the stability of the composites. One can get a fair idea of the stability from Figs. 7 and 8 in van Loon (1984) which give a measure of the strength and duration of the subtropical high and the trough in the westerlies in several single Warm Events. Similar evidence appears in the temperature changes at Rarotonga (vLS, Fig. 10) for 17 individual Warm Events and in the SLP at Adelaide (28 events) and Rapa (8 events) in Figs. 3 and 4 of vLS. It is quite evident from these station data that no single or a few strong instances created the signal of a Warm Event or the reversal from $Year_{-1}$ to $Year_0$, which is a striking trait of the anomaly maps.

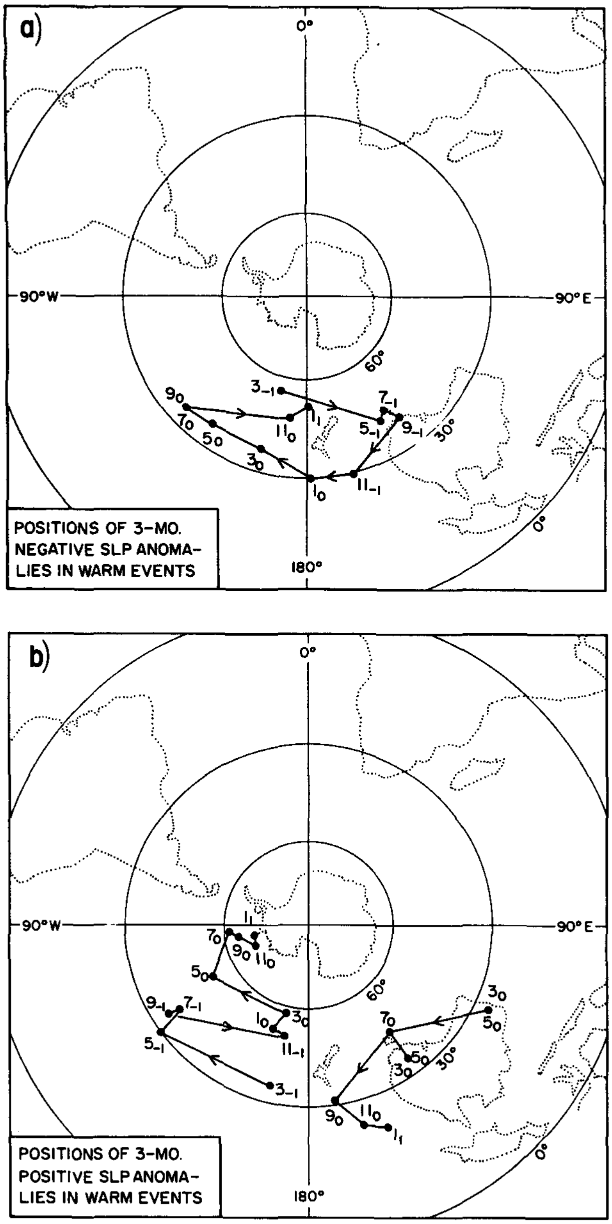


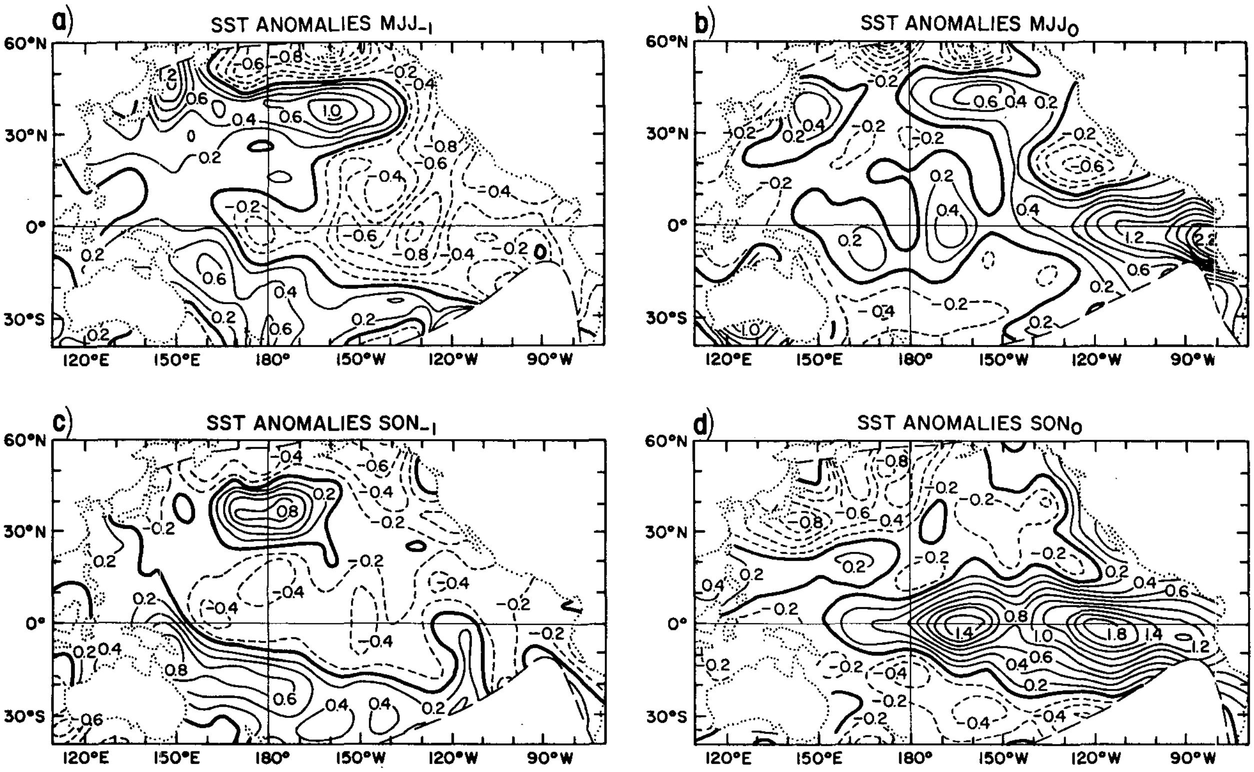
FIG. 3. (a) The movement of the major three-month average anomalies of sea level pressure. The averages overlap by one month: 3_{-1} is Feb–Mar–Apr of Year_{-1} and 5_{-1} is Apr–May–Jun of Year_{-1}. b) As in Fig. a, but for positive anomalies.

4. The anomalies of sea surface temperatures in the Pacific Ocean

It is not our purpose in this section to repeat the fundamental analysis performed by Rasmusson and Carpenter (1982) but to stress how the reversal of the SLP pattern from Year_{-1} to Year_0 is reflected in the SST anomalies. Our 3-month mean anomalies of SST cannot, at any rate, be compared directly with those of Rasmusson and Carpenter, as ours are deviations from a mean which contains neither Warm nor Cold Events. We use the 30-year Comprehensive Ocean Atmosphere Data Set, 1950–79, during which period there were eight Warm Events (Table 1 in vLS). The data set and the objective analysis we have used are described in vLS; and although the analysis covers the whole of the Pacific, we show isohypses only in the area where the 2° by 2° boxes contain at least one observation per month of the 3-month mean for at least four of the eight Warm Events. That leaves blank a large area west of South America; strictly speaking we should also have left three comparatively small areas in the equatorial region blank. The reader can gauge their position from the analyses in Rasmusson and Carpenter where they are shaded.

We begin with MJJ_{-1} (Fig. 4a) when positive SST anomalies dominate the region from Indonesia southeastward across the South Pacific Ocean in the zone where the anomalous geostrophic wind (Fig. 1b) blows with a northerly component between the negative pressure anomalies over Australia and the positive pressure anomalies in the central ocean, and where north of Australia the trades are weak as shown by the westerly anomalies. One year later, Fig. 1f, the anomalous wind has reversed and negative SST anomalies now reach from Indonesia southeastwards into the subtropics (Fig. 4b). Consistent with the anomalously low SLP and westerly geostrophic wind anomalies in Figs. 1c and d, the positive SST anomalies strengthen in the southern spring of Year_{-1} and reach as far as South America (Fig. 4c), which is in good agreement with Rasmusson and Carpenter's Figs. 17 and 18. Finally, in the spring of Year_0 (Fig. 4d), the negative anomalies of Fig. 4b have become stronger and extend farther toward the southeast.

The average development of the SLP/geostrophic wind and SST anomalies in a Warm Event is thus parallel over the region from Indonesia, across the tropics and subtropics of the Pacific, to South America. We should like here to support, with the better evidence, the argument which we made in vLS, how the interplay between wind and sea surface in this region can strengthen or weaken the subtropical high and the trade winds. The region in question is one where the SPCZ prevails; in the mean the axis of this zone lies from the Torres Strait to about 30°S, 135°W. When the convergence zone expands toward the south as usual during the spring of the year before a Warm Event, it expands over a sea surface which is warmer than normal (Fig. 4c), and the convection and rainfall in the zone become stronger than normal (vLS). With the stronger convection we observe lower SLP, that is, a weakened subtropical high, and westerly anomalous winds north of about 30°S (Fig. 1d). A SPCZ located southwest of its normal position in the spring of the year before a Warm Event was observed by Rasmusson and Carpenter, is inherent in Trenberth's (1976) analysis, and is also



a) SST ANOMALIES MJJ$_{-1}$

b) SST ANOMALIES MJJ$_0$

c) SST ANOMALIES SON$_{-1}$

d) SST ANOMALIES SON$_0$

FIG. 4. Anomalies of sea surface temperature (°C) in a) May–Jun–Jul$_{-1}$; b) May–Jun–Jul$_0$; c) Sep–Oct–Nov$_{-1}$; d) Sep–Oct–Nov$_0$.

noted by Meehl (1986). The intense subtropical high in the southern fall and winter (Fig. 1b) is, through this observed chain of events, the cause of the anomalous subtropical and tropical westerlies (weak trades) one and two seasons later. The anomalously low pressure in the SPCZ is marked by the positions 11_{-1} and 1_0 of the negative anomalies in Fig. 3a, and from this stage the negative SLP anomalies move into the center of the ocean (3_0 to 9_0 in Fig. 3a), the normal position of the trough in the westerlies in winter (van Loon, 1984), to weaken further the subtropical high.

As noted above, in the winter and spring of Year$_0$ the negative SST anomalies associated with the anomalously strong southerlies on the west side of the negative SLP anomalies (Figs. 1f and 1g) are extensive in the subtropical and tropical latitudes of the South Pacific Ocean (Figs. 4b and 4d). The SPCZ must now expand toward the south in spring over water which is colder than normal and suppresses the convection and rainfall. The SLP is therefore above normal in the region of the SPCZ (Fig. 1h) and the easterlies strong over most of the Pacific north of 30°S, within the region analyzed in Fig. 1. The stage is then potentially set for another Year$_{-1}$, with the positive SLP anomalies moving eastward from their position in ND$_0$J$_{+1}$ in Fig. 1h. The movement of the SLP anomalies in Fig. 3 is part of the strong tendency to a biennial oscillation in the South Pacific (Trenberth, 1975, 1980; van Loon and Shea, 1985).

We should like to plead on the basis of these observed sequences that the Southern Oscillation has its origin on the Southern Hemisphere because well organized and strong anomalies are observed in the Southern Hemisphere long before anything comparable is seen in the Northern Hemisphere (Figs. 1a and 1b). The fact that the anomalies in Fig. 1 change sign from Year$_{-1}$ to Year$_0$, especially from Australia to South America where they are also largest, is cause for believing that the air–sea interaction in the tropical and subtropical domain of the SPCZ plays the major role in forcing the Southern Oscillation.

5. Conclusion

The anomalies of SLP and SST on the Southern Hemisphere during the year before and the year of the development of a Warm Event in the Southern Oscillation show a parallel and physically logical sequence. In the year before the event becomes visible through positive SST anomalies on the coast of Peru and in the equatorial zone of the Pacific Ocean, positive SLP anomalies develop northeast of New Zealand and move into the center of the ocean while negative SLP anomalies move from southeast of New Zealand into Australia. From late southern fall to the southern spring of Year$_{-1}$, positive SST anomalies form in the region between the positive SLP anomalies over the central ocean and the negative SLP anomalies over Australia and cause intensified convection and rainfall in the South Pacific Convergence Zone as it expands toward the south as usual in the southern spring and summer. The pressure in the intensified SPCZ is below normal and the anomalous winds on its north side, north of about 30°S, are therefore westerly; that is, the trades weaken across the South Pacific Ocean from the Tasman Sea to South America.

During the year of the Warm Event the negative SLP anomaly moves from north of the Tasman Sea to the center of the South Pacific Ocean, and positive SLP anomalies develop over Australia. In the anomalous southerlies between these two anomalous pressure fields, negative SST anomalies form from late southern fall to southern spring. The negative SST anomalies suppress the convection and rainfall in the SPCZ as it expands southward from winter to summer. The SLP in the zone of suppressed convection is above normal and the anomalous winds on its north side, north of about 35°S, are therefore easterly; that is, the trades strengthen across most of the South Pacific Ocean.

Well defined anomalies of large size appear early in Year$_{-1}$ in the pressure and geostrophic wind field over nearly all the Southern Hemisphere and change sign from Year$_{-1}$ to Year$_0$. The anomalies develop in the Southern Hemisphere well before anything comparable appears in the Northern Hemisphere. These observations and their obvious association with air–sea interaction in the tropical–subtropical region where the South Pacific Convergence dominates, make it likely that the area of Australasia and the tropical and subtropical South Pacific Ocean plays *the* major role in the forcing of the Southern Oscillation.

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