The Role of Cross-Equatorial Tropical Cyclone Pairs in the Southern Oscillation

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ABSTRACT

The locations and frequencies of cross-equatorial tropical cyclone pairs over the Pacific Ocean are compared between years of contrasting equatorial Pacific sea surface temperature (SST) and atmospheric circulation anomalies, i.e., high versus low Southern Oscillation (SO) indices, during the period 1971–79. Weak southeast trade winds associated with low SO indices allow warm (29°C) surface water in the equatorial (0–5°S) zone to extend eastward across the dateline, encouraging formation of cyclone pairs near the dateline. The cyclone pairs, in turn, provide the linkage between warm water and equatorial convection (as indicated by Canton Island rainfall) during southern summer.

In general, the occurrences of cyclone pairs vary in longitude with the eastward excursions of warm equatorial water; furthermore, cyclone pairs appear to provide a positive feedback by advancing the eastward warm water extent. In 1974–75, when no cyclone pairs developed near the dateline in spite of sufficiently high SST’s and low SO indices, an apparently developing low SO index anomaly collapsed. The possibility is therefore raised that the occurrence (or absence) of a single synoptic event may influence the outcome of an entire Southern Oscillation anomaly.

1. Introduction

One of the working hypotheses in studies of interannual climatic fluctuations is that variations in equatorial Pacific sea surface temperatures (SST’s) assert significant influences on the global climate and atmospheric circulation via tropical Pacific circulation changes. The hypothesized mechanism has warmer equatorial SST’s in regions of normally cool upwelling, inducing (or otherwise correlating with) longitudinal redistributions (and possibly net increases) of convection near the equator, resulting in altered Hadley circulation transports of angular momentum to the circulation at higher latitudes. These interannual changes in the large-scale atmospheric circulation and SST distributions are usually regarded as manifestations of the Southern Oscillation (e.g., Bjerknes, 1969; Trenberth, 1976; Wright, 1977).

The low-level circulation over the western Pacific Ocean (Atkinson and Sadler, 1970; Newell et al., 1972; Gray, 1981) is typified by a single near-equatorial trough which remains in the summer hemisphere during most of the year. However, during the transition months, there is a tendency for double near-equatorial troughs to form over the western Pacific, as seen on Atkinson and Sadler’s mean monthly low-level flow charts for April, November, and December. During these months, equatorial westerlies flow toward the dateline between cyclonic regions at ~5° on either side of the equator. Long-term maps of integrated daily satellite cloud cover (Miller and Feddes, 1971) show the zone of westerlies between the cyclones to be an area of active convection, and the southern cyclonic region merges with the South Pacific Convergence Zone (Trenberth, 1976) that extends southeast into the extratropics.

One manifestation of the Southern Oscillation is an eastward shift of the equatorial convective activity associated with a weakened South Pacific subtropical high and slackened Southern Hemisphere trade winds (Krueger and Winston, 1975; Ramage, 1975). Fig. 1 shows the distribution of convective activity across the tropical Pacific (20°N–20°S, 130°E–130°W) during three Decembers with contrasting Southern Oscillation indices. The data shown (provided by O. Garcia, NOAA Environmental Research Laboratory, Boulder, CO) are monthly frequencies of daily occurrences within 1° grid squares of Highly Reflective Clouds (HRC) on satellite imagery (Kilonsky and Ramage, 1976; Garcia, 1981). Decembers 1972 and 1977 were both low Southern Oscillation index months (weak South Pacific high and trade winds) with Tahiti minus Darwin mean sea-level pressure differences of 2.4 and 2.0 mb below normal. Although the relative strengths of the northern and southern convective zones are quite different between the two months, both months show frequent convection in an area bridging the equator between the two near-equatorial zones, and extending eastward to 160 or 170°W on the equator. In contrast, in December 1973, a high Southern Oscillation index month (Tahiti minus Darwin mean sea-level pressure difference

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2. Equatorial synoptic systems

Canton Island (172°W, 3°S) lies within the region of great equatorial SST and convection (precipitation) variability, as noted by several authors (Krueger and Gray, 1969; White and Walker, 1973; Ramage, 1977). From Fig. 1 it can be seen that Canton Island occasionally lies within the cross-equatorial band of convection, as during December 1972 and 1977, when precipitation totals were, respectively, 427 and 522 mm. In contrast, only 5 mm fell during December 1973. The resulting annual (for the July through June rainfall year) rainfall totals have varied by an order of magnitude, ranging from 2705 mm in 1972–73 to 258 mm in 1975–76. Annual totals for 1955–56 through 1978–79 are shown in Fig. 2 (1967–68 through 1970–71 are missing).

An examination of 10 years (1957–67) of 200–1000 mb wind profiles at Canton Island shows the local circulation to be typified by persistent and deep easterlies all months of the year, with frequent upper westerlies (in the 200–500 mb layer, sometimes down to 700 mb) during the southern summer months (November–March). The winter (April–October) flow changes little from year to year, as does the winter rainfall. However, in some summers the typical flow pattern is replaced by alternating spells (several days to several weeks duration) of deep easterlies and deep westerlies. It is during the spells of deep westerly winds that most of the anomalous rainfall occurs at Canton Island (Ramage, 1977). The influence of these relatively infrequent west wind events on annual rainfall totals is illustrated in Fig. 2. Noted along with the annual totals are the portions of the total falling on days with westerly wind components and the number of west wind days. Twelve of the 20 years noted have totals close to the median value of 400 mm. The other eight years show rainfall anomalies of several times the median, most of which fell on westerly wind days. Over 20 years, 40% of the total rain fell on the 5% of days with westerly winds.

The synoptic evolution of two anomalously wet seasons at Canton Island, 1957–58 and 1977–78, has been examined. The 1957–58 season was a major El Niño event in the eastern equatorial Pacific, while 1977–78 was not. Fig. 3 shows a characteristic sequence of surface circulation patterns that occurred twice during each of the two seasons. The map for 10 November 1977, is typical of undisturbed conditions, with the near-equatorial convergence zone (CZ) north of the equator, and easterlies crossing the date-

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line. However, a cold front [as analyzed on the National Meteorological Center (NMC) tropical surface charts] is pushing northward from the New Zealand region. This front (or trough line) stalls at \( \sim 10^\circ \)S, and by 23 November a low forms on its northwestern extremity. A second low forms north of the equator by 26 November. Both lows became tropical storms and moved poleward by the end of November, but low pressure zones remained on both sides of the equator. A near-equatorial trough at \( \sim 10^\circ \)S maintains the westerly flow at Canton Island through early December, then slowly weakens as the northern low moves out of the region. The sequence was repeated in late December, with formation of the cyclone pair on 19 December. In all four cases, during two seasons, the equatorial westerlies broke down when one or both of the paired low pressure areas departed the equatorial regions as a tropical cyclone.

Table 1 lists details, derived from twice-daily NMC tropical surface analyses, Mariner's Weather Log, and Climatological Data—Hawaii and Pacific,\(^2\) of the cross-equatorial cyclone pairs (or simply, "cyclone pairs") that formed during the 1977–78 season. The formation dates and durations refer to the existence of closed lows on both sides of the equator; generally, equatorial westerlies due to a single low occurred for several days before and after this interval. The longitudes given are the averages of the initial longitudes of identifiable vortices (tropical depressions) in each hemisphere. The initial cyclone (N or S) is indicated, as are the names of resulting tropical storms. Every occurrence of paired lows and equatorial westerlies during this season resulted in at least one named tropical storm, while the 19 December–12 January event (which may be treated as a single event because of the continuity of equatorial westerlies) resulted in four. Cyclone pair formations near the dateline pushed the equatorial westerlies some 20–40° farther east, and brought heavy rains to Canton Island. The climatology of cross-equatorial cyclone pairs is expanded in the next section by considering those events that resulted in named tropical storms on both sides of the equator.

Global 500 mb analyses produced for the International Geophysical Year (1957–58) were compared with the surface maps. There were two disturbances of the type in Fig. 6 during 1957–58, with the formation of cyclone pairs occurring on 5 November and 4 January. In both cases, the preceding northward-moving "cold front" and subsequent cyclogenesis south of the equator were associated with a 500 mb trough moving equatorward from the vicinity of Tasmania, passing over the surface subtropical high to initiate the disturbance. Similar synoptic se-

\(^2\) Published monthly by National Climatic Center, Federal Bldg., Asheville, NC 28801.

Fig. 2. Twelve-month rainfall totals at Canton Island for the July–June rainfall year. Cross-hatched portions of bars indicate amounts falling during spells of surface westerlies; the total number of days with westerly winds is noted for those seasons in which they occurred. Amounts shown for 1971–72 are for December–June.

Consequences linking extratropical troughs with tropical cyclogenesis are noted for the Australia–South Pacific region by McRae (1956) and Gray (1981), and for the western Atlantic by Colón and Nightingale (1963). McRae proposes that the upward motion induced by the trough divergence field encourages cyclogenesis, and Colón and Nightingale state that the role of the trough is to reduce vertical shear over the point of cyclogenesis. In addition to these mechanisms, the trough may also provide an effective outflow to higher latitudes for convectively released heat (Sadler, 1976).

More than half the rainfall associated with equatorial westerlies during 1957–58 fell during the event of 9 January–6 February 1958. Synoptically, this event differed from those discussed so far, with the convergence zone to the south of the equator in response to an expanded north circumpolar vortex (500 mb westerlies down to 15–20°N). Low-latitude upper troughs from the southern extratropics apparently induced cyclonic disturbances on the CZ south of Canton Island. A cyclone pair never formed, and this westerly spell broke down as the 500 mb troughs approached the tropics at more eastern longitudes (from 160°W in mid-January to 130°W in February), leav-
ing an undisturbed CZ in the mid-equatorial Pacific. The extratropical troughs over the eastern Pacific failed to induce tropical disturbances, perhaps because of the lower SSTs.

Two more westerly wind disturbances (but with a large northerly component to the winds) occurred in early March (1–3; 7–9), and appear to reveal yet another kind of extratropical forcing: Northern Hemisphere trade wind surges (e.g., Riehl, 1979), possibly related to deep troughs near Hawaii. The trade surges pushed the convergence zone southward as far as 12°S, with westerly winds at Canton Island as the northern trades recurved upon crossing the equator. Gray (1981) describes this synoptic sequence in terms of momentum surges from the winter hemisphere, crossing the equator to encourage cyclogenesis in the summer hemisphere. The disturbed period ended as a southern tropical cyclone formed on 11 March and moved poleward. During the 1957–58 season, the primary extratropical influence on the equatorial disturbances appeared to shift from Southern Hemispheric origin in November–December to Northern Hemispheric in February–March, reflecting the relative strengthening of the Northern Hemisphere circulation.

The synoptic sequence in Fig. 3 appears to be the most important of the several types discussed, since it is the pattern that either reflects or initiates the start of the anomalous equatorial weather. These disturbances are apparently triggered by upper troughs from the southern extratropics.

3. Climatology of cross-equatorial tropical cyclone pairs

The existence of cyclone pairs has been known for some time. Palmer (1952) found cyclone pairs to be most frequent in the Pacific during November, Dec-

<table>
<thead>
<tr>
<th>Formation of pair</th>
<th>Duration (days)</th>
<th>Formation longitude of cyclone pair (deg)</th>
<th>Easternmost longitude of west winds (deg)</th>
<th>Canton precipitation (mm)</th>
<th>Named tropical storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 October</td>
<td>1</td>
<td>130 E</td>
<td>150 E</td>
<td>0</td>
<td>Harriet*</td>
</tr>
<tr>
<td>6 November</td>
<td>3</td>
<td>158 E</td>
<td>167 W</td>
<td>0</td>
<td>Kim*</td>
</tr>
<tr>
<td>26 November</td>
<td>3</td>
<td>173 E</td>
<td>170 W</td>
<td>15</td>
<td>Lucy</td>
</tr>
<tr>
<td>2 December</td>
<td>7</td>
<td>180</td>
<td>140 W</td>
<td>289</td>
<td>Steve*</td>
</tr>
<tr>
<td>19 December</td>
<td>9</td>
<td>180</td>
<td>160 W</td>
<td>198</td>
<td>—</td>
</tr>
<tr>
<td>6 January</td>
<td>6</td>
<td>176 E</td>
<td>165 W</td>
<td>77</td>
<td>Mary*</td>
</tr>
</tbody>
</table>

* System (North or South) formed first. Braces indicate continuous occurrence of equatorial westerlies between two events and, as such, may be considered single events with redevelopments.
December, April and May, and remarks that their occurrence was noticed by Reid (1849) more than a century earlier. Here, the climatology of cyclone pairs over the central and western Pacific (east of 100°E) is examined. Using named tropical cyclone tracks published in *Mariners Weather Log* and data provided by the New Zealand Meteorological Office, the initial points of the northern and southern cyclones associated with the 22 cyclone pairs found for the period September 1971 through January 1980 are shown in Fig. 4. The judgment of whether two cyclones had dynamically associated origins was a subjective one, but in all cases, the initial formations (tropical disturbance stage on the published charts) for the northern and southern systems occurred within 9 days of each other, with a standard deviation of ±4 days about the mean time difference of 0 days. In latitude, the initial systems were never more than 22° apart, with the initial northern and southern disturbances, respectively, always within 9 and 15° of the equator. The longitudinal differences of initial disturbance location ranged from +9° (northern system east of the southern one) to -17°; the mean difference was -2° with a standard deviation of ±9°. Since all joint cyclone formations satisfying these limits of time, longitude and latitude are counted as cyclone pairs, the limits are, in effect, strictly applied criteria for defining these pairs. Doubling these time and longitude limits only increases the number of pairs from 22 to 26. The limits therefore enclose a true clustering in time and location separations of joint cyclone formations.

The clustering of cyclone formations in space and time suggests a dynamic association between the initial northern and southern cyclones. Further support for this possibility, as well as some insight into the conditions required for cyclone pair development, can be derived from a comparison of the climatology of cyclone pairs with that of Pacific tropical cyclones of each hemisphere. The eight-year (1972–79) monthly frequencies of named cross-equatorial cyclone pair formations between 100°E and 180° are shown in Table 2, along with the frequencies of all tropical cyclone formations in the western North Pacific and Australia–South Pacific regions, and of the low-latitude (9°N to 15°S) cyclone formations in the two regions. This low-latitude cyclone zone includes all cyclone formations associated with cross-equatorial pairs. From the frequencies of low-latitude cyclones on each side of the equator, an estimation can be made of the expected chance frequency of two low-latitude cyclones forming within the maximum time (±9 days) and longitude (+9 to -17°) differences noted for cyclone pairs. Relative to the date and longitude of formation of a southern cyclone, a northern cyclone must form within a “window” 18 days (or 0.6 month) by 26° (or one-third of the 100°E–180° western North Pacific region). Therefore, about one-fifth of the mean monthly frequency of low-latitude northern cyclones would be expected to form close enough in time and longitude to a low-latitude southern cyclonic formation to be considered a cyclone pair. Taking January data from Table 2, this would yield 0.15 chance pairs for each low-latitude southern cyclone, or three cyclone pairs during the eight Decembers of record. This expected number of December cyclone pairs is half the observed number (6). The expected occurrences for other months (listed in Table 2) are also approximately half the observed numbers, as is the expected eight-year total of 11.7 cyclone.
TABLE 2. Eight-year (1972–79) number of named tropical storms, by month of formation, in the western North Pacific region (100°E to 180°) and the Australia–South Pacific region (east of 100°E), and of cross-equatorial named cyclone pairs between the two regions. “Low latitude” cyclones are those forming between 9°N and 15°S. The eight-year number of cross-equatorial pairs “expected” from random joint occurrences of northern and southern cyclones is listed for each month. Data from Mariners Weather Log and the New Zealand Meteorological Service.

<table>
<thead>
<tr>
<th>Western North Pacific</th>
<th>Australia–South Pacific</th>
<th>Cross-equatorial cyclone pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>“Expected”</td>
</tr>
<tr>
<td>January</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>February</td>
<td>1</td>
<td>12</td>
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<td>March</td>
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<tr>
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<td>6</td>
<td>13</td>
</tr>
<tr>
<td>TOTAL</td>
<td>68</td>
<td>198</td>
</tr>
</tbody>
</table>

pairs. It thus appears that at least half of the observed cyclone pairs are dynamical associations.

It would be expected that the atmospheric and oceanic conditions that permit (and limit) low-latitude northern and southern cyclones are likely the same as those for cyclone pairs. From a study published by Gray (1981), SST’s west of the Dateline appear to be sufficiently high all year on both sides of the equator for tropical storm development. The limiting factors are, therefore, atmospheric. Sufficiently high initial low-level vorticity and low vertical tropospheric wind shear are among the atmospheric prerequisites for tropical storm development (Gray, 1968, 1979; Palmén and Newton, 1969; Riehl, 1979). Gray’s (1981) mean seasonal maps of these parameters show large vertical wind shears to be the major limiting factor in the North Pacific during winter (January–March). These shears, combined with weak low-level vorticity, are the main limiting factors in the South Pacific during July–September. Judging from the nearly complete absence of South Pacific tropical cyclones during the southern winter, the atmospheric inhibitions on their formation are rarely broken. However, the occurrence of North Pacific tropical cyclones during northern winter indicates that the main inhibiting factor, large vertical wind shears, is occasionally relaxed.

A link between a relaxation of the inhibitions on wintertime North Pacific tropical cyclones and the pre-existence of a South Pacific cyclone is indicated by the fact that during northern winter, few North Pacific cyclones occur outside of cross-equatorial pairs. From mid-November through April, 1972–79, 65% of all western North Pacific cyclones, and all those east of 160°E, were associated with a southern cyclone. However, Table 2 shows that many southern cyclones occur outside of pairs. Thus, the limiting factor for the creation of cyclone pairs is that which limits northern tropical cyclones (probably strong vertical wind shear), and the most likely agents for relaxing this restriction are associated with the formation or existence of the southern cyclone. The low-level vorticity due to the equatorial westerlies associated with a southern cyclone may also aid in the formation of a northern cyclone, as suggested by Ramage (1974) for cyclone pairs in the eastern Indian Ocean, and Leigh (1969) for the Pacific.

4. Climatological interrelationships between cyclone pairs, equatorial convection and SST’s, and the Southern Oscillation

The seasonal and interannual variabilities of equatorial SST’s, convection and cyclone pairs are compared with the larger-scale fluctuations of the Southern Oscillation using monthly data for the period September 1971 through January 1980. The Southern Oscillation is represented by monthly mean Tahiti minus Darwin sea-level pressure differences. The other variables are expressed in terms of their month-to-month longitudinal variations within the equatorial zone. SST’s are defined by the easternmost longitude of the 29°C isotherms, averaged between 0 and 5°S. These data are taken from the monthly mean charts published in Fishing Information (data west of the dateline are not available on these charts). Convection is described by the longitude of the easternmost occurrence (west of 130°W) of HRC frequencies of 3 days per month at 2°S from September 1972 to April 1974, and during 1979, and by the
easternmost longitude of monthly mean satellite-derived albedos of 20%, averaged between 0 and 5°S (Winston et al., 1979), for the period June 1974 through February 1978; this parameter will be referred to as simply “HRC longitude”. The latitude band (0–5°S) chosen is typical of the westernmost extent of the clear area between the convective zones. The values of HRC frequency and mean albedo are chosen because of their good correlation to each other (r = 0.80 during 31 months of overlapping data) and to the occurrence of anomalously heavy precipitation at Canton Island (monthly totals 100 mm or more above the median). Each of the 22 cross-equatorial cyclone pairs is described by the average longitude of the initial points of the two tracks and by the formation month of the second cyclone. It should be noted that these 22 events are those that produced named tropical storms in both hemispheres. There are naturally more cases with weaker vortices in either or both hemispheres and with equatorial westerlies. However, it is apparent from the effects of the named cyclone pairs on Canton Island rainfall and on equatorial SST's (discussed in Section 5) that the named pairs are indeed the most important.

a. The seasonal cycle

Eight- or nine-year median values of Tahiti minus Darwin sea-level pressure differences, and of 29°C SST and HRC longitudes for each month are shown in Fig. 5. Also shown is the median cyclone pair longitude for those months with two or more events during the period. It can be seen that during southern summer (November–April), as compared to winter, active convection extends farther east into the central equatorial Pacific, despite stronger southeast trade winds (as indicated by Tahiti minus Darwin Δp) and no seasonal change in the equatorial extent of 29°C surface water. The median extent of active convection near the longitude of Canton Island is responsible for the extreme variability of rainfall at that Island between southern summers. The active equatorial convection can be seen to extend 20–30° east of the location of cyclone pairs, at approximately the same distance equatorial westerlies are seen to extend east of cyclone pairs in the individual cases examined in Section 2. It is apparent that the occurrence of cross-equatorial cyclone pairs, and of other synoptic-scale systems that produce equatorial westerlies, during southern summer is primarily responsible for the seasonal variability of convection in the central equatorial Pacific. The warmth of the sea surface is, by itself, not a controlling factor in the intensity of convection, as discussed by Ramage (1977).

b. Interannual variability

The medians of HRC longitude and of Tahiti minus Darwin Δp plotted in Fig. 5 have been subtracted from the individual monthly values to generate, respectively, time series of HRC longitude anomalies and a Southern Oscillation Index (SOI) (Fig. 6). The SOI is plotted on an inverted scale. Since the longitudes of the equatorial 29°C SST isotherm and of cyclone pair events show no marked seasonal cycle, their actual values are shown in Fig. 6. Also noted are months with heavy rainfall (100 mm or more above the median) at Canton Island. Because of its inclusion in the next section, the December 1976 event that produced heavy rains at Canton Island, but named cyclones in only the South Pacific is also shown in Fig. 6. Apparent in Fig. 6 are the generally good correlations among all the variables shown. At least one named cyclone pair occurs each southern summer during the period; their close relation to equatorial convection is indicated by the correlation of r = 0.72 between cyclone pair longitudes and monthly HRC longitude anomalies (n = 21, excluding the western of two November 1977 cyclone pairs). Some eastward extensions of active convection and Canton Island rain events are not associated with named cyclone pairs but probably are due to other (usually weaker) synoptic systems, as in December 1976.

Both the cyclone pair longitudes and HRC longitude anomalies agree well with changes in the SOI.
(r = -0.67, n = 21, and r = -0.73, n = 91, respectively). Because there are no SST’s west of the Dateline in this study, meaningful correlation with the 29°C SST longitude cannot be computed. However, tendencies are apparent for cyclone pairs to form within 20° west of the eastern extent of 29°C equatorial SST’s, and for the warm water to extend farther east during periods of low SOI. These correlations imply that the interannual variability of cyclone pair occurrences, particularly near the dateline, is due to changes in the longitude of favorable oceanic and atmospheric conditions connected to the Southern Oscillation. The warming of equatorial Pacific water during periods of low SOI is well known. Tropical cyclogenesis can be affected by environmental conditions 8 latitude degrees from the incipient center (e.g., Gray, 1981); thus, SST anomalies between 0 and 5°S can likely influence cyclogenesis in the 9°N–15°S zone.

The influence of atmospheric conditions on cyclogenesis is complex. The weakening of the southeast trade winds during low SOI should encourage convection through reduced low-level convergence, although this mechanism does not provide the organized synoptic-scale circulation of a cyclone pair. For a single-layer model, Matsuno (1966) has shown that quasi-geostrophic Rossby waves near the equator take the form of two cyclones (or anticyclones) straddling the equator. Furthermore, their model shows cross-equatorial cyclones, with strong westerlies on the equator, to be the stationary circulation resulting from a mass source to the west, and a sink to the east. In the lower level of a two-layer atmosphere, the mass source and sink correspond to the descending and ascending branches, respectively, of the zonal Walker circulation characteristic of low SOI. The observed manifestation of the equatorial Rossby wave is likely the double near-equatorial trough discussed in Section 1. However, the double trough and equatorial westerlies are intermittent, their occurrence being associated with organized synoptic-scale systems (Section 2). It therefore appears that the equatorial Rossby wave circulation expected during low SOI is modulated by the intermittent appearance of central Pacific cyclone pairs which serve to intensify the pattern. The formation of cyclone pairs appears to be influenced by low-latitude southern extratropical systems (Sections 2 and 3). During low SOI southern summers, the 500 mb subtropical westerlies over the south Pacific tend to be stronger than during high SOI (van Loon and Rogers, 1981), thus bringing extratropical systems closer to the equator in the vicinity of the dateline. The SO-related atmospheric influences on cyclone pair generation therefore appear to be twofold: low SOI favors the formation of the double near-equatorial trough, and tropical cyclogenesis
on the double trough is encouraged by the associated southern extratropical circulation.

Special attention should be paid to the events during the southern summer of 1974–75. This was the season of an abortive El Niño, during which an apparently developing El Niño and associated low SOI anomaly collapsed in early 1975 (Patzert, 1978). The developing anomaly during late 1974 is apparent in the SOI, HRC longitude anomalies and 29°C SST longitudes shown in Fig. 6. Like the strongly negative SOI seasons of 1972–73, 76–77 and 77–78, and even like the slightly negative SOI season of 78–79, 29°C equatorial SST’s extended eastward across the Dateline. However, unlike those seasons, cyclone pairs developed not near the dateline, but some 40° farther west. The absence of any organized synoptic activity near the dateline is indicated by the lack of heavy rain at Canton Island (Fig. 2). Despite favorably warm equatorial water and low SOI during late 1974, the double near-equatorial trough and equatorial westerlies over the central Pacific, that are so characteristic of low SOI anomalies, failed to develop. This failure is related to the absence of cyclone pairs, since the development of cyclone pairs is instrumental in organizing the larger-scale double near-equatorial trough (Section 2).

The absence of central Pacific cyclone pairs during 1974–75, despite favorably low SOI and high SST’s, may have been due to a lack of low-latitude southern extratropical systems during November and December, when southern extratropical influences on tropical development usually appear to be greatest (Sections 2 and 3). The Southern Hemisphere 500 mb circulation during those months was similar to the high SOI seasons of 1973–74 and 75–76. Compared to low SOI seasons (1972–73, 76–77, and 77–78), westerlies were weaker over the subtropical South Pacific, particularly between 25 and 40°S, and 150°E to 150°W, implying fewer or no very low-latitude extratropical systems. Interestingly, in all six seasons, the nature (strong or weak) of the westerlies over the subtropical South Pacific was apparent the preceding southern winter, suggesting there may be a hint of predictability to the synoptic situations to be anticipated over the equatorial Pacific during a coming southern summer.

The case of 1974–75 indicates that the evolution of a SO “cycle” can be influenced by the occurrence (or non-occurrence) of cyclone pairs, which, in turn, appear to be influenced by the southern extratropical circulation. Certainly, more similar cases need to be found in the historic record to confirm the importance of synoptic-scale systems in the Southern Oscillation.

5. Cyclone pair and SST interactions

While the SST’s do not limit tropical storm development west of the dateline, Gray’s maps show that the SST’s rapidly become unfavorable moving eastward across the dateline. Thus, as discussed in Section 4, cyclone pair formation near the dateline depends on the eastward extent of warm surface water during the southern summer. Apparent in Fig. 6 is a tendency for the warm water to advance farther eastward in the month following a cyclone pair near the dateline, particularly when the cyclone pair breaks a protracted (several months or longer) spell of undisturbed and relatively dry weather at Canton Island. During the 1971–79 period there were five such events associated with named tropical cyclone pairs; these are listed in Table 3. Also listed is the December 1976 event, which produced heavy rains at Canton Island and two named South Pacific tropical storms, but no named storms in the North Pacific. The central month listed for each event is the one encompassing the bulk of the duration and amount of heavy rainfall at Canton Island. For each event, the changes in eastward extent of 29°C surface water, averaged between 0 and 5°S, between the preceding, central and following months is also listed. In every case, the warm water advanced eastward (by an average of 17°) between the central and following months, reversing the westward retreat that occurred (every time but one) from the preceding to central months, and resulting in a net eastward advance between the preceding and following months. The decreases in eastward warm water extent between the preceding and central months may represent a surface cooling due to the heavy rains, rather than a true retreat of the SST anomaly.

The spatial distribution of the SST changes between the central and following months for one representative event (December 1977), and a summary of all six events are given in Figs. 7 and 8, respectively. In the December 1977 event, a tongue of warming extends eastward from the dateline, immediately south of the equator, coincident with the axis of surface westerlies (Fig. 3) which extended as far east as 140°W (Table 1). The warming at 20°S is normal for that time of year, while the warming of the waters near South America suggests a teleconnection between the central and eastern Pacific. The six-event summary map (Fig. 8) shows the spatial variations of warmings >1°C between the central and following months. An area between 0–5°S and 155–175°W showed warmings >1°C on four of the six occasions; local warmings of this magnitude affected some part of this area during all six events. It appears likely that the warming is caused by eastward advection of warm surface water, combined with sea-surface convergence and downwelling due to the westerly winds between the paired near-equatorial cyclones. Fur-

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2 Monthly averages of Australian Bureau of Meteorology analyses of daily 500 mb geopotentials were used for these comparisons.
Table 3. Changes of extent of warm (29°C) equatorial surface water associated with Canton Island westerly wind/heavy rain events and cross-equatorial cyclone pairs, 1972–79.

<table>
<thead>
<tr>
<th>Central month of event</th>
<th>Monthly total Canton Island precipitation (mm).</th>
<th>Date of onset of heavy rains</th>
<th>Preceding to central month</th>
<th>Central to following month</th>
<th>Preceding to following month</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1972</td>
<td>423</td>
<td>27 September</td>
<td>−9</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>December 1976</td>
<td>122</td>
<td>14 December</td>
<td>−13</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>March 1977</td>
<td>348</td>
<td>9 March</td>
<td>&lt; −11</td>
<td>&gt; 15</td>
<td>4</td>
</tr>
<tr>
<td>December 1977</td>
<td>522</td>
<td>30 November</td>
<td>−4</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>January 1979</td>
<td>370</td>
<td>21 December</td>
<td>−1</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>December 1979</td>
<td>M*</td>
<td>1 December</td>
<td>&gt;4</td>
<td>17</td>
<td>&gt; 21</td>
</tr>
<tr>
<td>Mean</td>
<td>−6</td>
<td></td>
<td></td>
<td>17</td>
<td>11</td>
</tr>
</tbody>
</table>

* Rainfall data for Canton Island ends in June 1979; the onset of heavy rains for this event is estimated from satellite imagery.

thermore, the convergence of oceanic westerly momentum enhances the eastward surface water advection (Philander, 1981). West of Peru, large areas experienced El Niño-like warming during five of the six events (March 1977 being the exception). Thus, cross-equatorial cyclone pairs seem to play a role in maintaining or advancing an already developed equatorial SST anomaly.

6. Summary and conclusions

An assessment is made of the role of tropical synoptic-scale systems in the Southern Oscillation. On the interannual time scale, convective activity and warm SST anomalies in the equatorial band (0–5°S) are shown to shift eastward to the vicinity of the dateline in association with a weakened South Pacific anticyclone and southeast trade winds (indicated by low SOI). However, the equatorial extent of warm water does not participate in the annual eastward shift of equatorial convection during the southern summer, suggesting that the primary seasonal controls on equatorial convection are atmospheric, not oceanic.

Canton Island lies within the region of great interannual variability of equatorial SST and convection. Excessive precipitation at Canton Island almost always occurs during periods of deep westerly winds, which, in turn, are shown to be a feature of cross-equatorial cyclone pairs near the Dateline. These cyclone pairs occur exclusively during the southern summer, and are apparently an important link for producing active convection from warm equatorial SST anomalies in the central Pacific.

Cross-equatorial cyclone pairs occurred every southern summer during the period 1972–79, and the interannual variation of their formation longitude generally correlates with that of warm equatorial surface water and with variations of the SOI. However, as is the case for convective activity, warm surface water appears to be a necessary, but not sufficient, condition for cyclone pair formation. The major limitation on cyclone pair development (possibly vertical tropospheric wind shear in either hemisphere) is only occasionally broken, and then only during the southern summer. The formation of a South Pacific tropical cyclone may be instrumental in providing conditions favorable to the formation of northern cyclones during the northern winter season.

Cross-equatorial cyclone pairs are not merely symptoms of the Southern Oscillation; they also ap-

![Fig. 7. Change of monthly averaged sea surface temperature, December 1977 to January 1978, showing the equatorial warming associated with westerly surface winds.](image-url)
pear to play a role in maintaining or even expanding the equatorial anomalies. Their organized circulation is instrumental in developing and maintaining the double near-equatorial trough over the central Pacific that is characteristic of low SOI seasons. The equatorial westerlies between the paired cyclones are shown to effect a net eastward expansion (either through advection or reduced upwelling) of the warm equatorial SST anomaly. The collapse of an apparently developing high SST/low SOI anomaly during 1974–75 may have been due (at least in part) to the absence of cyclone pairs near the dateline, despite favorably low SOI and warm equatorial water. The absence of cyclone pairs may, in turn, have been related to a lack of low-latitude extratropical systems over the South Pacific.

It is apparent that synoptic-scale systems do play a significant role in the Southern Oscillation. Of particular interest is the potential importance of single synoptic events in maintaining or expanding the equatorial anomalies, or, as evidenced by the case of 1974–75, in providing the "make-or-break" factor in deciding the eventual outcome of a developing anomaly.

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