# *THE SOUTHERN OSCILLATION, EQUATORIAL PACIFIC ANOMALIES AND EL NIÑO*

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## RESUMEN

Ciertos índices de presión (diferencias en presión atmosférica a nivel del mar entre Easter Island y Darwin, Australia y entre la Isla Juan Fernández y Darwin) delineados como promedios consecutivos de 12 meses, fueron previamente utilizados para caracterizar la oscilación del sur y para monitorear y predecir cambios significativos oceánicos-atmosféricos en el Pacífico Ecuatorial, incluyendo las ocurrencias de El Niño. El valor de utilizar índices de presión adicionales para estos propósitos se explora aquí. Ya que el interés primario son los cambios sobre el Pacífico, Darwin se usa para representar el centro ecuatorial indonesio de baja presión, pero localidades adicionales (Totegegie, Rapa y Tahiti) se usaron a lo largo de la cresta subtropical del Pacífico Sur. En general, hay una consistencia marcada entre las tendencias de los diversos índices; sin embargo, en algunas ocasiones, los puntos de inflexión pueden ser apreciados con varios meses de anticipación cuando se usa una posición de la cresta en lugar de otra y la amplitud de los picos y vaguadas en los índices es a menudo mucho mayor cuando se usa un sitio particular de la cresta.

Promedios consecutivos de 3 y 6 meses de los índices que retienen tanto el ciclo anual regular como la fluctuación irregular interanual, son usados aquí para mostrar la importancia de relaciones de fase entre estas 2 fluctuaciones en la determinación de la intensidad de desarrollos anómalos. En el caso poco común de El Niño en 1972, los picos de las 2 fluctuaciones estaban en fase al inicio de 1971 y sus vaguadas estaban en fase a mediados de 1972, de modo que una caída de 14 mb en los promedios consecutivos de 3 meses del índice Darwin oriental, ocurrió sobre un periodo de 18 meses. Esto indica un marcado debilitamiento del sistema de vientos alisios del sureste, que nosotros creemos que es un factor causal del evento severo de 1972. En el evento subsecuente de 1975, el periodo de la oscilación austral se acortó, y aunque las cimas de las 2 fluctuaciones estaban en fase, las vaguadas no lo estaban; por consiguiente, el grado de relajación estaba limitado y resultó un evento débil.

Se presenta evidencia adicional para apoyar una relación estrecha entre el sistema de alisios del sureste, modificado por la oscilación austral, y las condiciones anómalas oceanográficas y meteorológicas en el Pacífico ecuatorial.

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## ABSTRACT

Certain pressure indices (differences in sea level atmospheric pressure between Easter Island and Darwin, Australia and between Juan Fernandez Island and Darwin), plotted as 12-month running mean values, were previously used for characterizing the Southern Oscillation and for monitoring and predicting significant equatorial Pacific ocean/atmosphere changes, including El Niño occurrences. The value of using additional pressure indices for these purposes is explored here. Since the primary interest was in changes over the Pacific, Darwin was used to represent the Indonesian equatorial low pressure center, but additional sites (Totegegie, Rapa and Tahiti) were used along the South Pacific subtropical ridge. In general, there is remarkable consistency between the trends of the various indices; however, on some occasions inflection points can be noted several months earlier when using one ridge site rather than another, and the amplitude of peaks and troughs in the indices is often much greater when using a particular ridge site.

Three- and 6-month running means of the indices, which retain the regular annual cycle as well as the irregular interannual fluctuation, are used here to show the importance of phase relations between the two fluctuations in determining the intensity of anomalous developments. In the case of the unusual 1972 El Niño, the peaks of the two fluctuations were in phase in early 1971 and their troughs were in phase in mid-1972 so that a 14 mb drop in the 3-month running mean value of the Easter-Darwin index took place over an 18-month period. This indicated an extreme weakening of the southeast trade wind system, which we believe to be a causal factor for the severe 1972 event. In the subsequent 1975 event, the Southern Oscillation period shortened, and although the peaks of the two fluctuations were in phase the troughs were not; hence the degree of relaxation was limited and a weak event resulted.

Additional evidence is presented to support a close relationship between the southeast trade system, as modified by the Southern Oscillation, and anomalous meteorological and oceanographic conditions in the equatorial Pacific.


## INTRODUCTION

An earlier article (Quinn, 1974a) suggested that 12-month running mean plots of Southern Oscillation indices (difference in sea level atmospheric pressure between Easter Island and Darwin, Australia and between Juan Fernandez Island and Darwin) could be used not only to represent the variable amplitude and period of the Oscillation but also to monitor and predict associated anomalous equatorial Pacific meteorological and oceanographic conditions. It was noted that both the onset and intensity of equatorial events could be indicated by the running mean trends; and, if relaxation from an unusually high Easter-Darwin peak (> 13 mb) set in early enough in a prior year, it could set off an El Niño in the early part of the following year. It was thought that relaxation from the high peaks signified an extensive weakening of the southeast trade system, which was considered a basic cause for the anomalous developments.

This paper discusses the use of additional indices, index components, and relationships between the regular annual fluctuation and the irregular interannual fluctuation (the Southern Oscillation) to gain further insight into the nature of individual developments and to improve monitoring and prediction capabilities. Also, through a comparison between trends in the running means of the indices and equatorial Pacific rainfall it is suggested that the equatorial Pacific changes are related to variations in strength of the southeast trade system imposed by the Southern Oscillation.

Occasionally the term *El Niño-type* development will appear; the term refers to the occurrence of anomalously warm sea surface temperatures in the equatorial Pacific (as the result of a slackening in equatorial upwelling), along with abnormally heavy precipitation, and at times a disastrous invasion of anomalously warm surface waters along the coast of Peru (the actual El Niño occurrence). This condition is thought to be brought about by relaxation from a prolonged period of strong southeast trades (represented by high running mean values of the indices) to a period of unusually weak southeast trades (represent by low running mean values of the indices). The degree of relaxation and its timing determine whether or not a strong El Niño occurs along the Peruvian coast (Quinn, 1974a). The use of the broader term allows us to account for events that evolve in a similar manner but which vary in timing and intensity. This type of development is in contrast to the El Niño antithesis or anti-El Niño which occurs when the strong southeast trade system prevails (high running mean values of the indices) and there are strong upwelling, anomalously low sea surface temperatures, and abnormally small amounts of rainfall over the equatorial Pacific, as well as strong coastal upwelling, low sea surface temperatures and high primary productivity off the coast of Peru (Quinn, 1975).

## INDICES AND COMPONENTS

The Southern Oscillation according to Berlage (1966) is a fluctuation in the intensity of the intertropical general atmospheric and hydrospheric circulation; this fluctuation being primarily dominated by an exchange of air between the South Pacific subtropical high and the Indonesian equatorial low. Although the complementary nature of changes taking place in the two core areas is recognized as the principal cause for the large interannual fluctuations in pressure indices, characteristics of particular equatorial Pacific developments appear to depend upon the location of the pressure centers and the relative intensity of component input to the indices. Rainfall over the western equatorial Pacific was found to be very closely related to the nature of the equatorial low contribution, as represented by the Darwin pressure trend (Quinn and Burt, 1970; Allison *et al.*, 1972); however, the complementary contribution by the subtropical high component, which is the larger contributor to the index change (and which more clearly represents the southeast trade input), was also found to be important when considering the central and western equatorial Pacific precipitation (Quinn and Burt, 1972). Activity in the eastern equatorial Pacific (including El Niño invasions) was considered by Bjerknes (1961) to be closely related to the strength of the southeast trades, and hence to the strength and movements of the South Pacific subtropical high. In view of the above findings and our particular concern for the eastern tropical Pacific part of the activity, attention here was focused primarily on the subtropical ridge component of the Southern Oscillation index.

In 1962 the most active part of the subtropical high core appeared to be further east than usual and nearer to Juan Fernandez Island (Fig. 1b and Quinn, 1974a); as might be expected, above normal pressures and subnormal rainfall were noted at subtropical Chilean coastal stations (e.g., at Valparaiso the average pressure for 1962 was more than a millibar higher than normal and the total rainfall 46% below normal). To see how the Oscillation was represented much further to the west, the Tahiti (17° 33'S, 149° 37'W) component was used in a Tahiti-Darwin index (Fig. 2). Although Tahiti lies to the north of the subtropical ridge axis, it has an excellent pressure record extending back through 1935; a 12-month running mean plot of the index (Fig. 2) shows clearly the influence of the Southern Oscillation.

However, the peak to trough ranges are smaller than for similar cases in the Easter-Darwin plot (Figs. 1a and 1b), and the peaks and troughs often occur several months later in the Tahiti-Darwin plot. It is interesting that the 1962 peak which is so prominent in the Juan Fernandez-Darwin plot (Fig. 1b) becomes insignificant in the plot for Tahiti-Darwin. Based on these findings, it appeared that it would be beneficial to include indices using data from additional sites along the subtropical ridge in the monitoring and prediction technique. In correspondence with Monsieur A. Colombani, the Chief of the Meteorological Service for French Polynesia, he recommended the use of Totegegie (23° 6'S, 134° 52'W, Gambier Islands) and Rapa (27° 37'S, 144° 20'W, Austral Islands) to obtain better evaluations of the Oscillation in the western part of the subtropical high core. Considering Figs. 1a, 1b and 2 one notes a remarkable consistency between the trends of the various indices. However, at times pre-event peaks and attendant-event troughs are much more prominent when using one ridge site rather than another; likewise, at times the shift in trend at a peak or trough can be noted several months earlier when using one ridge site rather than another. Since the height of a pre-event peak tends to indicate the intensity of a development, and the time of change from an up-trend to a significant down-trend at the peak tends to indicate when the event will set in (Quinn, 1974a), there appears to be an advantage in having the guidance from several indices.

Changes in trend from rising to falling values at a 12-month running mean peak or from falling to rising values at a trough are often apparent many months earlier in the subtropical ridge component of an index than are the complementary changes (in the opposite sense) in the trend of the equatorial low component (Quinn, 1974a); and, the combined result may be a delay in the change in trend (beyond that shown by the ridge component) for the 12-month running mean plot of the index. For example, in Fig. 3 the Easter component shows a peak early in 1955, the Darwin component has its complementary trough extending from late 1955 through early 1956, and in Fig. 1a the resulting index peak occurs in mid 1955;

considering the secondary index peak of 1964 and Figs. 1b and 4, the Totegegie component peak occurs two months prior to the Totegegie-Darwin index peak and four to five months prior to the Darwin trough. As mentioned earlier, the subtropical ridge input and its variations in trend are particularly critical to El Niño developments.

By taking advantage of the earliest indications for change, through a consideration of all indices and their components, it will occasionally be possible to extend the forecast range by a month to several months. Our experience so far indicates that the Easter-Darwin index may usually be the best for estimating developmental intensity since the long term mean location of the southeast Pacific high is nearer to Easter. However, a plot for one of the other indices can sometimes provide an earlier indication for a significant change in index trend (see Figs. 1a, 1b and 2).

## ANNUAL AND INTERANNUAL FLUCTUATIONS

Twelve-month running mean plots are used to detect and evaluate the interannual changes that relate to equatorial Pacific events and El Niño invasions. Once plot trends indicate a large pre-event peak is developing, it becomes advantageous to refer also to plots with less smoothing to emphasize changes with shorter periods. To study the phase relations between the annual and interannual fluctuations of indices, the 3- and 6-month running mean plots are particularly useful, since they not only reflect the routine annual cycle, but also modifications imposed on it by the Southern Oscillation. These shorter period running mean plots show an annual peak near the beginning of the year and an annual trough near the middle of the year (Quinn, 1975). (On an annual basis the lowest index occurs near the middle of the year since the Easter Island pressure is generally lowest in May and the Darwin pressure is highest near the middle of the year.) This regularity makes the annual cycle predictable. When the Southern Oscillation is insignificant, the 3-month running mean peak to trough difference for the Easter-Darwin index is about 6 mb.

(For the 6-month running mean this difference is about 4 mb.) The Southern Oscillation is an irregular fluctuation (in both amplitude and period) which causes a distortion of the annual cycle. Its period ranges from about 1 1/2 to 5 years; therefore, its expected changes with time must be based on empirical approaches.

When the annual and interannual contributions are in phase, they reinforce one another and high peaks and deep troughs appear in the 3- and 6-month running mean plots of the indices. When they are out of phase, they counteract one another, and the affected annual peaks and troughs have less amplitude. Equatorial extremes in sea surface temperature and rainfall appear to be closely associated with situations where the annual fluctuation and Southern Oscillation are in phase or nearly so. In such cases, the index may make a large excursion from the high peak of a strong southeast trade situation near the beginning of a year to a deep trough and very weak southeast trade condition near the middle of the following year. If the 12-month running mean peak for the Easter-Darwin index is unusually high ($>$ 13 mb) and the two fluctuations are in phase, a particularly strong El Niño-type development would be expected in the equatorial Pacific and there would also be the likelihood of a strong Peruvian coastal El Niño.

The 3- and 6-month running mean plots of the Easter-Darwin index (Figs. 5 and 6) indicate that the 1972 El Niño was of an extreme nature. The Southern Oscillation amplitude was very large (Fig. 1b), and its peak amplitude coincided with the regular annual peak to give an unusually high 3-month running mean value (16.3 mb) near the beginning of 1971; of even more importance, it was followed by a moderate annual trough in mid-1971, a stunted annual peak at the end of 1971, and then the next annual trough and the interannual trough were in phase giving an extremely low 3-month running mean value (2.1 mb) in mid-1972. Therefore, there was an excursion of about 14 mb between the in-phase peaks near the beginning of 1971 and in-phase troughs of mid-1972. In our opinion, this reflected an extreme relaxation from a very strong southeast trade system to a very weak one over a period of about 18 months.

If this opinion is correct, it appears that the weak easterlies caused the equatorial Pacific upwelling to slacken, allowed equatorial sea temperatures to rise, and increased flow in the equatorial counter-current systems was favored. The stage was set for the warm surface water invasion off the coasts of southern Ecuador and Peru, which resulted in the disastrous 1972 El Niño. The extreme nature of the 1972 development is discussed in (Ramage, 1975).

Recognizing the built-in six-month lag in the 12-month running mean values, we can usually determine whether or not the two fluctuations are in phase (or nearly so) at a pre-event peak about 6-9 months prior to a possible El Niño invasion. (Usually, but not always, the heavy precipitation over the central and western equatorial Pacific sets in a few or more months after El Niño.) However, our prognostication for the critical phasing between the two fluctuations at the subsequent trough is limited to an empirical projection. The fall from a large 12-month running mean peak to the following trough usually takes place over a period of 15-21 months, with the average near 18 months, and an average rate of fall of about 0.33 mb/month. Considering the 12-month running mean plots, it has been noted that if the rate of rise to a high pre-event peak is relatively rapid, the rate of fall to the subsequent trough is also relatively rapid; and when the rate of rise from an earlier trough to a high pre-event peak is near to or exceeds the average rate of fall from such a peak (0.33 mb/month), one should be aware that a critical shortening in the Southern Oscillation period may be taking place. Therefore, if we find the annual and interannual peaks to be in phase near the beginning of a year but the rate of rise to the interannual peak is close to or greater than 0.33 mb/month, the following interannual trough is likely to occur between annual troughs. When the interannual trough is out of phase with the critical annual trough which occurs about 18 months after the high peak, the result is a shallow trough and a weak event. This approach assumes we can get a rough estimate of the applicable Southern Oscillation period (in the case of a relatively sharp peak) by doubling the time it takes to rise from an earlier trough to the pre-event peak. The ideal circumstance for a strong El Niño occurrence is to have a pre-event peak (> 13 mb) near the beginning of a year and an in-phase trough near the middle of the following year, as happened in the case of the 1972 El Niño.

Fig. 7 shows how the western equatorial Pacific rainfall trend (as represented by Tarawa) relates to the Rapa-Darwin index trend when both are plotted as 12-month running means. Although Tarawa rainfall data are used since the record is unbroken over the period of interest, Quinn and Burt (1970, 1972) have shown that in most cases the equatorial rainfall variations are related for equatorial Pacific stations between 155°W and 165°E. Table 1 shows correlation coefficients pertaining to two of the indices and the Tarawa rainfall at various lags. The best correlation occurs between the Easter-Darwin index and Tarawa rainfall when the rainfall lags 2-3 months behind the pressure. The best correlation occurs between the Rapa-Darwin index and the Tarawa rainfall when the rainfall lags three to four months behind the pressure.

TABLE I. Lag correlation coefficients between pressure indices and Tarawa rainfall (using 12-month running mean values).

| Lag in months | Easter-Darwin index and Tarawa rainfall | Rapa-Darwin index and Tarawa rainfall |
|---|---|---|
| -1 (rain ahead of pressure) | −0.6819 | −0.5497 |
| 0 (no lag) | −0.7313 | −0.6187 |
| 1 (pressure ahead of rain) | −0.7646 | −0.6758 |
| 2 | −0.7804 | −0.7141 |
| 3 | −0.7760 | −0.7328 |
| 4 | −0.7539 | −0.7320 |
| 6 | −0.6553 | −0.6769 |

Table 1 suggests that trends in the pressure indices should be useful for predicting changes in equatorial weather conditions. Outlooks for El Niño-type activity, using the method of Quinn (1974a) as augmented by additional considerations discussed in this paper, should have a fairly high probability of verifying. However, the general irregularity of the Southern Oscillation, and the essential condition that troughs of the two fluctuations be in phase (or very nearly so) during the mid-part of the year following a pre-event peak, cause the occurrence of a strong El Niño invasion off the coast of Peru to be a relatively rare event; and, forecasts for events of this intensity would be less likely to verify.

Since the routine annual fluctuation is about 6 mb for the Easter-Darwin index (when using 3-month running means), the interannual contribution to the 14 mb excursion downward over an 18-month period must have been larger than the annual contribution in the case of the 1972 event. This indicates that the Southern Oscillation input is a key factor in equatorial Pacific changes and El Niño invasions.

It is interesting to note that the two strong El Niño developments of recent years, the ones that set in during early 1957 and early 1972, show similar 3- and 6-month running mean profiles (Figs. 5 and 6). Unusually high in-phase peaks occurred near the beginnings of 1956 and 1971; moderate annual troughs near the mid-parts of 1956 and 1971; subdued annual peaks interrupt the extended falls near the beginning of 1957 and 1972; and large rapid falls occur in early 1957 and early 1972 reaching deep in-phase troughs by the mid-parts of 1957 and 1972. In both cases the highest index peak occurred near the beginning of a year about 18 months prior to the deep in-phase trough. It may be that the extended (but seasonally interrupted) period of relaxation in the southeast trade system, which starts about 12-15 months prior to the initial onset of El Niño, allows the equatorial current system sufficient reaction time to set the stage for a significant warm surface water invasion along the coasts of southern Ecuador and Peru by the mid-late part of the Southern Hemisphere summer. This initial onset time is in agreement with Schweigger (1961) who has stated that equatorial countercurrent invasions do not usually occur before the second half of February. Generally, the anomalously warm peruvian coastal waters remain through early fall but by mid or late fall they are moved away from the Peruvian coast as the coastal winds show their usual seasonal increase in strength when the subtropical high moves northward. Cooler waters prevail along the Peruvian coast during the winter; then, if the original development was of a large magnitude (e.g., 1957, 1972) warm surface waters return to the coast of Peru by the end of spring or early summer as the subtropical high again moves south. This seasonal excursion is evidenced in the recurring sea temperature peaks of Fig. 6 in Wooster and Guillen (1974) or Fig. 10 in Miller and Laurs (1975). Seasonal control along the southern Ecuadorian and Peruvian coasts is very strong.

In our opinion the occurrence or recurrence of a later El Niño (e.g., 1941, 1953, 1965) during the period following initial relaxation (e.g., 1939, 1951, 1963 when weaker events occurred) from a large peak (e.g., 1938, 1950, 1962) may take place if running means of the index remain low (e.g., 1939-1941) or return to a low value (e.g., 1953, 1965) after a short excursion upward into a smaller peak (e.g., 1952, 1964). (In the prior discussion it was assumed the 1938 peak would have been much higher and would have appeared earlier in an Easter-Darwin plot than in the Tahiti-Darwin plot of Fig. 2; also the Juan Fernandez-Darwin plot of Fig. 1b best represents the 1962-65 development.) The more complex secondary developments require further study, but they definitely appear to capitalize on changes brought about by the initial relaxation from an unusually high index peak in their further evolvement.

## DISCUSSION

Wyrtki (1972) has shown that changes in the transport of the equatorial countercurrent decisively affect the temperature distribution in the eastern tropical Pacific and are strongly linked with such climatic abnormalities as El Niño. Also, graphic relationships indicate that the fluctuations in countercurrent transport and sea surface temperature anomalies off the coast of Central America (see Fig. 2 of

Wyrtki, 1973), are closely associated with the long-term variations in southeast trade strength as represented by the 12-month running mean trends of the Southern Oscillation index (Quinn, 1974a). Likewise, Fig. 1 of Bjerknes (1969) showing the Canton Island sea surface temperature trend and Fig. 3 of Seckel and Yong (1970) showing the Christmas Island sea surface temperature trend indicate conformance with index trends, in that the high sea surface temperatures relate to low indices and the low sea surface temperatures to high indices. Fig. 7 further confirms this close relationship between the Southern Oscillation and the anomalous equatorial Pacific developments. Based on the foregoing indications and the findings in the previous section as to the magnitude of the interannual contribution, it is our view that the Southern Oscillation, through its effects on the strength of the southeast trade system, exerts considerable control over equatorial Pacific meteorological and oceanographic conditions and El Niño invasions off the coasts of southern Ecuador and Peru.

Although the close relationship between the Southern Oscillation and the equatorial Pacific changes appears to be quite clearly demonstrated, the large-scale on which such developments take place and the great variability in the nature of individual events suggest that other parts of the global system are heavily involved. Berlage (1966) states that the Southern Oscillation is a near-global phenomenon. Namias (1973) has shown certain relationships between the North Pacific atmospheric circulation and equatorial events. Dorman *et al.* (1974), from an investigation of Ocean Station vessel N (30°N, 140°W) data, noted a correlation between certain large pressure anomalies and the more extreme equatorial Pacific anomalies. Fig. 8 shows a 12-month running mean plot of the Ship N sea level pressure data in comparison to a similar plot of the Easter Island data. The correlation coefficient pertaining to these two plots is extremely low (0.2783 at no lag, and reaching a maximum of 0.3233 when Ship N lags three months behind Easter), but an eye-ball scan of this short record suggests what may be happening. Obviously the Ship N plot is noisier, and there is no similarity between the two plots between 1961 and 1963; also, the lag is quite variable for cases where features are reflected in both plots. However, the 1955 peak, 1957-58 trough, 1964 peak, 1965-66 trough, 1967, peak, 1968-69 trough 1970-1971 peak, and 1972 trough are roughly represented in each case. It appears that in most cases the larger interannual changes are reflected in the Ship N data but are not as large or as clearly represented as they are in the Easter data. A reflection of the Southern Oscillation over the northeastern Pacific would be expected from Troup's (1965) circulation model, which represents the Southern Oscillation's exchange of air between the eastern and western hemispheres as a zonal-vertical toroidal circulation over the lower latitudes of the Indo-Pacific region.

We must certainly obtain a much clearer insight into the interactions with northern hemispheric circulation features, as well as with other parts of the global tropics and subtropics if we are to understand what takes place as the unusual large-scale equatorial Pacific events evolve and how they may influence developments over the North Pacific.

## RECENT TEST

A test of the prediction method was made in 1974, based essentially on the approach suggested in Quinn (1974a); and without the benefit of additional guidance which has been provided as a result of further investigation. The outlook (Quinn, 1974b) was presented at the Eastern Pacific Oceanic Conference held at Lake Arrowhead, California on October 2, 1974, and called for an El Niño-type development in 1975, with a weak coastal El Niño off the coast of northwestern South America in early 1975. The 12-month running mean trend of the Easter-Darwin index (Fig. 1b) had reached a relatively high peak by the end of 1973 and started falling off in early 1974; this was the basis for the outlook. The weak specification for the coastal El Niño was based at this time on the running mean peak having an index a little less than 13 mb, and particularly on the fact that the Easter component (Fig. 3) of this index peak was significantly less than 1022 mb (1021.5 in this case).

Based on the outlook, the El Niño Watch cruises (sponsored by the NSF IDOE/ONR NORPAX Program) were set up to investigate the onset and course of the expected event. The first cruise confirmed the southward movement of a large tongue of warm, low salinity water across the Equator just east of the Galapagos Islands to 5°S in February-March 1975; and although weak upwelling was present along the coast of northern Peru, no cool water was advected northwest from this upwelling area, as in normal years (Wyrtki *et al.*, 1975). Further confirmation on this event appeared in the unusually heavy rainfall (over twice the normal amounts of rainfall were recorded for both February and March at Guayaquil) and flooding which occurred along the coast of Ecuador at this time (Enfield, 1975). The second cruise in late April-May showed a return to normal conditions.

In brief, the Southern Oscillation period was significantly shorter than it was for the case leading up to the 1972 development. The result was a shallow interannual trough occurring near the end of 1974 for the indices involving components from the three westernmost sites along the ridge, and near the beginning of 1975 for indices involving components from the two easternmost sites (Fig. 1b). Hence, the troughs of the two fluctuations were out of phase and the development was weak. Although the event occurred at close to its expected time and intensity in the region between the Galapagos Islands and northwestern South America, it was much weaker and earlier than expected in the western equatorial Pacific. Nevertheless, the index trends were in line with what actually happened. The shallow index trough correlates with the small peak in the Tarawa rainfall. (The 12-month running mean rainfall peak in Fig. 7 is about 150% of the average value.) This particular case was unusual in that the Tarawa rainfall peak preceded the El Niño, and the Darwin component peak, which was very small, preceded the Easter component trough.

## CONCLUSIONS

The use of the additional indices (involving several sites along the

South Pacific subtropical ridge) in the monitoring and prediction method was found to be an asset since: (1) the nature and intensity of an event could be more thoroughly evaluated; (2) the changes in trend at peaks and troughs, which guide predictions, can often be noted earlier when using one ridge site rather than another; and (3) a certain amount of confidence is added to the outlook when one finds general agreement between index trends. In general, the Easter-Darwin index appears to provide the best estimate for developmental intensity; but it is often one of the other indices which provide the earliest indication of a significant change in index trend.

The following index characteristics appear common to those large-scale equatorial Pacific changes that result in a strong El Niño occurrence:

1. A pre-event peak in the 12-month running mean of the Easter-Darwin index plot in excess of 13 mb occurring at or near the beginning of a year. (This assures that the irregular interannual peak and the regular annual peak of the index are in phase.)

2. A generally steep and continuous fall from the 12-month running mean peak (at a rate averaging near 0.33 mb/month for the Easter-Darwin index) to a trough about 18 months later. (This assures that the interannual trough and a regular annual trough are approximately in phase near the middle of the following year.)

The first condition can be assured prior to issuing a prediction. With regard to the second condition, our assessment is more limited. However, we can monitor the rate of index fall for the first three to five months following the peak to see if it is near the desired figure before issuing the forecast. Also, if the rise from a previous trough to the preevent peak was extremely rapid, we can double the time taken to rise from trough to peak and get a rough estimate of the Southern Oscillation period. If this period is so short that it will cause the interannual trough to be out of phase with the critical annual trough of the following year, then the resulting event will be weak.

Although the indices appear to be excellent tools for monitoring various aspects of the equatorial Pacific developments in general, the forecast method applies primarily to the nature of the initial events following relaxation from unusually high peaks and not to associated later seasonal recurrences. It must be realized that the time involved in relaxation from peak to trough determines how far in advance of event occurrence a forecast can be issued. If we attempt to exceed this lead time limit, our outlooks become more speculative since they must be based on our limited case history experience from the past. Figs. 5 and 6, which refer to the strong 1957 and 1972 events, suggest common profiles for the 3 and 6-month running mean trends of indices pertaining to strong El Niño occurrences.

Available evidence indicates that the Southern Oscillation, through its effects on the southeast trade system, exerts considerable control over the occurrence of anomalous equatorial Pacific meteorological and oceanographic conditions and El Niño invasions along the coasts of southern Ecuador and Peru. A recent test of the prediction approach, involving the use of Southern Oscillation indices, indicates it can be effective.

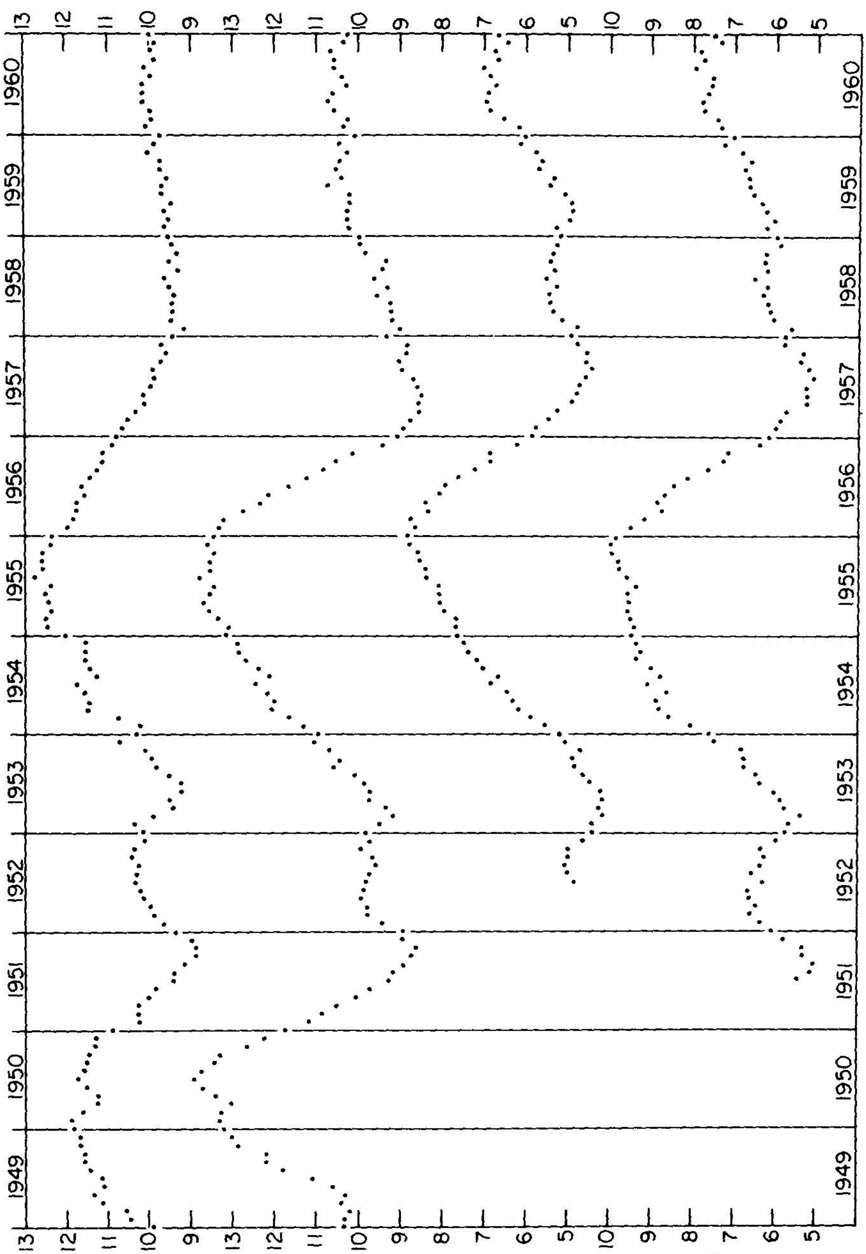


Fig. 1a. Comparison of 12-month running mean plots (points plotted at the middle of the 12 months) for the difference in sea level atmospheric pressure (mb) between Juan Fernandez Island and Darwin, australia (JF-D), betweenn Easter Island and Darwin (E-D), between Totegegie (Gambier Islands) and Darwin (T-D), and between Rapa (Austral Islands) and Darwin (R-D) for 1949-60.

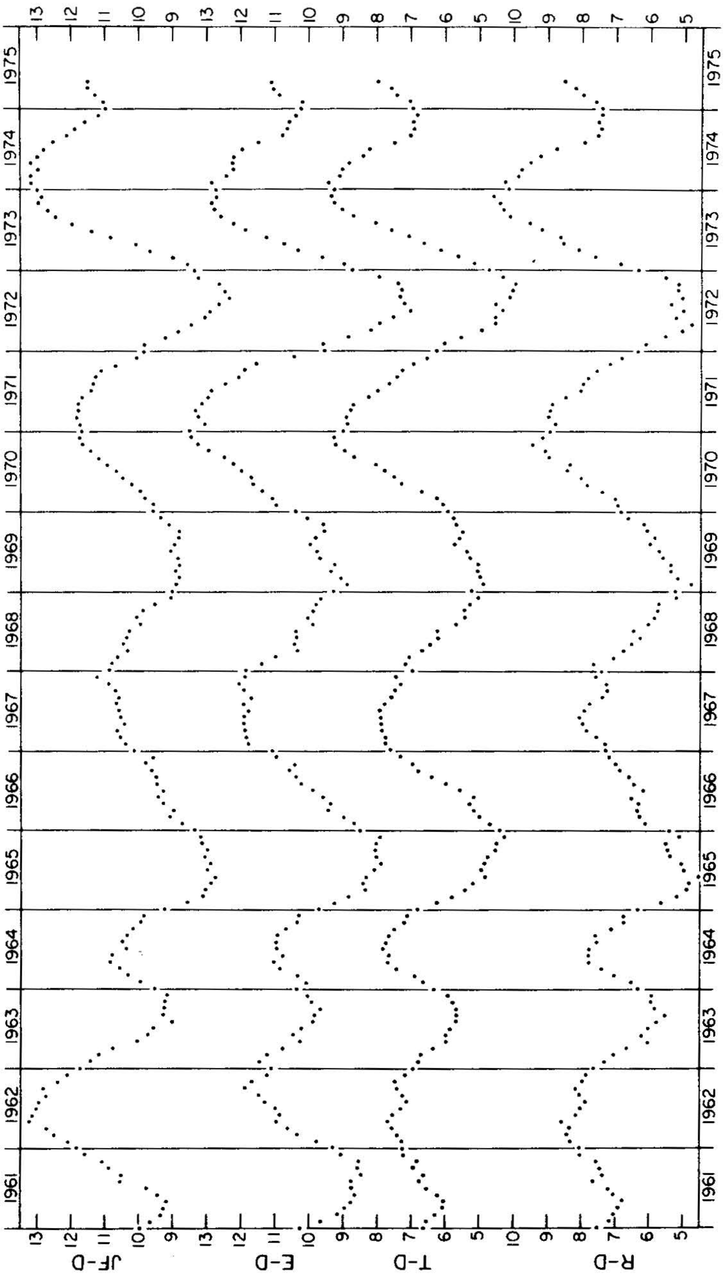


Fig. 1b. Comparison of 12-month running mean plots (points plotted at the middle of the 12 months) for the difference in sea level atmospheric pressure (mb) between Juan Fernandez Island and Darwin, Australia (JF-D), between Easter Island and Darwin (E-D), between Totegegie (Gambier Islands) and Darwin (T-D), and between Rapa (Austral Islands) and Darwin (R-D) for 1961-75.

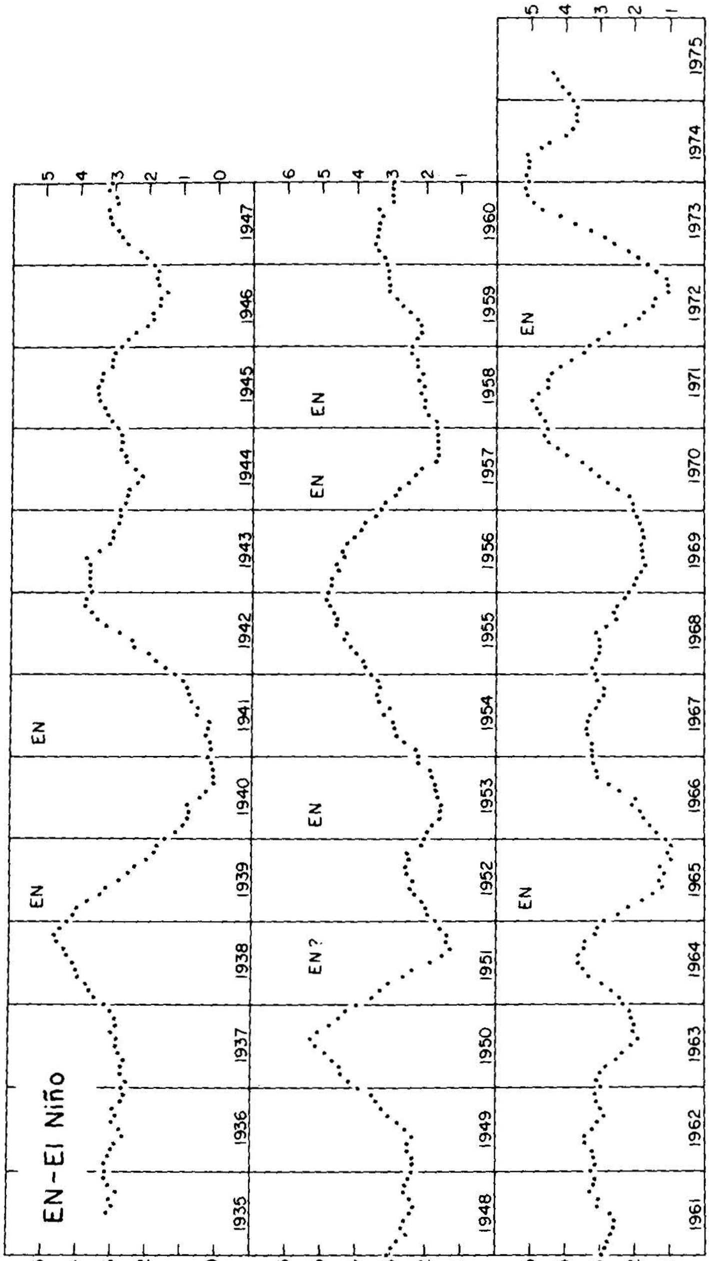


Fig. 2. The 12-month running means (points ploteed at the middle of the 12 months) of the difference in sea level atmospheric pressure (mb) between Tahiti (Society Islands) and Darwin, Australia, for 1935-75. El Niño occurrences are indicated.

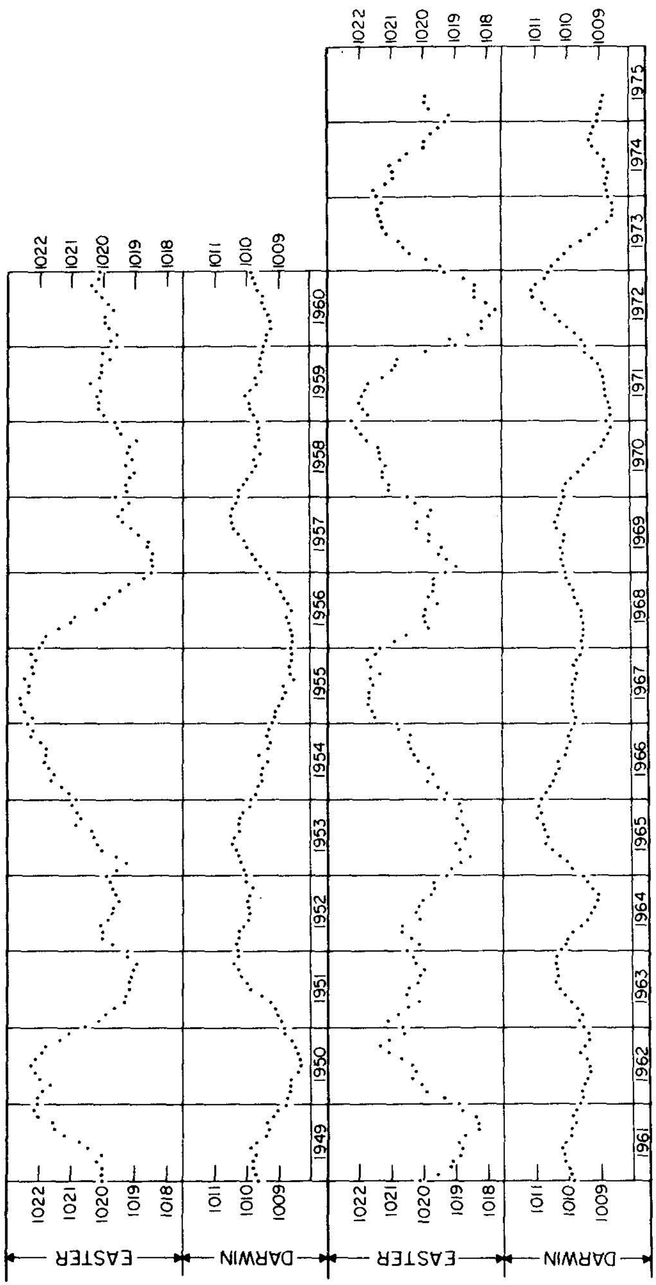


Fig. 3. The 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Easter Island and Darwin, Australia for 1949-75.

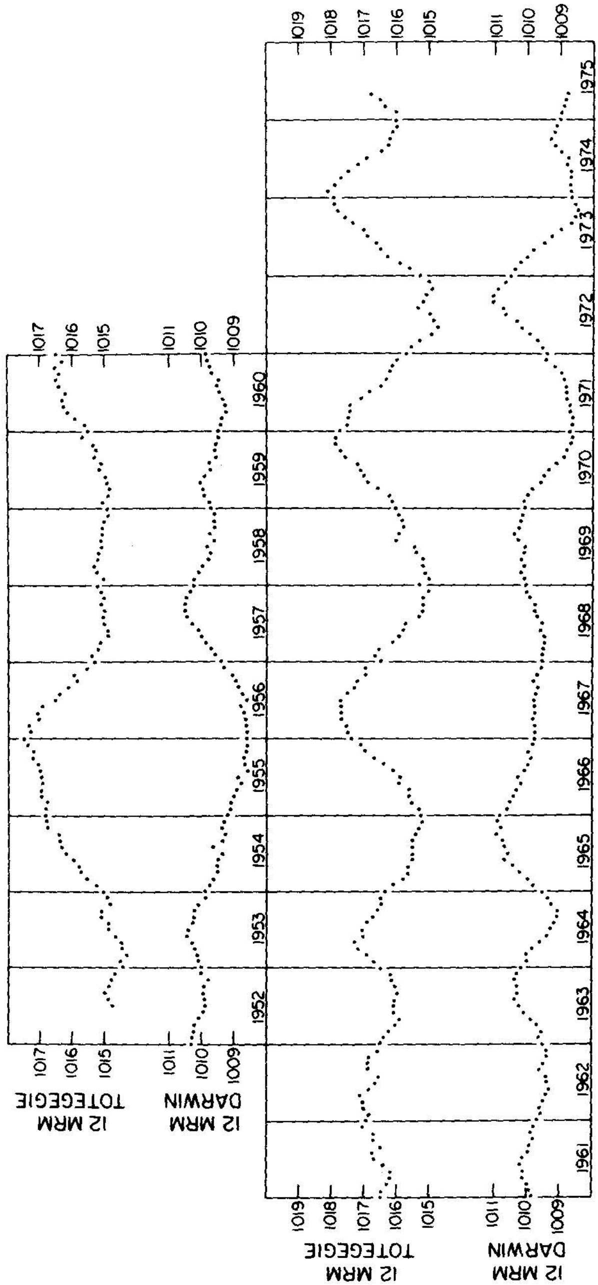


Fig. 4. The 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Totegegie (Gambier Islands) and Darwin, Australia for 1952-75.

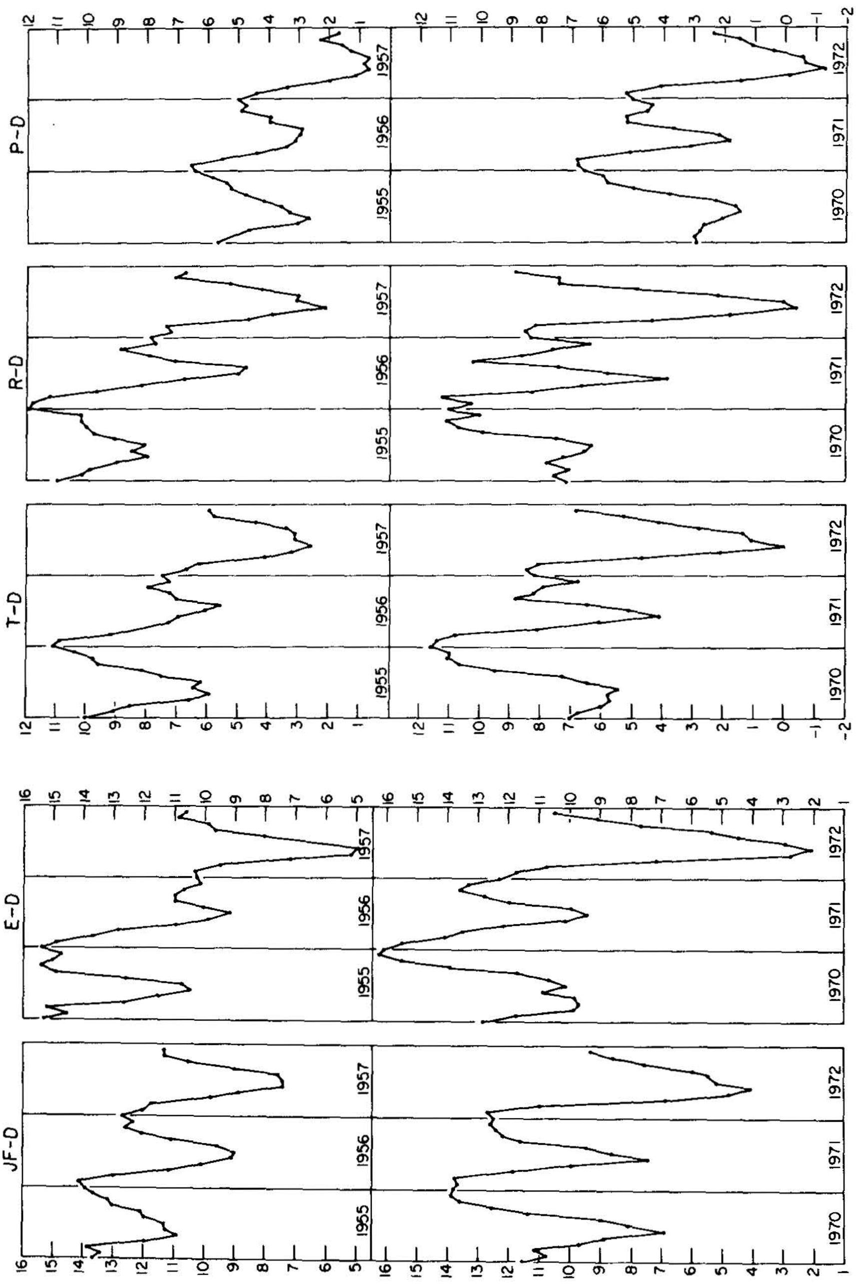


Fig. 5. Comparison of 3 month running mean plots (points plotted at the middle of the 3 months) for the difference in sea level atmospheric pressure (mb) between Juan Fernandez Island and Darwin, Australia (JF-D), between Easter Island and Darwin (E-D), between Totegegie (Gambier Islands) and Darwin (T-D), between Rapa (Austral Islands) and Darwin (R-D), and between Tahiti (Society Islands) and Darwin (P-D) for 1955-57 and 1970-72.

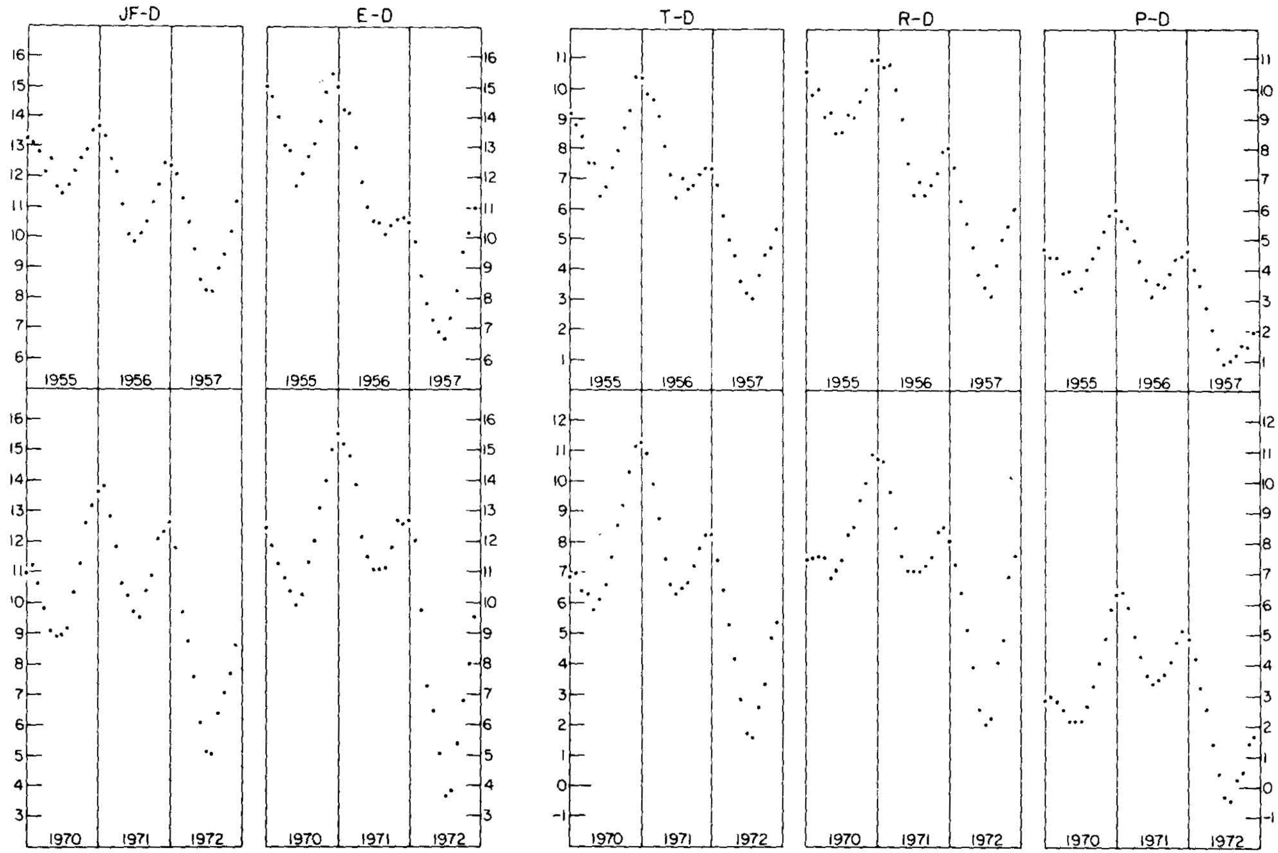


Fig. 6. Camparison of 6-month running mean plots (points plotted at the middle of the 6 months) for the difference in sea level atmospheric pressure (mb) between Juan Fernandez Island and Darwin, Australia (JF-D), between Easter Island and Darwin (E-D), between Totegegie (Gambier Islads) and Darwin (T-D), between Rapa (Austral Islands) and DArwin (R-D), and between Tahiti (Society Islands) and Darwin (P-D) for 1955-57 and 1970-72.

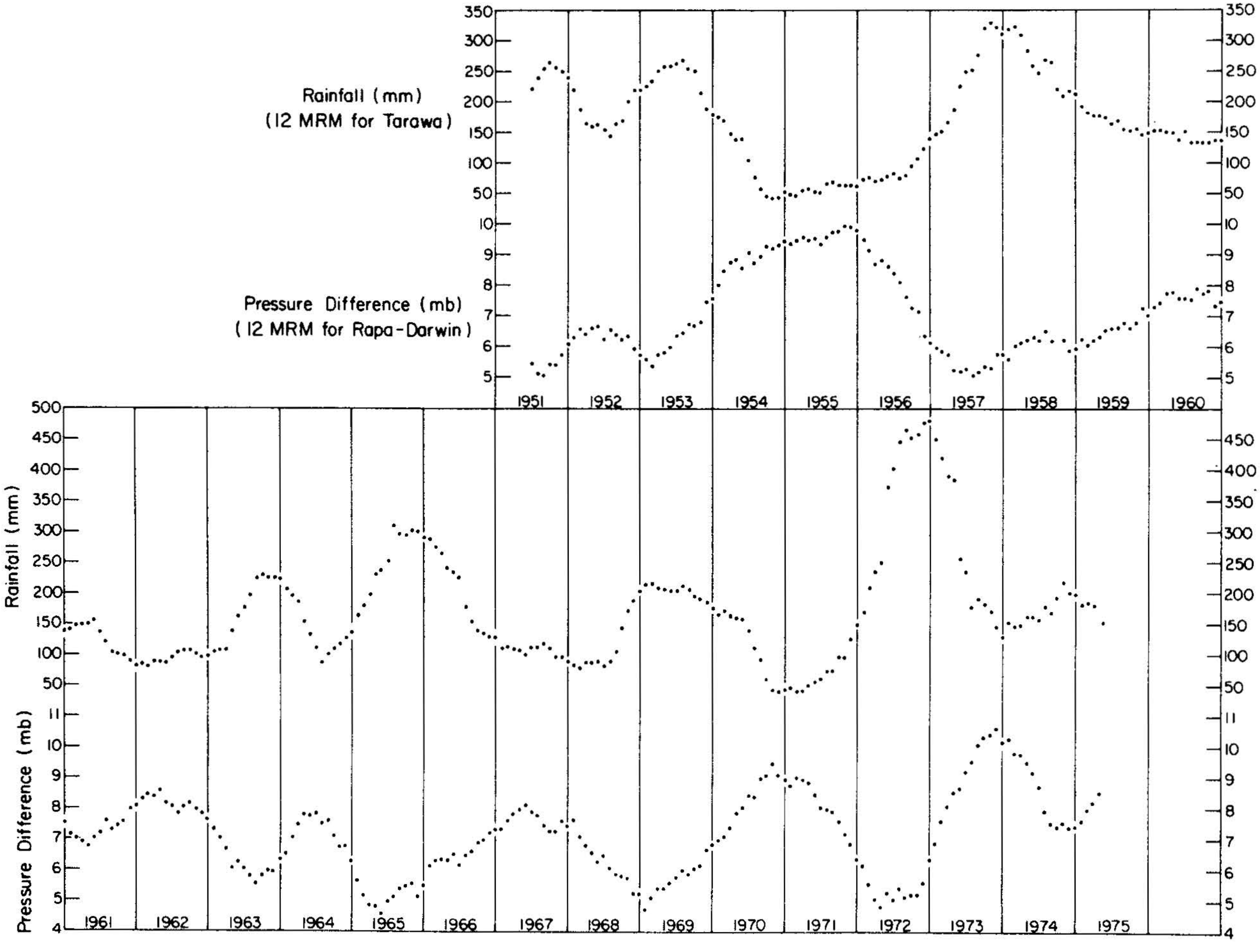


Fig. 7. Comparison of 12-month running mean values (plotted at the middle of the 12 months) of rainfall (mm) for Tarawa (Gilbert Islands) to 12-month running means of the difference in sea level atmospheric pressure (mb) between Rapa (Austral Islands) and Darwin, Australia, for 1951-75.

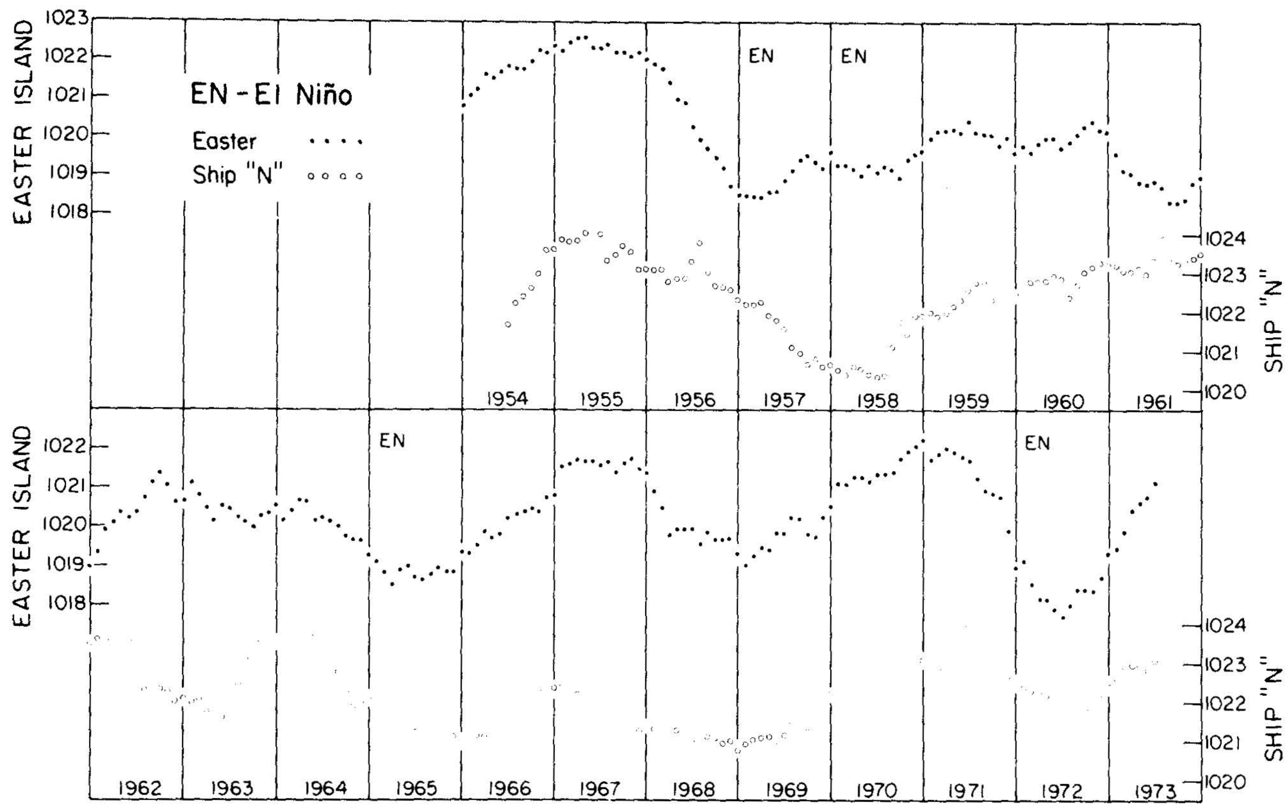


Fig. 8. A comparison of the 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Easter Island and Ship N for 1954-73. Times when El Niño occurred are indicated.

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## *BIBLIOGRAPHY*


ALLISON, L. J., J. STERANKA, R. J. HOLUB, J. HANSEN, F. A. GODSHALL and C. PRABHAKARA, 1972. Air-sea interaction in the Tropical Pacific Ocean. NASA *Technical Note,* NASA TN D-6684, 84 p.

BERLAGE, H. P., 1966. The Southern Oscillation and world weather. *Mededel. en Verhandel.,* No. 88, Kon. Ned. Meteor. Inst., 152 p.

BJERKNES, J., 1961. "El Niño" study based on analysis of ocean surface temperatures 1935-57. *Inter-Amer. Trop. Tuna Comm. Bull.,* 5(3): 219-303.

BJERKNES, J., 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.,* 97: 163-172.

DORMAN, C. E., C. A. PAULSON and W. H. QUINN, 1974. An analysis of 20 years of meteorological and oceanographic data from Ocean Station N. *J. Phys. Oceanogr.,* 4: 645-653.

ENFIELD, D. B., 1975. A brief report on surface oceanographic and meteorological conditions in Ecuador during the first quarter of 1975. *CUEA Newsletter* 4(2).

MILLER, F. R. and R. M. LAURS, 1975. El Niño of 1972-73 in the eastern tropical Pacific Ocean. *Inter-Amer. Trop. Tuna Comm. Bull.,* 16(5): 403-448.

NAMIAS, J., 1973. Response of the equatorial contercurrent to the subtropical atmosphere. *Science,* 181: 1244-1245.

QUINN, W. H., 1974a. Monitoring and predicting El Niño invasions. *J. Appl. Meteor.,* 13: 825-830.

QUINN, W. H., 1974b. Outlook for El Niño type conditions in 1975. *NORPAX Highlights* 2(6).

QUINN, W. H., 1975. Forecasting El Niño and its antithesis. *Proceedings* of Symposium of Fisheries Biology, February 16-22, 1975. The Autonomous University of Baja California, Ensenada, B. C., México.

QUINN, W. H. and W. V. BURT, 1970. Prediction of abnormally heavy precipitation over the equatorial Pacific dry zone. *J. Appl. Meteor.,* 9: 20-28.

QUINN, W. H. and W. V. BURT, 1972. Use of the Southern Oscillation in weather prediction. *J. Appl. Meteor.,* 11: 616-628.

RAMAGE, C. S., 1975.Preliminary discussion of the meteorology of the 1972-73 El Niño. *Bull. Amer. Meteor. Soc.,* 56: 234-242.

SECKEL, G. R. and M. Y. Y. YONG, 1970. Harmonic functions for sea-surface temperatures and salinities, Koko Head, Oahu, 1956-69 and sea-surface temperatures, Christmas Island, 1954-69. *Fishery Bull.,* 69(1): 181-214.

TROUP, A. J., 1965. The southern oscillation. *Q. J. Roy. Met. Soc.,* 91: 490-506.

WOOSTER, W. S. and O. GUILLEN, 1974. Characteristics of El Niño in 1972. *J. Mar. Res.,* 32: 387-404.

WYRTKI, K., 1973. Teleconnections in the equatorial Pacific Ocean. *Science,* 180: 66-68.

WYRTKI, K., E. STROUP, W. PATZERT, R. WILLIAMS and W. QUINN, 1975. *Science* (in press).