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USE OF SOUTHERN OSCILLATION INDEX ANOMALIES FOR PREDICTING EL NIÑO TYPE ACTIVITY

by

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ABSTRACT

The Southern Oscillation (S.O.), as represented by pressure indices (differences in sea level atmospheric pressure between sites located in the Indonesian equatorial low region and in the South Pacific subtropical high region), has been used to monitor and predict persistent, large-scale changes in meteorological and oceanographic conditions over the equatorial Pacific and the oceanic region off the northwest coast of South America. Triple 6-month running mean and 3-month running mean filters are now being applied to S.O. Index anomalies, index component anomalies, sea surface temperature (SST) anomalies, rainfall anomalies, etc. in time section analyses for these purposes. This approach considers the concept that fluctuations in the nature and location of the atmospheric centers of action (the semi-permanent highs and lows that appear on mean charts of sea level pressure) are intimately associated with large-scale, long period changes in weather. Over our region of interest we are primarily concerned with the movements and changes in intensity of the Indonesian Equatorial low, the South Pacific subtropical high and northeast Pacific subtropical high.

The SST anomaly trends have been particulary useful for verifying indications from the circulation indices. The amplitude of the irregular interannual fluctuation (the S.O.) can at times be as large as or larger than the regular annual fluctuation. If these two fluctuations are in phase (on relaxation from a pre-event index anomaly peak) they tend to reinforce each other, and a stronger event occurs; if they are out of phase, they tend

to counteract each other and a weaker event results. Aplications to both El Niño and to anti-El Niño type activity are discussed. Cases are also discussed where relaxation from a large pre-event index anomaly peak involves more than a single stage process.

Forecasts for a weak event in early 1975 and a moderate event in 1976 verified. Further study of a very long index anomaly record in relation to event occurrences indicates the pre-event peak is an an excellent predictor for el Niño type activity.

It is evident that this monitoring and prediction approach can become an excellent aid to judicious utilization of the Peruvian anchoveta fishery and the eastern equatorial Pacific skipjack tuna fishery. It appears that the index anomaly trends and other closely allied indicators may also prove useful for foreshadowing certain persistent large-scale environmental changes in other parts of the global tropics and subtropics.

RESUMEN

La oscilación del sur (O.S.), representada por índices de presión (diferencias en presión atmosférica al nivel del mar, entre lugares localizados en la región de baja presión Ecuatorial de Indonesia y en la región de alta presión subtropical del Pacífico Sur), ha sido utilizada para monitorear y predecir cambios persistentes a gran escala en condiciones meteorológicas y oceanográficas sobre el Pacífico Ecuatorial y la región oceánica frente a la costa noroeste de América del Sur. Para estos propósitos se están aplicando filtros triples de medias de 6 meses y de 3 meses en análisis de sección de series de tiempo de índice O.S., anomalías índice componentes, anomalías de temperatura superficial del mar, anomalías de precipitación pluvial, etc. Esta manera de atacar el problema considera el concepto de que las fluctuaciones en la naturaleza y localización de los centros atmosféricos de acción (los centros de semi permanentes de alta y baja presión que aparecen en las cartas de valores medios de presión al nivel del mar) están intimamente asociados con cambios en el clima de período largo y de gran escala. En nuestra región de estudio, nos interesa principalmente los movimientos y cambios de intensidad del centro de baja presión Ecuatorial de Indonesia, el centro de alta presión subtropical del Pacífico del Sur y el de alta presión subtropical del Pacífico Nororiental.

Las tendencias de las anomalías de temperatura superficial del mar han sido particularmente útiles para verificar las indicaciones de los índices de circulación. La amplitud de las fluctuaciones irregulares interanuales (la O.S.) puede algunas veces ser tan grande o más que la fluctuación anual regular. Si estas dos fluctuaciones están en fase (en relajamiento después de un pico en la anomalía índice de un pre-evento) tienden a reforzarse mutuamente y ocurre un evento mas fuerte; si están fuera de fase tienden a contrarrestarse y ocurre un evento mas débil. Se discuten aplicaciones a actividades del tipo El Niño y anti-El Niño. También se discuten casos donde el relajamiento del pico de la anomalía índice de un pre-evento grande involucra procesos de más de una etapa.

Se verifican predicciones para un evento débil a principios de 1975 y para un evento moderado en 1976. Estudios de una gráfica muy larga de la anomalía índice con relación a la ocurrencia de eventos indican que el pico de pre-evento es un predictor excelente para El Niño.

Es evidente que este tipo de monitoreo y prediccion puede resultar en una excelente ayuda hacia la utilización racional de la pesquería Peruana de anchoveta y la de atún del Pacífico Ecuatorial Oriental. Puede ser que las tendencias de las anomalías índice y otros indicadores estrechamente relacionados sean útiles para clasificar ciertos cambios persistentes del medio ambiente a gran escala en otras partes tropicales y subtropicales del globo.

INTRODUCTION

Anomalous equatorial Pacific meteorological and oceanographic conditions and the related El Niño events that affect the waters off the west coast of South America are the results of certain large-scale changes in atmospheric and oceanic circulation. These changes appear to be closely associated with the variations in amplitude and period of an irregular interannual fluctuation in the atmospheric circulation called the Southern Oscillation. Time section plots of pressure index (difference in sea level atmospheric pressure between sites representing the Indonesian equatorial low and sites representing the South Pacific subtropical high) anomalies have been used to monitor the Southern Oscillation. Also a method using trends in the monthly mean and 3- and triple 6-month running mean plots of the index anomalies has been developed for monitoring and predicting the ocean-atmosphere changes associated with this Oscillation (Quinn, 1974, 1977).

This paper will provide some background information on this approach and how it might be used to assess physical environmental effects in certain tropical Pacific fishery areas. For clarification purposes the following definitions are provide.

The Southern Oscillation (S.O.) was identified as such by Walker (1924). Berlage (1957) loosely defined it as a fluctuation in the intensity of the inter-tropical general atmospheric and hydrospheric circulation which is most clearly manifested over the Indo-Pacific region; the fluctuation to a large extent being dominated by an exchange of air between the South Pacific subtropical high and the Indonesian equatorial low. Troup (1965) defined it as an exchange of air between the Eastern and Western Hemispheres, principally in tropical and subtropical latitudes, and noted that there were various smaller scale displacements of mean pressure systems connected with it. Troup associates this exchange of air with variations in a mean toroidal circulation driven by temperature differences between the two areas (the westernmost equatorial Pacific-Indonesian area/the eastern tropical and subtropical Pacific area). For simplicity Troup (1965) considers there is a single drift of most importance in the upper troposphere and that this flow is from the area of the Indonesian equatorial low across the Pacific to its central and eastern regions. It is compensated by a return flow near the surface from the eastern Pacific to the region of the low. There is descent in this circulation over the central and eastern Pacific, ascent in the vicinity of the equatorial low and a toroidal circulation in the vertical-zonal plane is maintained. The pressure changes which result in the index variations discussed in this paper are a consequence of variations in this circulation and related movements of the associated atmospheric centers of action.

The Walker Circulation is considered to be an important part of the mechanism of Walker's Southern Oscillation (Bjerknes, 1969). According to Bjerknes it is a thermal circulation which results from the gradient of sea temperature along the equator. In general air rises over the warm westernmost equatorial Pacific and sinks over the cool eastern and central equatorial Pacific. Hence there is a zonal vertical circulation along the equator with a horizontal pressure gradient wesward along the surface and eastward in the upper troposphere. This circulation enters into an exchange of absolute angular momentum with adjacent parts of the atmosphere to the north and south (Bjerknes, 1969). The extent of this equatorial Pacific cell and its circulation strength appear in large part to be determined by the extent and intensity of the upwelling of cooler waters to the surface over the eastern, central and at times part of the western equatorial Pacific, which is also to a great extent determined by the strength of the southeast trades and equatorial easterlies. One might consider the Walker Circulation to be the equatorial aspect of the S.O.

The term El Niño-type development is occasionally used for convenience. This broad connotation represents the ocurrence of anomalously warm sea surface temperatures in the equatorial Pacific along with abnormally heavy rainfall, and at times a disastrous invasion of anomalously warm surface waters along the coast of Peru (the actual El Niño occurrence). This condition is brought about by relaxation from a prolonged period of strong southeast trades (represented by high S.O. index anomalies) to a period of unusually weak southeast trades (represented by low S.O. index anomalies). The magnitude of this relaxation and its timing appear to determine whether or not a strong El Niño occurs along the Peruvian coast (Quinn, 1974). The heavy central and western equatorial Pacific precipitation usually starts a few or more months after the El Niño sets in, but this may not always be the case. By using the broader term one avoids getting into arguments over what is and what is not an El Niño and can then account for those events that evolve in a similar manner but vary in timing and intensity.

The anti-El Niño refers to the contrasting situation when the filtered plots of the S.O. index anomalies rise steeply for many months and reach and remain at high values. This indicates that a strengthening and strong southeast trade system prevails; therefore, we can expect strong upwelling, anomalously low sea surface temperatures and abnormally low amounts of rainfall over the equatorial Pacific (Quinn and Burt, 1972; Quinn, 1974) with generally strong coastal upwelling, low sea surface temperatures, lower sea level and more favorable physical environmental conditions for primary productivity along the coast of Peru.

BACKGROUND

The idea that the S.O. might be particularly useful for long-range prediction of ocean and weather conditions over the Indo-Pacific region was discussed much earlier by Berlager (1957) and Troup (1965). Although the S.O. is a nearglobal phenomenon

(Berlage, 1966), it ~~is most~~ clearly evidenced over the Indo-Pacific tropics and subtropics. Bjerknes (1969) was particularly interested in the equatorial aspects of the S.O. and found indications of a relationship between the variations in his Walker Circulation and changes in the circulation and weather over the northeast Pacific. All three of these authors recognized the important contribution of variations in the strength of the southeast trades (hence, variations in the strength of the South Pacific subtropical high) to changes over the equatorial Pacific. However, the extreme lack of data over the southeast Pacific has always drastically limited the effective use of this important center of action (the South Pacific subtropical high). The time-section analysis method has been consistently advocated for use over the tropical oceans where the station density is very low (Riehl, 1954). Therefore, as will be explained subsequently, the use of this method, modified so as to be applicable to the study of long-term fluctuations, has been extended into the subtropics of the Pacific.

From the standpoint of long-range forecasting, we are primarily interested in deviations from normal. Therefore, it is desirable to eliminate regular oscillations, such as the diurnal cycle (by using daily means to obtain monthly values (for temperatures, pressures, winds, etc.) or monthly total amounts (for rainfal) and the seasonal or annual cycle (by subtracting the long-term average or normmal monthly values from the individual monthly values). Data so processed would show no particular regularity and no apparent cycle (Panofsky, 1965). The filtered and unfiltered monthly anomalies can then be used to detect, identify and evaluate any unusual changes that are taking place.

For the S.O. we are interested in fluctuations of an intermediate scale, with periods ranging generally between the extremes of about one and six years.

The remainig short period fluctuations in the anomalies can be largely eliminated by smothing (filtering with a low pass filter; e.g., the triple 6-month running mean). At the other end of the time scale there may be a gradual change of the variate over many years which could be part of oscillations that are long compared to the record (The cause for changes of this nature may not be due to a true change in the weather; man-caused changes in sensor surroundings, relaxation or degradation of sensor elements, etc., may be involved). Ordinarily these extremely long gradual changes are not a problem in our study of the S.O.

In earlier papers the 12-month running mean was applied directly to the monthly values of pressure, pressure differences (indices), sea surface temperatures (SST's), rainfall, and zonal wind components as a low pass filter. However, this particular filter not only smoothed the data but also largely eliminated the annual cycle. Recently, in order to more clearly define the interannual fluctuations (the S.O.), a switch was made to use of the triple 6-month running mean filter (wich involves three successive passes of the 6-month running mean over the data) on the monthly anomalies. For comparison purposes note the 12-month running mean plot of the Easter-Darwin index at the bottom of Fig. 2 and the triple 6-month running mean plot of the Easter-Darwin index anomalies for the same period in Figs. 2a and 2b. The smoother plots and more clearly defined peaks and troghs of the recent approach are of particular value in post analysis studies and for defining long-range trends; however, the fact that you lose three months of time with each application of the 6-month running mean is a drawback to its use in forecasting, so we additionally use the 3-month running mean and monthly plots of anomalies for locating inflection points and evaluating the trends on a more inmediate basis in support of forecasts.

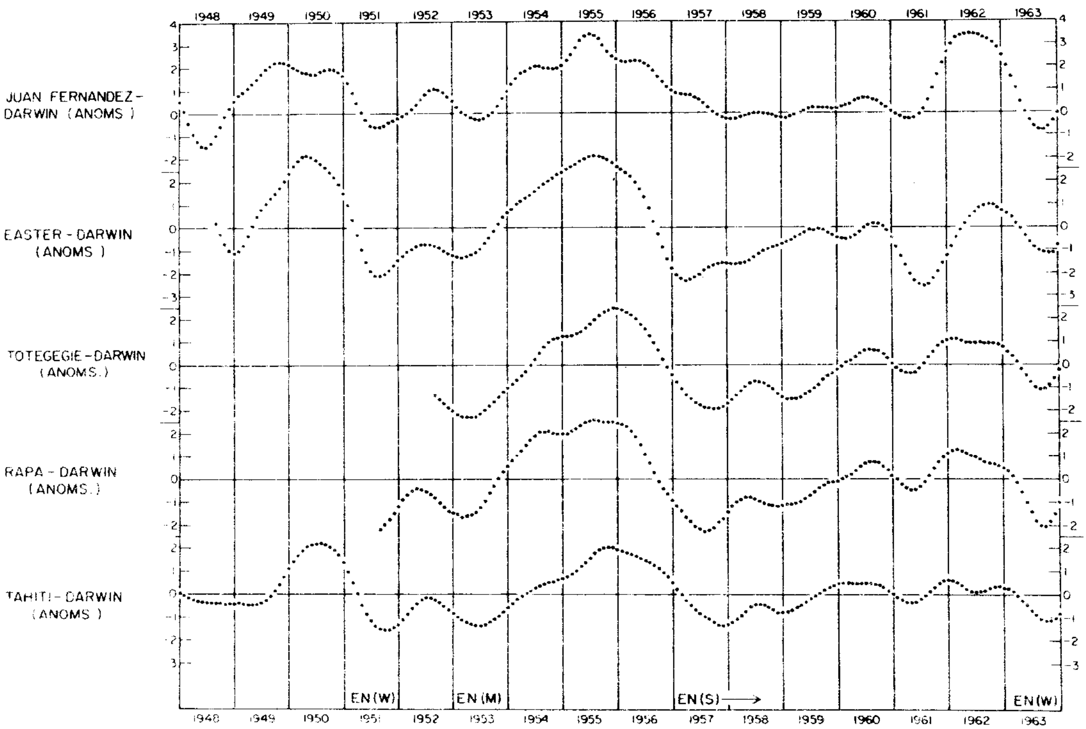

Fig. 2a. Triple 6-month running mean plots of anomalies of the difference in sea level atmospheric (mb) between Juan Fernandez I. (33°37'S, 78°50'W) and Darwin, Australia (12°26'S, 130°52'E), between Easter I. (27°10'S, 109°26'W) and Darwin, between Totegegie (23°06'S, 134°52'W) (Gambier Is.) and Darwin, between Rapa (27°37'S, 144°20'W) (Austral Is.) and Darwin and between Tahiti (17°33'S, 149°37'W) (Society Is.) and Darwin for 1948-63. El Niño type events (EN) are indicated as strong (S) moderate (M), and weak or very weak (W) in intensity.

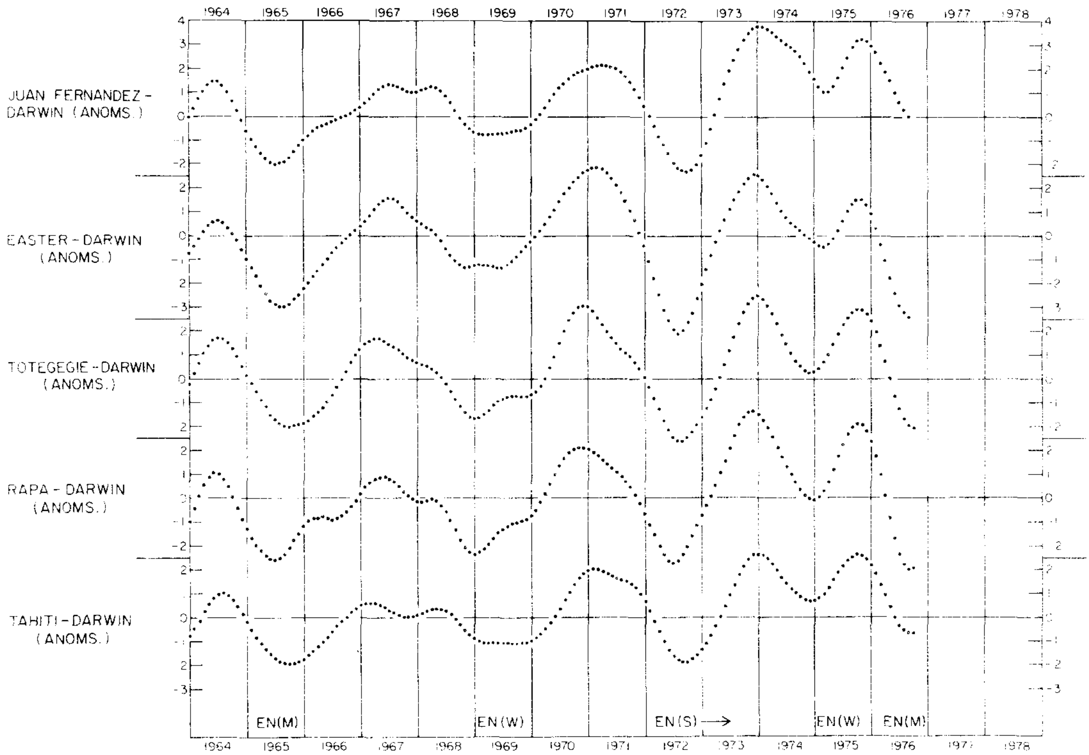

Fig. 2b. Triple 6-month running mean plots of anomalies of the difference in sea level atmospheric pressure (mb) between Juan Fernandez I. and Darwin, between Easter I. and Darwin, between Totegegie and Darwin, between Rapa and Darwin and between Tahiti and Darwin for 1964-76. El Niño type events (EN) are indicated as strong (S), moderate (M), and weak or very weak (W) in intensity.

Anomalies of several pressure difference indices and index components (e.g., Figs. 2a, 2b and 3) are currently being followed in time-section analyses in order to monitor the S.O. and its effects on the southeast trade systems. For most of the indices, the Darwin pressure has been used to represent the Indonesian equatorial low component; but, pressures from several sites along or near the South Pacific subtropical ridge (Juan Fernandez, Easter, Totegegie, Rapa, and Tahiti Islands) are being used, due to the particular interest in equatorial Pacific changes and El Niño occurrences. The Darwin component reflects the effects of movements and changes in intensity of the Indonesia equatorial low; whereas, the ridge components indicate changes in location and strength of the subtropical high and the subtropical area most actively affected by the S.O. One index component (located at the former Ship N position, 30°N, 140°W.) is also used to reflect those changes in the northeast Pacific subtropical high which are associated with the S.O. At times, changes in this North Pacific component are significant and infer a larger scale and/or intensity for the development under way. Fig. 3 illustrates the complementary nature of the

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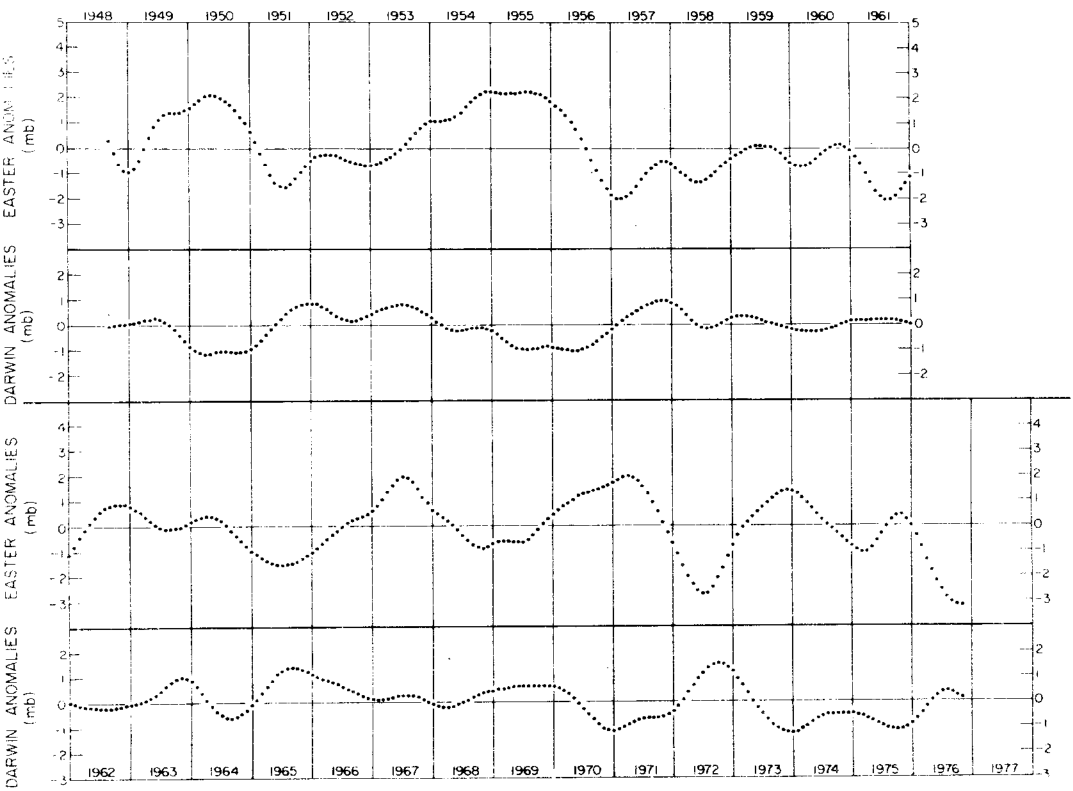

Fig. 3. Triple 6-month running mean plots of sea level atmospheric pressure anomalies (mb) for Easter Island and Darwin, Australia for 1948-1976.

component inputs to the S.O. indices. It also indicates the complementary nature of the changes taking place in the Indonesian equatorial low and the South Pacific subtropical high as result of the S.O. (Quinn, 1974). Hence, the indices are used to combine the component changes, and the trends of their anomalies with respect to time represent the S.O. However, when looking into the nature of a development and predicting its future course, it is often desirable to study both the index anomalies and the separate component inputs.

It has been found that the filtered plots of the index anomalies not only represent the variable amplitude and period of the S.O., but they also reflect the stage and intensity of the associated equatorial Pacific developments (Quinn, 1974, 1977). By being aware of the related developmental sequence leading up to the unusual equatorial condi--tions, once one determines the existing developmental stage and intensity, he can anticipate conditions that will prevail in a later stage.

THE PLOTS

Fig. 4 shows plots of monthly means as well as 3- and triple 6-month running means of the Easter-Darwin index anomalies for years leading up to the two recently ocurring strong events (the 1957 and 1972 El Niños). As we approach a pre-event peak in the index anomaly, the shorter period means become particularly important for support of event forecasts.

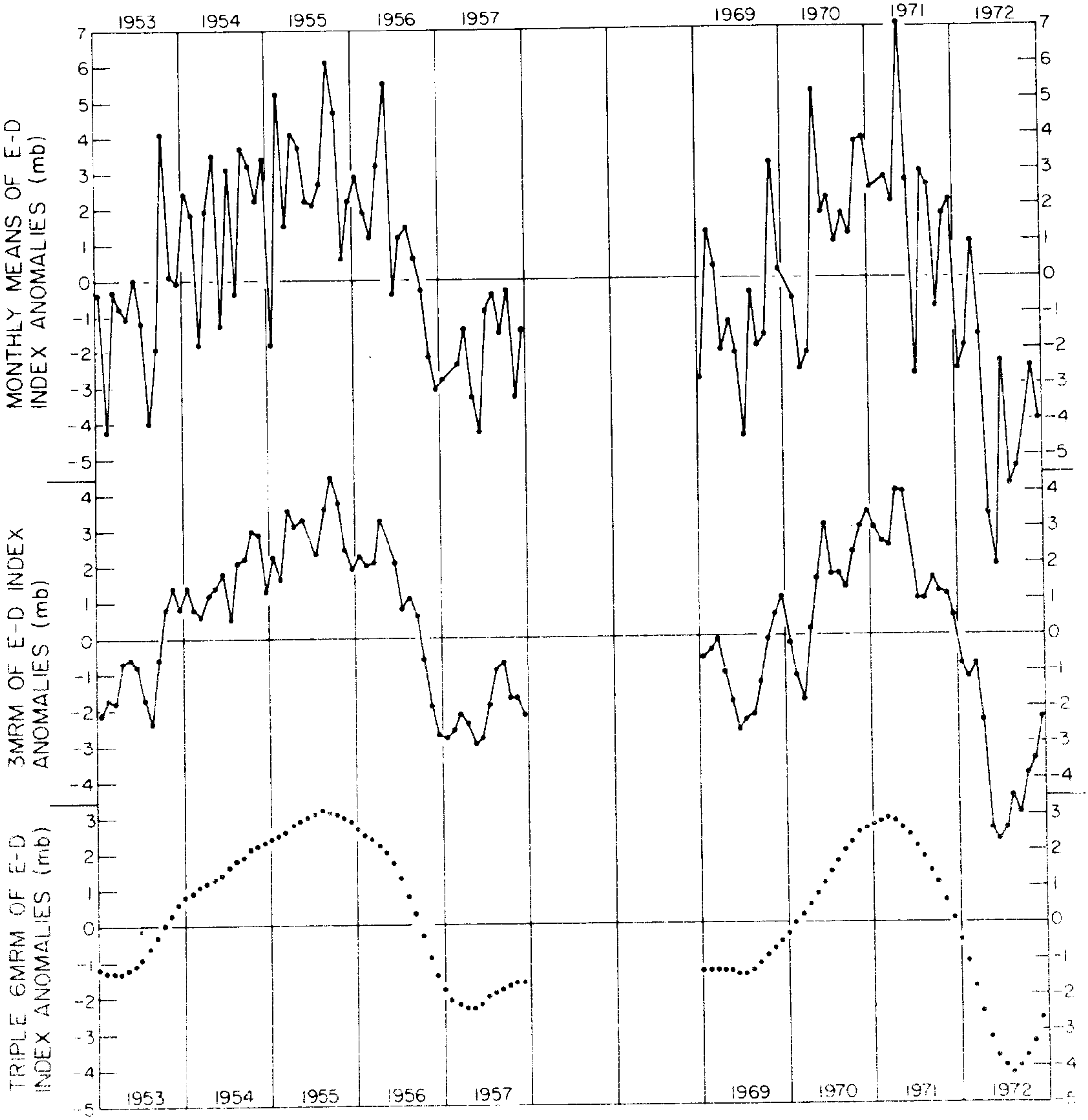

Fig. 4. Monthly mean, 3-month running mean, and triple 6-month running mean plots of anomalies of the difference in sea level atmospheric pressure (mb) between Easter I. and Darwin, Australia for 1953-57 and 1969-72.

From Figs. 2a and 2b it is apparent that the El Niño type activity occurs in conjunction with the relaxations following anti-El Niño peaks in the anomalies. However, the intensity of an event depends not only on the degree of relaxation but also on the time of year when it occurs. The stronger cases (EN (S) and EN(M)), when significant Peruvian coastal El Niños were noted, were situations where the interannual relaxation was large and indices continued to fall rapidly on through the early months of the year so as to reinforce the regular seasonal relaxation of the southeast trade system (Southern Hemisphere summer season). Cases where the interannual relaxation is too small, or it occurs too early or too late to follow on through the seasonal relaxation period, result in weaker events. The determinations of event intensities in Figs. 2a and 2b were based on degree of activity. For example, the 1957-58 and 1972-73 events were considered strong; the 1953, 1965 and 1976 events, moderate; the 1951 and 1960 events, weak; and the 1963 and 1975, events very weak.

The studies of Berlage (1957, 1966) and Troup (1965) indicated that the S.O. (through its zonal-vertical torroidal flow between the eastern and western hemispheres) affected not only the South Pacific subtropical high but also the North Pacific subtropical high region. Fig. 5 compares the Rapa-Darwin index to the Ship N-Darwin Index. (Since the loss of Ship N, data for this location is obtained from the synoptic sea level pressure analyses). The plots are correlated at 0.80, well within the 1% confidence level. From visual inspection one can see there is no consistent lead-lag relationship between the two index trends; in one case the change in trend shows up first south of the equator and in another it shows up first north of the equator; neverthless, it is evident that the two high pressure areas are being similarly affected by the S.O.

Fig. 6 shows how closely the western equatorial Pacific rainfall trend (as represented by Tarawa) relates to the Rapa-Darwin index. Although Tarawa rainfall data are used here, Quinn and Burt (1970, 1972) show that for the most part the large, long-term variations in equatorial rainfall are generally similar for equatorial Pacific stations between 155°W and 165°E.

Fig. 1. shows how the 12-month running mean plot of the Easter-Darwin index relates to the 12-month running mean plots of zonal wind components at 850 mb and 150 mb over Canton Island. It shows that when the index is high the easterly component is strong at 850 mb and the westerly

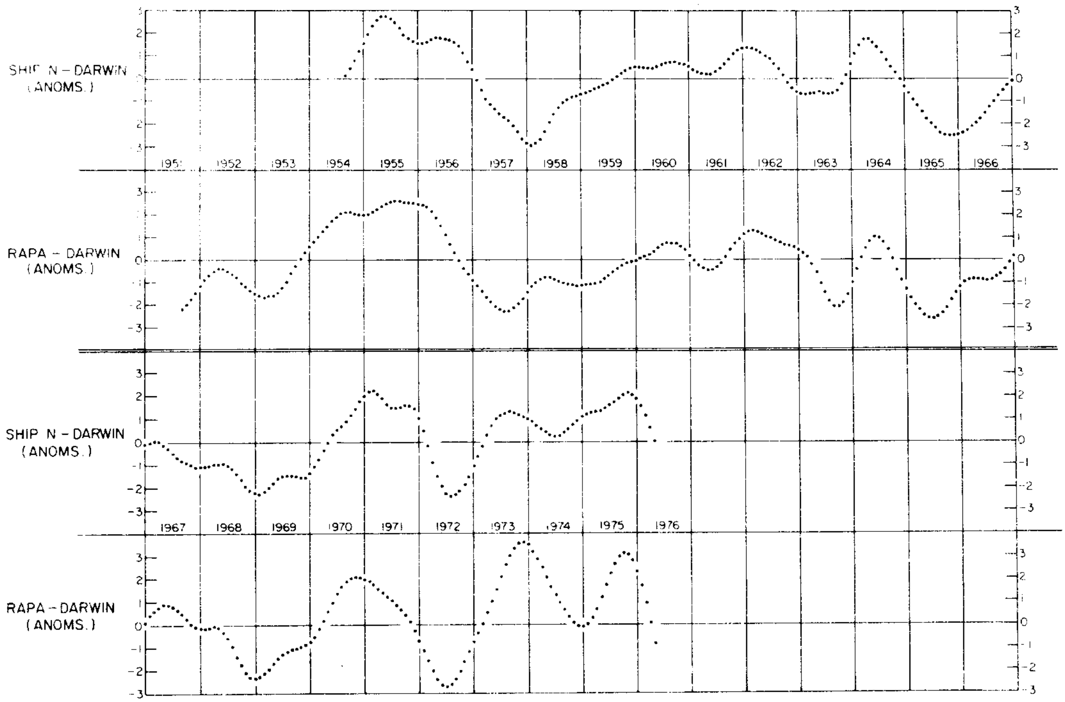

Fig. 5. Plots of triple 6-month running means of anomalies of the difference in sea level atmospheric pressure (mb) between Ship N (30°N, 140°W) and Darwin, Australia, and between Rapa (27°37'S, 144°20'W) (Austral Is.) and Darwin.

component is strong at 150 mb; and when the index is low the easterly component is weak at 850 mb (individual monthly values show reversals in direction when deep index troughs occur) and the westerly component is weak or reverses direction at 150 mb. These zonal wind fluctuations are result of the variable zonal vertical circulation of the Pacific Walker cell as it shifts in longitudinal position, extent and intensity. The resulting variations in strength of these zonal wind components at the surface (represented by 850 mb components here) significantly affect the equatorial oceanic circulation and sea surface temperatures. When southeast trades and equatorial easterlies are strong the south equatorial current is strong, equatorial upwelling isstrong, equatorial SST's are low and equatorial rainfall is bellow normal. (The equatorial dry zone is extensive.) When the southeast trades and equatorial easterlies are weak, the south equatorial current is weaker, equatorial upwelling is suppressed, equatorial SST's rise above normal and rainfall is abnormally high in the central and western equatorial Pacific,

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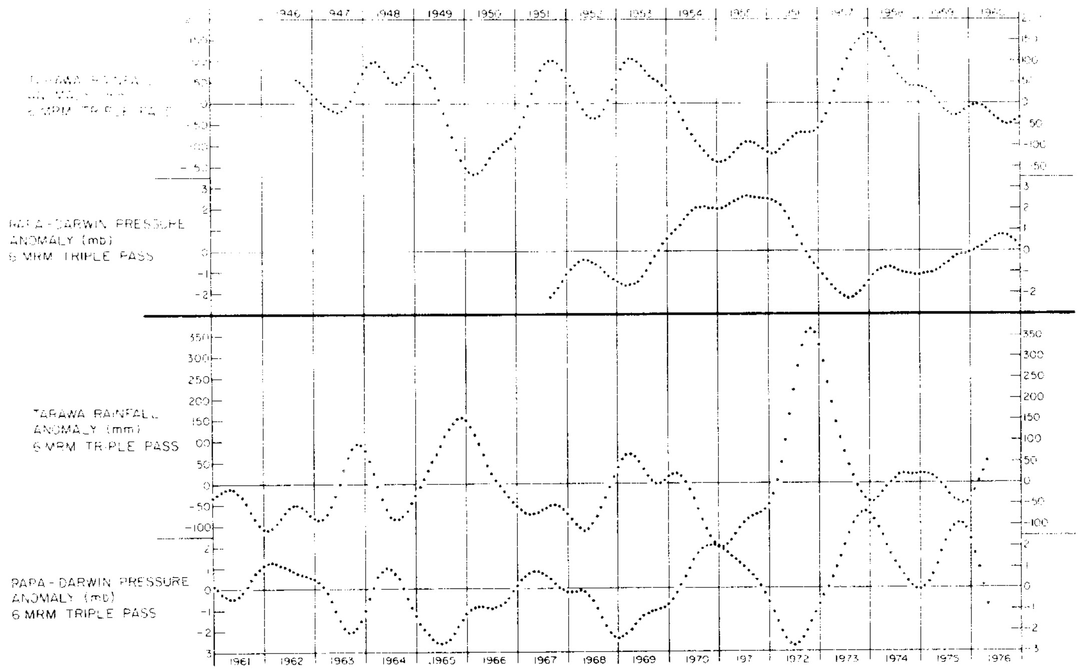

Fig. 6. Plot of triple 6-month running means of anomalies of the difference in sea level atmospheric presure (mb) between Rapa (Austral Is.) and Darwin, Australia compared to a similarly filtered plot of Tarawa (Gilbert Is.) rainfall anomalies (mm).

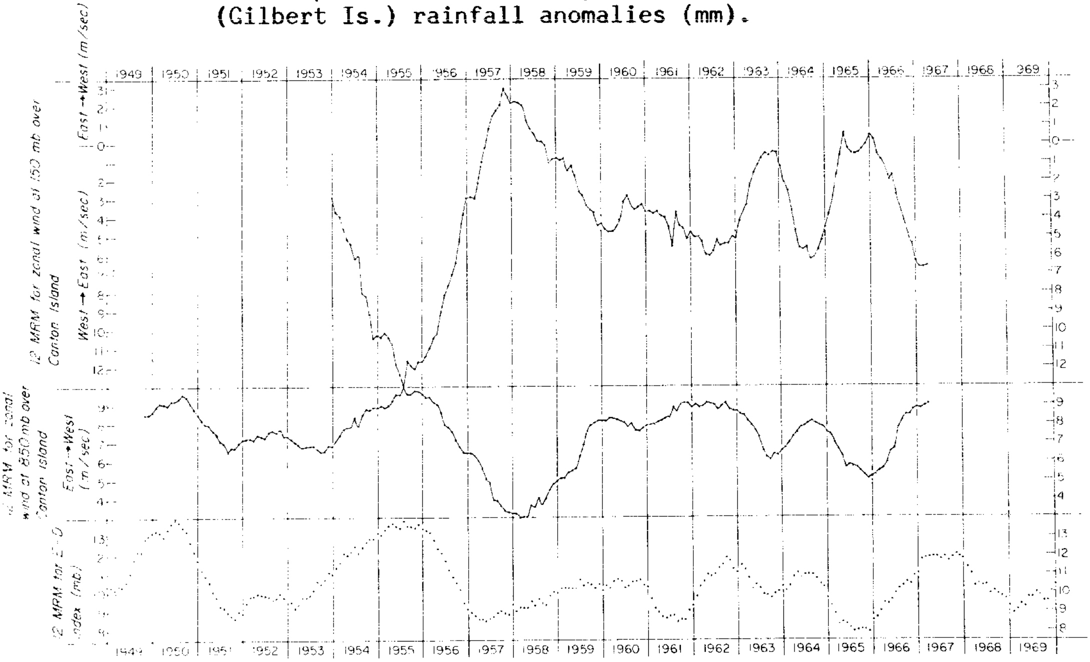

Fig. 1. The 12-month running means of the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia are compared to 12-month running means of the zonal wind components (m/sec) at the 850 mb and 150 mb levels over Canton Island.

A close relationship of fluctuations in north equatorial countercurrent transport and resulting sea surface temperature (SST anomalies off the coast of Central America illustrated in Figure 2 of Wyrtki, 1973) to the interannual variations in southeast trade strength (as reflected in the 12-month running mean trend of the S.O. index), was noted in Quinn (1974). In a recent climatological investigation of the southeast part of the North Pacific, time series plots of SST were studied for several Marsden Square (MS) quadrants in order to find particularly suitable areas for diagnosing changes associated with the El Niño type developments. Fig. 7 shows two of the quadrants selected; MS 10 (1) reflects changes taking place along the equator, and MS 10(3) reflects changes in an area affected by the north equatorial countercurrent. Fig. 8 shows how the Easter-Darwin index anomaly trend relates to SST anomaly trends for MS 10(1) and MS 10(3) when the data are subjected to the triple 6-month running mean filter. MS 10(1) is next to the equator, and when the circulation is relatively strong (S.O. index is High) it shows lower SST's due to the advection of cooler Peru current water into the area and/or equatorial upwelling; when the circulation is weak (index is low), SST's rise. MS 10(3)

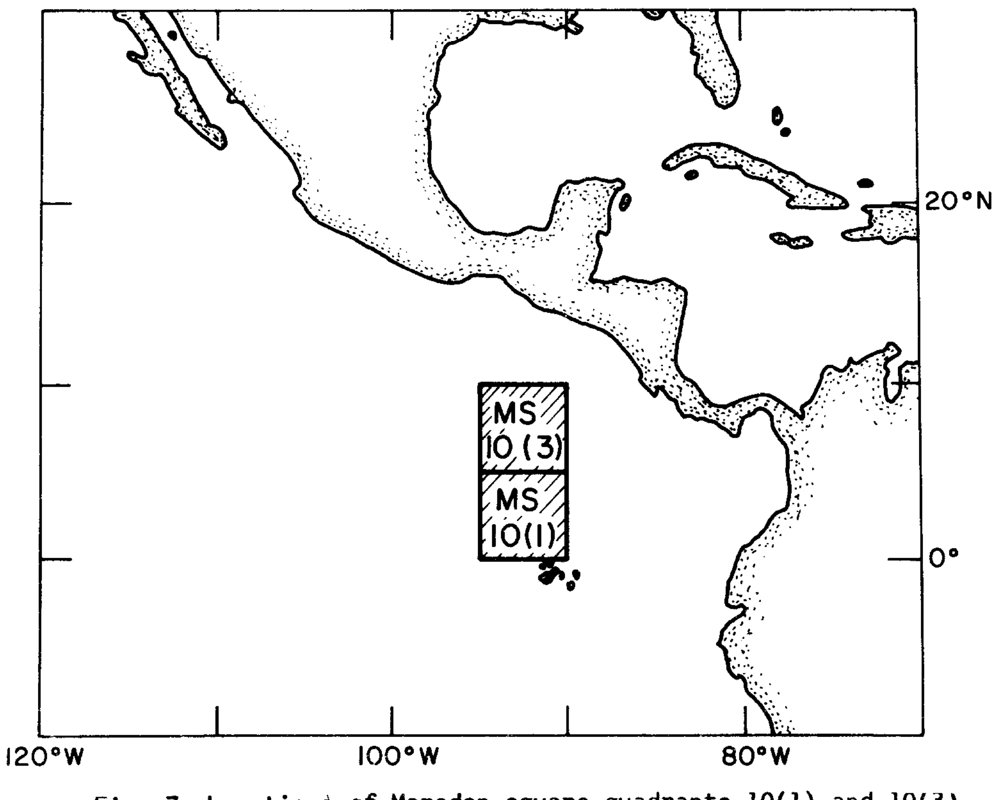

Fig. 7. Locations of Marsden square quadrants 10(1) and 10(3).

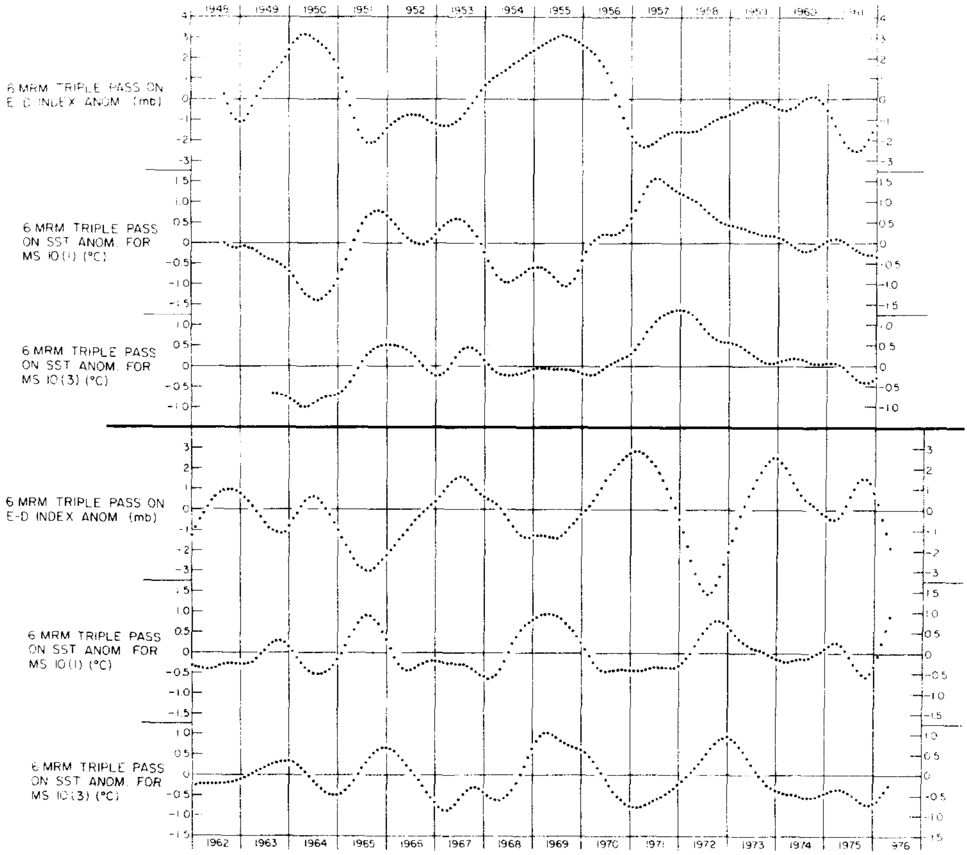

Fig. 8. Plot of triple 6-month running means of anomalies of the difference in sea level atmospheric pressure (mb) between Easter I. and Darwin, Australia compared to similarly filtered plots of sea surface temperature anomalies (°C) for Marsden squares 10(1) and 10(3).

SST's reflect changes in the north equatorial countercurrent transport discussed early in the paragraph.

Three-month running mean plots of the index anomalies and the SST anomalies for MS 10(1) (e.g., Fig. 9) become particularly useful to the forecast process between 18 and 3 months prior to the onset of El Niño. However, they should also be followed closely during the course of an event to determine whether a subsequent secondary trough in index is likely or a persistent recovery from the initial event is probable.

Events of significant magnitude are reflected in both the index and SST anomaly trends. The SST trends are particularly useful for confirming and evaluating the significance of indications from the circulation indices. One would have to look long and hard to find another illustration which so vividly shows the ocean-atmosphere coupling involved in the anomaluos equatorial Pacific activity as Fig. 8 does.

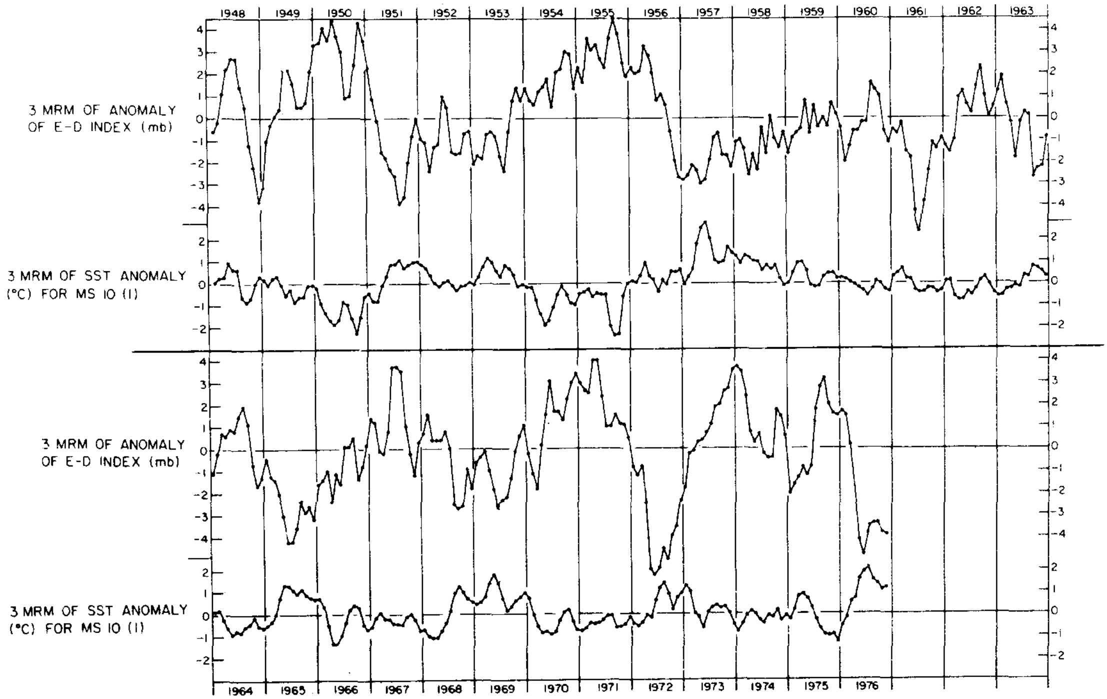

Fig. 9. Plot of 3-month running means of anomalies of the difference in sea level atmospheric pressure (mb) between Easter I. and Darwin, Australia compared to a similarly filtered plot of sea surface temperature anomalies (°C) for Marsden Square 10(1).

STATISTICAL FINDINGS

Figs. 2a and 2b show the general compatibility between index trends, and Fig. 3 shows the complementary nature of the component trends that cause the index features. Correlation coefficients between the index components at various lags are shown in Table 1 and reveal the high degree of correlation between the complementary changes taking place in the components. The highest negative correlations occur when the equatorial low component (Darwin) lags subtropical high components (Juan Fernandez Easter, Totegegie and Rapa) of the indices by 2-5 months. Changes in the Rapa component generally show up further in advance (5 months) of the complementary Darwin changes than do the other ridge component changes (2-4 months).

Tables 2, 3, 4 and 5 show the correlation coefficient at a number of lags between the indices and rainfall for several island sites in the equatorial Pacific (Tarawa at 1°21'N, 172°56'E; Washington at 4°43'N, 160°25'W; Ocean at 0°52'S, 169°35'E; Fanning at 3°55'N, 159°23'W);

and the high degrees of correlation are readily apparent. The highest negative correlations are noted when the rainfall lags behind the pressure values. The changes

Table 1. Lag correlation coefficients between pressure at ridge sites (Juan Fernandez, Easter, Totegegie, Rapa) and Darwin (considering 12-month running means).

Lag in Months	Juan Fernandez and Darwin	Easter and Darwin	Totegegie and Darwin	Rapa and Darwin
-1 (Darwin ahead of ridge site)	-.463	-.593	-.613	-.495
0 (no lag)	-.478	-.653	-.656	-.586
1 (ridge site ahead of Darwin)	-.494	-.703	-.686	-.663
2	-.504	-.741	-.701	-.730
3	-.508	-.758	-.699	-.778
4	-.504	-.759	-.682	-.809
5	-.493	-.744	-.652	-.825
6	-.473	-.713	-.604	-.819
7				-.795
Period of record	1911-75	1948-75	1952-75	1951-75

Table 2. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegie-Darwin, Rapa-Darwin) and Tarawa rainfall (considering 12-month running means).

Lag in Months	JF-D Index and Tarawa Rainfall	E-D Index and Tarawa Rainfall	T-D Index and Tarawa Rainfall	R-D Index and Tarawa Rainfall
-1 (rain ahead of pressure)	-.664	-.682	-.675	-.550
0 (no lag)	-.702	-.731	-.722	-.619
1 (pressure ahead of rain)	-.722	-.765	-.752	-.676
2	-.723	-.780	-.762	-.714
3	-.707	-.776	-.751	-.733
4	-.674	-.754	-.720	-.732
5	-.626		-.670	
6	-.566	-.655	-.605	-.677
Period of record	1948-75	1948-75	1952-75	1951-75

in the Rapa index show the greatest lead time over rainfall changes, and generally lead rainfall by 3-4 months at the 4 stations studied here.

Table 6 shows the lag correlation coefficients between index and SST anomalies. Changes show up about a month earlier in the index anomaly trend than they do in the MS 10(1) SST anomaly trend and about three months earlier than in the MS 10(3) SST anomaly trend.

Table 3. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegie-Darwin, Rapa-Darwin) and Washington Island rainfall (considering 12-month running means).

Lag in Months	JF-D Index and Wash. Rainfall	E-D Index and Wash. Rainfall	T-D Index and Wash. Rainfall	R-D Index and Wash. Rainfall
-1 (rain ahead of pressure)	-.627	-.663	-.671	-.661
0 (no lag)	-.651	-.708	-.714	-.667
1 (pressure ahead of rain)	-.660	-.740	-.742	-.725
2	-.655	-.754	-.752	-.764
3	-.631	-.751	-.741	-.784
4	-.593	-.733	-.713	-.783
5	-.545		-.673	-.771
6	-.504	-.658	-.618	-.739
Period of record	1946-73	1948-73	1952-73	1951-73

Table 4. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegie-Darwin, Rapa-Darwin) and Ocean Island rainfall considering 12-month running means.

Lag in Months	JF-D Index and Ocean Rainfall	E-D Index and Ocean Rainfall	T-D Index and Ocean Rainfall	R-D Index and Ocean Rainfall
-3	-.713	-.621		-.574
-2			-.773	
-1 (rain ahead of pressure)	-.752	-.706	-.804	-.696
0 (no lag)	-.756	-.732	-.823	-.744
1 (pressure ahead of rain)	-.749	-.744	-.825	-.775
2	-.733	-.743	-.811	-.794
3	-.707	-.727	-.781	-.798
4				-.789
6	-.568	-.599	-.608	-.727
Period of record	1911-70	1948-70	1952-70	1951-70

DISCUSSION

The ongoing study of index and index component anomaly trends in relation to El Niño type event occurrences of various intensities has been projected over a period in excess of a century in length, and it substantiates the preevent index anomaly peak as an excellent predictor for such activity; this is particularly so when all indices clearly show the same trend and a corroborative equatorial SST anomaly trend is evident.

Table 5. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegie-Darwin, Rapa-Darwin) and Fanning Island rainfall considering 12-month running means.

Lag in Months	Jf-D Index and Fanning Rainfall	E-D Index and Fanning Rainfall	T-D Index and Fanning Rainfall	R-D Index and Fanning Rainfall
-2	-.556	-.603	-.634	-.501
-1 (rain ahead of pressure)	-.585	-.658	-.690	-.574
0 (no lag)	-.602	-.704	-.730	-.639
1 (pressure ahead of rain)	-.606	-.734	-.755	-.691
2	-.595	-.747	-.762	-.727
3	-.570	-.743	-.749	-.749
4	-.536	-.726	-.721	-.756
5	-.491	-.695	-.680	-.750
6	-.436	-.651	-.624	-.726
Period of record	1922-73	1948-73	1952-73	1951-73

Table 6. Lag correlation coefficients between Easter-Darwin (E-D) index anomalies and sea surface temperature (SST) anomalies for Marsden Square (MS) 10(1) and Marsden Square 10(3).

Lag in Months	E-D index and SST for MS 10(1)	E-D index and SST for MS 10(3)
-2	-0.693	
-1 (index lags SST)	-0.732	-0.588
0 (no lag)	-0.755	-0.636
1 (index leads SST)	-0.761	-0.672
2	-0.748	-0.694
3	-0.717	-0.702
4	-0.668	-0.693
5		-0.668
Period of record	1948-76	1949-76

It also appeared that this monitoring and prediction technique could be applied to the anti-El Niño condition. In Quinn and Burt (1972) it was noted that persistently high Easter-Darwin pressuré differences represented the extensive unusually dry equatorial Pacific conditions and several examples were cited where this anomalous extreme prevailed over periods 18 months to three years in length. In this case, one can again follow the trends in index anomalies to determine what is taking place; and when the 3-month and triple 6-month running mean plots show that a significant positive anomaly is setting in, it indicates that a strengthening southeast trade system is setting in and that widespread upwelling and anomalously low sea temperatures are in general returning to the equatorial Pacific and the northern coastal region of western South America. The heighth and breadth of the index anomaly peak give an estimate of the degree and time span respectively of this anti-El Niño condition. Persistence-type outlooks might be more appropriate for activity of this nature since it will often persist for periods in the 1-3 year time range. Running means of anomalies of all indices and equatorial SST's along with the monthly SST analyses over the tropical Pacific (U.S. Department of Commmerce, 1972-77) will be excellent tools for monitoring such developments and issuing the outlooks. An approaching deep trough in the index anomalies signals the end to the anti-El Niño type condition.

The weaker events are included in this discussion because the difference between weaker and stronger events depends not only on the height of preevent index peaks and the subsequent degree of relaxation but also on the timing of this interannual relaxation. If the latter is in phase with the regular annual relaxation, a moderate or strong event is likely to occur; if they are out of phase, a weak or very weak event is likely. We know when the annual relaxation takes place (Southern Hemisphere summer and early fall); and, in order to forecast whether or not the interannual relaxation is likely to be in phase with it, we must arrive at a rough estimate of the S.O. period. Ordinarily the rise from an earlier trogh to the pre-event peak takes longer than the fall to the subsequent trough; so, we can double the time it takes to rise to the pre-event peak and then substract a few months to arrive at a rough estimate of the S.O. period. Knowing this, if the relaxation potential (from pre-event peak to projected subsequent trough) is large and the index can be expected to fall rapidly on through the early months of the following year, we would expect a significant event to occur.

The relaxation time between the index anomaly peak and the onset of El Niño in a single stage development (such as the cases leading up to the 1957 and 1972 El Niños) usually allows one to put out a prediction about 3-9 months in advance of an event onset. However, cases have been noted where the relaxation from a large pre-event index anomaly peak involved more than a single stage process (Quinn and Zopf, 1977). In several cases of this nature there was the initial fall from a large pre-event (primary) peak which was not fully in phase with the seasonal relaxation and the result was a relatively weak event; then there was a rise to a smaller secondary peak followed by relaxation to a secondary trough which was in phase with the seasonal relaxation and resulted in a stronger event. Developments of this nature can be noted in 1950-53, 1962-65 and 1973-76 (Figs. 2a and 2b). Pre-event peaks ocurred in 1950, 1962, and late 1973- early 1974. The first relaxation troughs following these peaks occurred in late 1951, late 1963, and late 1974-early 1975, and weak or very weak events resulted in all three cases. There were rises to smaller secondary peaks by mid-1952, mid-1964 and late 1975, followed by falls to troughs by early to mid-1953, mid-1965, and mid-1976, resulting in moderate El Niños in all three cases. In cases of this type, forecast lead times for component events will often be greatly reduced (to 1-6 months in advance), depending on the circumstances involved, unless historical analogies lead to pattern recognition as the situation evolves; e.g., the 1962-66 trend was selected as an analogue for the 1973-77 trend in 1975 (Quinn, 1977).

TEST OF METHOD

A forecast for a weak event in early 1975 was given at the fall 1974 Eastern Pacific Oceanic Conference which resulted in the El Niño Watch cruises (Wyrtki et al., 1976). The event occurred about as forecast with regard to time of occurrence and intensity in the region between the Galapagos and western South America, but associated activity in the western equatorial Pacific (Fig. 6) was much earlier and weaker than expected. Nevertheless, the associated index trends appear to accurately represent what actually happened (Fig. 2b).

In summer 1975 an outlook for El Niño type activity in 1976 was prepared. The outlook was given at the October 1975 Eastern Pacific Oceanic Conference and at several subsequent meetings, workshops and seminars. It called for a rise from the shallow early 1975 trough in the 12-month running mean plot of the Easter-Darwin index to a small peak by the mid to latter part of 1975 and then to fall off to a deeper trough in 1976. The analogue selected for this development was the 1964-65 situation. (There was a rise from a shallow index trough in late 1963 to a small peak in mid 1964, then a fall to a deep trough in 1965 when El Niño occurred.) Heavy western equatorial Pacific precipitation was called for in the latter half of 1976-early 1977.

The expected small peak in the interannual index anomaly trends occurred in late 1975; then there was a falling trend to the trough near mid-1976. (See Figs. 2b and 9.) Figs. 8 and 9 show the corrobarative rise in SST anomalies at MS 10(1) and MS 10(3) as the index falls. Fig. 10 shows the positive SST anomalies off the coast of Peru and southern Ecuador extending westward over the equatorial Pacific. Table 7 shows the SST and SST anomalies for 2 stations along the coast of Peru during 1975-76, and Table 8 shows precipitation at Guayaquil during the last three events. (The 1972-73 case is considered to be strong, 1975 very weak, and 1976 moderate in intensity). Tarawa data has been used to represent the western equatorial Pacific rainfall; and the triple 6-month running mean trend on the rainfall anomalies clearly shows we are approaching a significant rainfall peak (Fig. 6). For the period April-December 1976 the rainfall

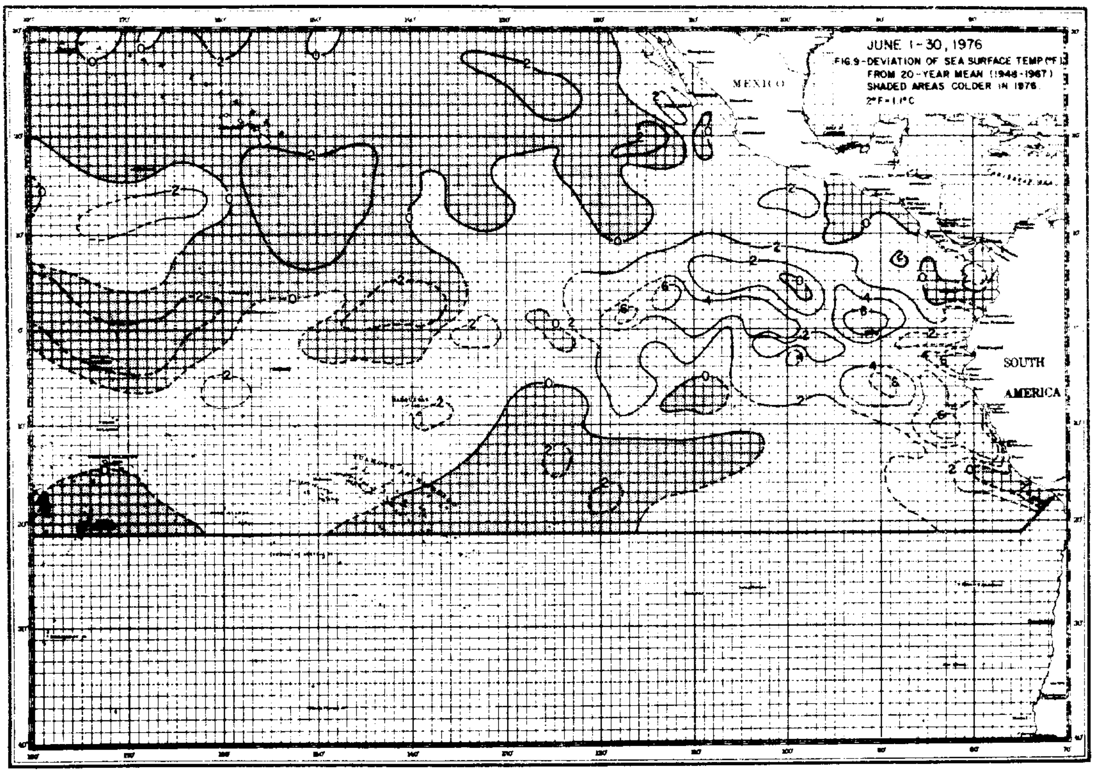

Fig. 10. Sea Surface temperature anomalies (°F) (deviations from 20-year mean, 1948-67) for June, 1976 (from U.S. Department of Commerce, 1976).

Table 7. Monthly mean sea surface temperatures and anomalies of temperature for Talara and Chimbote, Peru. 1975-1976.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Talara (4° 34'S, 81° 15'W)												
1975	16.3 -4.2	18.6 -3.2	22.4 +1.0	21.5 +1.3	19.8 +0.6	17.8 -0.5	18.0 +0.2	17.7 +0.1	18.1 +0.7	18.1 +0.4	16.2 -1.8	17.7 -0.6
1976	20.5 ±0.0	24.4 +2.6	23.6 +2.2	20.5 +0.3	20.5 +1.3	21.1 +2.8	20.8 +3.0	20.0 +2.4	18.8 +1.4	18.5 +0.8		
Chimbote (9° 10'S, 78° 31'W)												
1975	20.5 -0.2	21.0 -0.8	24.2 +2.0	21.2 +0.3	21.1 +1.4	18.7 +0.1	17.6 -0.2	17.0 -0.6	16.8 -0.4	17.0 -1.0	17.3 -1.4	18.0 -1.6
1976	18.5 -2.2	21.8 ±0.0	23.5 +1.3	21.3 +0.4	21.1 +1.4	21.0 +2.4	20.2 +2.4	19.8 +2.2	19.0 +1.8	19.4 +1.4		

Table 8. Rainfall at Guayaquil, Ecuador (02°10'S, 79°50'W) (in mm) for the indicated months.

	1972		1973		1975		1976	
Months	Total	Departure	Total	Departure	Total	Departure	Total	Departure
January	220	+ 9	701	+490	221	+ 10	417	+206
February	330	+ 45	210	- 75	487	+202	586	+301
March	407	+115	492	+200	607	+315	450	+158
April	143	- 62	181	- 24	202	- 3	182	- 23
May	35	- 19	136	+ 82	2	- 52	144	+ 90
June	152	+141	3	- 8	4	- 7	10	- 1
December	85	+ 57						

was 1130 mm above normal and it is expected that a few more months of this heavy rainfall will occur in early 1977. Evidence indicates the forecast for the 1976 event was accurate as to time of occurence and intensity (similar to the selected 1965 analogue).

In the summer of 1976, the further outlook to CUEA Peru called a hold-over effect on the 1976 positive SST anomalies causing warm SST's along the Peruvian coast December 1976-February 1977 with a return to near normal coastal SST's by March or April 1977. The analogue given for the 1976-77 holdover effect was the 1965-66 situation; however, the 1976 onset was a month or two later (than in 1965) and the lag effect in 1977 was also expected to extend for a month or two later (than in 1966).

PRACTICAL ASPECTS

The Peruvian anchoveta fishery, which ordinarily provides over half the world's supply of fishmeal, has become an increasingly important global resource over the past 15 years; therefore, anything that affects the output of this fishery is of world-wide significance. Johnson (1976) noted that the catch in this fishery declined from a high of over 12 million tons (about 1/5 the total world catch for all fish) in 1970 to about 2 million tons in 1973. Although overfishing in 1970-71 may have contributed heavily to this decrease in anchoveta catch, the strong El Niño of 1972-73 was undoubtedly also a major cause for this precipitous decline in catch (Fig. 11).. However, the 1975 catch was still only about 25% of the record 1970 catch, the 1976 catch remained low, and so far it appears that the 1977 catch will continue to be low, indicating the later unfavorable

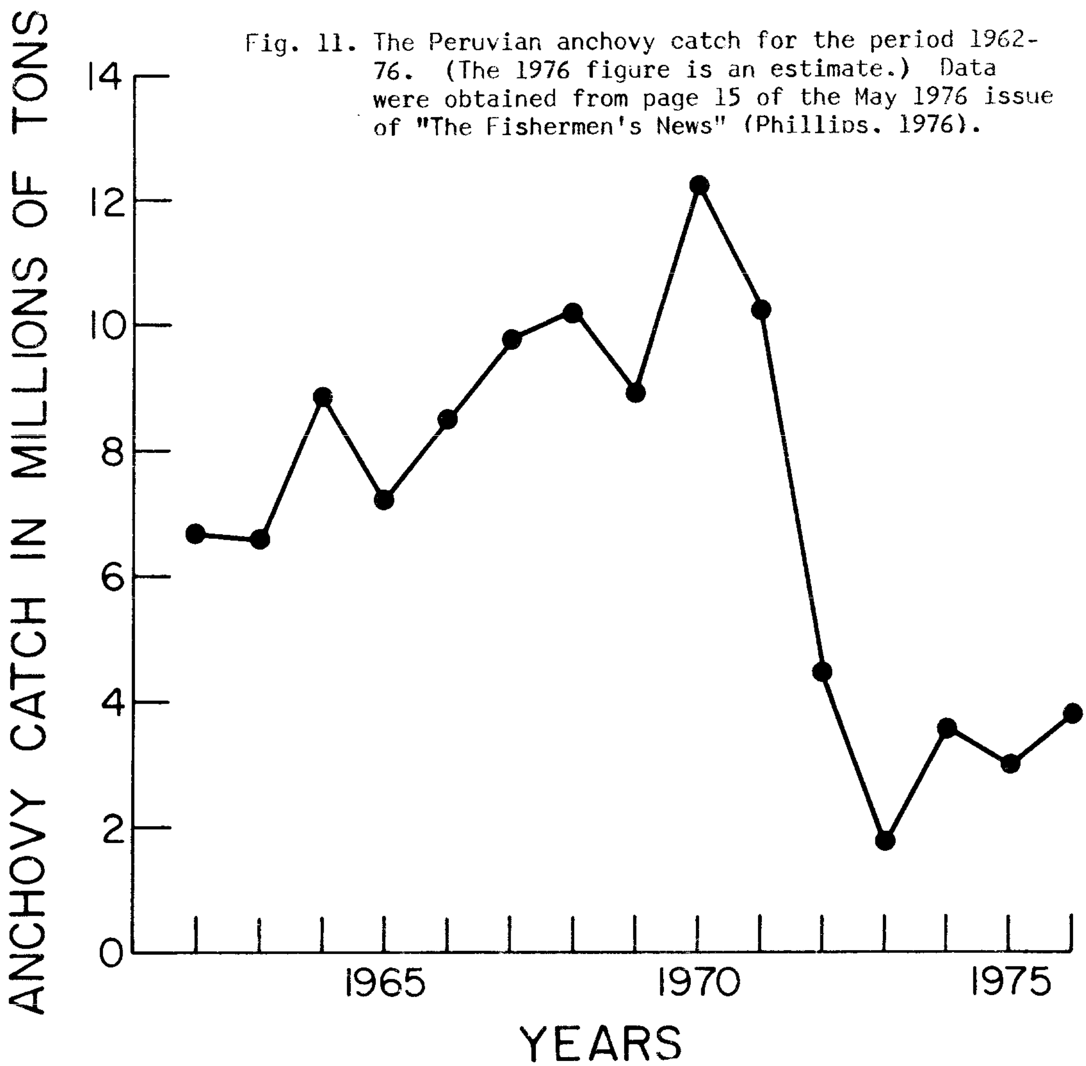

Fig. 11. The Peruvian anchovy catch for the period 1962-76. (The 1976 figure is an estimate.) Data were obtained from page 15 of the May 1976 issue of "The Fishermen's News" (Phillips, 1976).

environmental conditions (in lesser degree) have probably contributed to a delay in recuperation of the fishery. Although the monitoring and prediction approach discussed here applies only to the physical environmental aspects of the fishery it should prove advantageous in the management of this important fishery to closely follow the nature, extent, and expected changes in the El Niño and anti-El Niño developments through the use of the index anomaly plots. In the past, we often found ourselves well into an El Niño before it was clearly understood that one was taking place therefore, before we could estimate how strong and extensive it was likely to be.

Members of the Inter-American Tropical Tuna Commission have found significant correlations between the S.O. index trend and the skipjack tuna catch in the low latitudes of the eastern Pacific.

There is a high correlation between the occurrence of El Niño type activity (as indicated by the S.O. index anomalies) and east monsoon droughts in Indonesia. There is also a significant correlation between this activity and the droughts over northeast Brazil. Global effects of the S.O. are discussed by Berlage (1957, 1966). It is the opinion of the author that the more persistent interannual changes (of radical nature) in large-scale weather conditions over various parts of the globe will tie in with either the El Niño or anti-El Niño extremes (as depicted in the S.O. index anomaly trends) rather consistently; and that it may often be possible to foreshadow such changes through the use of the index anomaly trends and other closely allied indicators.

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