HISTORICAL TRENDS AND STATISTICS OF THE SOUTHERN OSCILLATION, EL NINO, AND INDONESIAN DROUGHTS

WILLIAM H. QUINN, DAVID O. ZOPF, KENT S. SHORT, AND RICHARD T. W. KUO YANG[1]

ABSTRACT

A 116-yr Southern Oscillation index record was used in conjunction with environmental data and reports from various authors on disturbances to the anchoveta fishery, marine bird life, etc. off the Peruvian coast, to infer the occurrence of past El Niño type events and their intensities. The resulting long time history substantiates our earlier report that certain Southern Oscillation index features are excellent precursors of subsequent El Niño type events. We suggest that statistics derived from this time history could be useful in the management of the Peruvian anchoveta fishery and for providing long-range outlooks on El Niño type activity.

Anomalously heavy precipitation in the central and western equatorial Pacific and Indonesian droughts were closely associated with El Niño type events.

In recent years the world demand for fishmeal has continued to increase, as has the world population. The Peruvian anchoveta fishery, which ordinarily provides over half the world's supply of fishmeal, has become a critical resource; and anything that affects the output of this fishery is of world-wide significance. Johnson and Seckel (1977) reported that the catch in this fishery declined from a high of over 12 million tons (about 1/5 of the total world catch of all fish) in 1970 to about 2 million tons in 1973. Although overfishing in 1970-71 may have contributed heavily to this decrease in anchovy catch, the strong El Niño of 1972-73 was undoubtedly also a major cause for the precipitous decline in catch (Figure 1). However, the 1975 catch was still only about 25% of the record 1970 catch, the 1976 catch remained low, and the target for 1977 has now been reduced to 2 million tons of anchoveta and other fish such as sardines and hake. Apparently the unfavorable environmental conditions caused by the very weak event of early 1975 and the moderate El Niño of 1976-77 have not only contributed to the delay in recuperation of the fishery, but also are causing a further degradation of it. In early October 1977 the Fisheries Ministry of Peru said (according to a Reuters wire service report) that the stocks were believed to be so low that the anchoveta fishing, which was suspended in May 1977, would not resume until the second half of 1978.

Statistical information pertaining to the historical occurrence of El Niño type events is presented to: 1) aid in long-term fishery assessment (Peruvian anchoveta fishery); 2) provide a basis for speculative long-range outlooks on event occurrence (beyond a year in advance); and 3) guide long-range predictions (1-12 mo in advance). Relationships between El Niño type events, Southern Oscillation index trends, index component trends, and Indonesian droughts are shown and discussed.

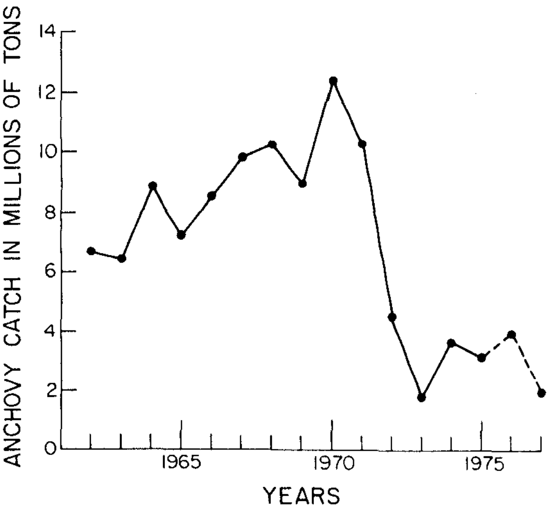

FIGURE 1.—The Peruvian anchovy catch for the period 1962-76 as obtained from the Industrial Fishery Products Market Review and Outlook for June 1977 (National Marine Fisheries Service 1977). The 1976 figure is a preliminary value. The 1977 figure is the Peruvian Fishery Ministry target value for anchovies and other species such as sardine and hake, as reported by Reuters wire service on 19 October 1977.

---

[1] School of Oceanography, Oregon State University, Corvallis, OR 97331.

Manuscript accepted January 1978.

Wooster (1960), Idyll (1973), Miller and Laurs (1975), and Caviedes (1975) furnished background information on El Niño; Quinn (1974) discussed monitoring and prediction; and Berlage (1957, 1966), Troup (1965), and Quinn (1971, 1976) provided background information on the Southern Oscillation and how it relates to phenomena discussed in this paper.

Definitions for terms frequently used in this paper follow: The Southern Oscillation was originally identified by Walker (1924). It was loosely defined by Berlage (1966) as a fluctuation in the intensity of the intertropical general atmospheric and hydrospheric circulation over the Indo-Pacific region. The fluctuation is dominated by an exchange of air between the South Pacific subtropical high and the Indonesian equatorial low. The differences in sea level atmospheric pressure between sites representing the South Pacific subtropical high and sites representing the Indonesian equatorial low are used as indices to represent the Southern Oscillation (Quinn 1974).

The El Niño type event refers to the appearance of anomalously warm sea surface temperatures and abnormally heavy rainfall in the equatorial Pacific and an invasion of anomalously warm surface water off the coast of Peru and southern Equador. This event, which is brought about by relaxation from a prolonged period of strong southeast trades, is represented by falling and low Southern Oscillation indices (Quinn 1974). The magnitude of the interannual relaxation and its timing with relation to the regular seasonal relaxation (Southern Hemisphere summer) appear to determine the strength of the El Niño invasion along the Peruvian coast. Heavy central and western equatorial Pacific precipitation usually starts a few or more months after El Niño initially sets in, but this may not always be the case. By using the term "El Niño type" we avoid arguments over what is and what is not an El Niño and can then account for events that evolve in a similar manner but vary in timing, intensity, and extent.

The anti-El Niño refers to the contrasting situation when a strengthening and strong southeast trade system prevails (represented by rapidly rising and high Southern Oscillation indices). At such times we can expect strong upwelling (due to the divergent equatorial flow under the influence of strong southeast trades and equatorial easterlies), anomalously low sea surface temperatures, and abnormally low amounts of rainfall over the equatorial Pacific. Also, off the coast of Peru, we find strong coastal upwelling, low sea surface temperatures, lower than average sea level, and generally favorable physical environmental conditions for biological productivity (due to the upwelling of nutrient-rich water from lower levels).

METHODS

Data Processing

Atmospheric pressure and much of the rainfall data before 1961 were obtained from the World Weather Records (Clayton 1927, 1934; Clayton and Clayton 1947; U.S. Department of Commerce 1959, 1968). Data for 1961-76 were obtained from Monthly Climatic Data for the World (U.S. Department of Commerce 1961-76). We were primarily interested in the large-scale interannual changes. Therefore, we eliminated regular oscillations from the data, such as the diurnal cycle, by using monthly mean values (or monthly amounts, for rainfall), and the seasonal or annual cycle by subtracting long-term average or normal monthly values from the actual monthly values. Data so processed show no particular regularity and no apparent cycle (Panofsky and Brier 1965). The filtered and unfiltered monthly anomalies were used to detect, identify, and evaluate any unusual changes that took place.

Our interests were focused on fluctuations of an intermediate scale (Southern Oscillation), with periods ranging between about 1 and 6 yr. The remaining short period fluctuations in the anomalies were eliminated by filtering with a low pass filter. At the other end of the time scale, there may be a gradual change of the variate over many years which is part of oscillations that are long compared with the record. These extremely long, gradual changes were not a factor in our study.

In earlier papers (e.g., Quinn 1974, 1976) the 12-mo running mean was applied directly to monthly values of pressure, pressure differences (indices), rainfall, etc. as a low pass filter. This filter not only smoothed the data to some extent but also eliminated the annual cycle. To more clearly define the interannual fluctuations (Southern Oscillation), we recently switched to the use of the triple 6-mo running mean filter on the monthly anomalies, which requires three successive passes of the 6-mo running mean over the data. It results in smoother plots and more clearly defined peaks and troughs, which are of particular assistance in establishing long-term trends. The loss of 3 mo time with each application of the 6-mo running mean is a drawback to its use in forecasting, so we also use the 3-mo running mean and monthly plots of anomalies for locating inflection points and evaluating trends on a more immediate basis in support of forecasts.

Anomaly trends for several indices were maintained in time section plots (Figure 2a, b) to evaluate the Southern Oscillation and its expected effects on the southeast trade system. Although these limited records (25-30 yr) clearly showed the close association of low indices with El Niño type activity, and high indices with anti-El Niño conditions (Quinn 1974, 1976), it was essential to extend the study over a much longer period to determine how frequently these climatic extremes occurred

The World Weather Records were searched for the longest and most complete atmospheric pressure records which could be used to extend our study into the past. Madras, India (1841-1976); Bombay, India (1847-1976); Djakarta, Indonesia (1866-1974); and Darwin, Australia (1882-1976) were within the area noted by Berlage (1957, 1966) to reflect Southern Oscillation-related pressure changes in the Indonesian equatorial low pressure cell. Santiago, Chile (1861-1976) had the only long pressure record that could possibly represent Southern Oscillation-related pressure changes affecting the South Pacific subtropical high pressure cell. Although Santiago is generally to the east of the subtropical high, it does reflect these pressure changes (Berlage 1957, 1966).

Correlations were run between the Tahiti-Darwin index and the Santiago-Darwin index on data for 1935-76 to further substantiate use of the Santiago-Darwin index for representing the Southern Oscillation and related El Niño type activity. The Tahiti-Darwin index was used for this comparison since it and the Santiago-Darwin index showed similar amplitudes in their interannual fluctuations. The similarity was due to the fact that Tahiti and Santiago are separated by analogous distances from the usual core of activity in the subtropical high (see fig. 10 in Berlage 1957, or fig. 10 in Bjerknes 1969). At zero lag the correlation coefficient between the two indices was 0.88. The maximum correlation was 0.89 when the Tahiti-Darwin index led the Santiago-Darwin index by 1 mo.

Figure 3a-h shows the triple 6-mo running mean plots of pressure anomalies for Madras (1841-1976), Bombay (1847-1976), Djakarta (1866-1974), and Darwin (1882-1976). They also show similar plots of pressure index anomalies for Santiago-Bombay (1861-81) and Santiago-Darwin (1882-1976). The anomaly plots were used along with other data in the evaluation of El Niño type events reported over the past 135 yr.

Classification of Events

The classification of El Niño type events by intensity is highly subjective since no two cases are exactly alike with regard to time of onset, duration, areal extent, thermal departure, degree of devastation, etc. Determinations concerning event occurrence and intensity were primarily based on: 1) reported disruptions of the anchoveta fishery and marine bird life off the coast of Peru; 2) scientific reports which discussed events that affected the coastal regions of Peru and southern Ecuador [e.g., Eguiguren (1894), Frijlinck (1925), Murphy (1926), Hutchinson (1950), Sears (1954), Schweigger (1961)]; 3) hydrological data for the Peruvian coastal region; 4) sea-surface temperature data along the coasts of Peru and southern Ecuador; 5) rainfall at coastal stations in Peru and southern Ecuador; 6) height of preevent peaks and depth of relaxation troughs in Southern Oscillation index trends; 7) related indications from index component trends (when pressure components from only one core of the Southern Oscillation were available); 8) sea-surface temperatures over the equatorial Pacific; 9) rainfall data for islands in the central and western equatorial Pacific.

We categorized events as strong, moderate, weak, or very weak, depending on the intensity of the activity and the time of year that it occurred. The true El Niño sets in during the first half of the year. A symptom which is common to El Niños is the presence of anomalously high sea-surface temperatures off the coasts of southern Ecuador and Peru. Other frequently mentioned features include a southward coastal current, heavy rainfall, red tide (aguage), invasion by tropical nekton, and mass mortality of various marine organisms including guano birds, sometimes with subsequent decomposition and release of hydrogen sulfide (known as El Pintor) (Wooster 1960).

Strong El Niños are recognized as such by all investigators; they involve positive sea-surface temperature anomalies along the coast in excess of 3°C, they display most of the aforementioned features, and the anchoveta fishery is seriously

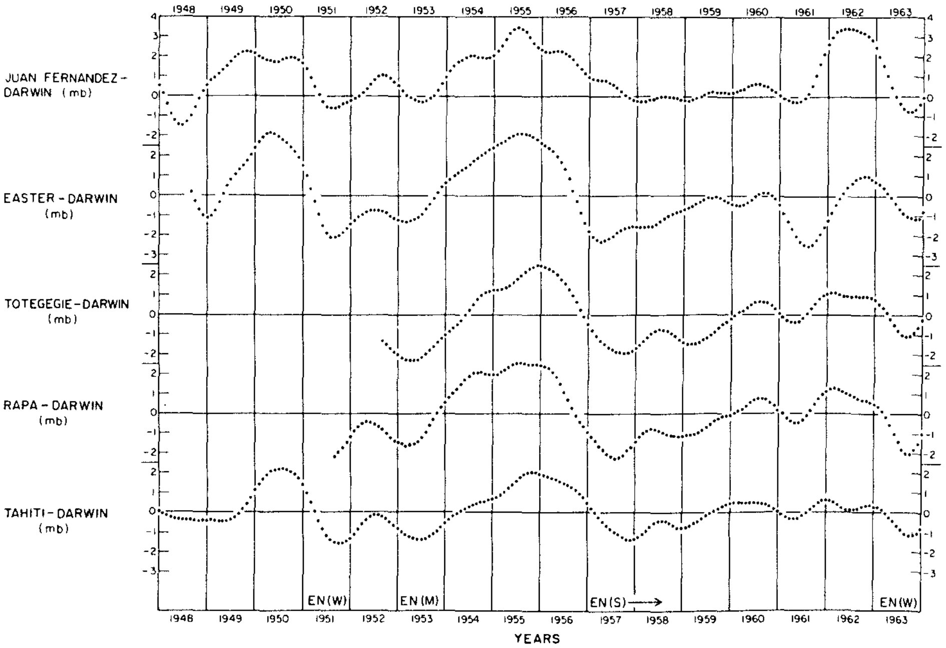

FIGURE 2a.—Triple 6-mo running mean plots of anomalies of the difference in sea level atmospheric pressure (millibars) between Juan Fernandez Is. (33°37'S, 78°50'W) and Darwin, Australia (12°26'S, 130°52'E), between Easter Is. (27°10'S, 109°26'W) and Darwin, between Totegegie (23°06'S, 134°52'W) (Gambier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

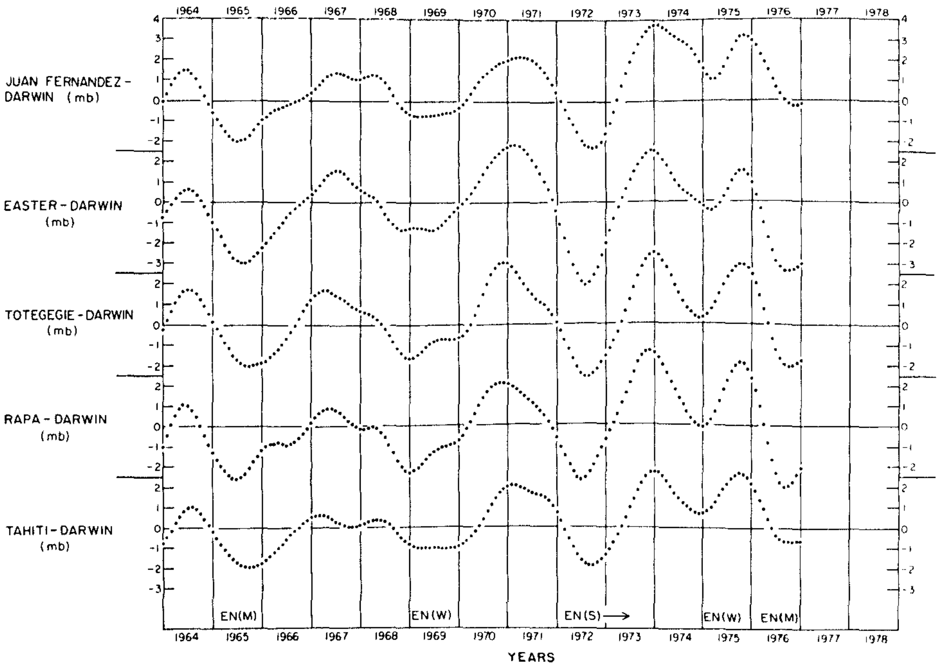

FIGURE 2b.—Triple 6-mo running mean plots of anomalies of the difference in sea level atmospheric pressure (millibars) between Juan Fernandez Is. and Darwin, between Easter Is. and Darwin, between Totegegie and Darwin, between Rapa and Darwin, and between Tahiti and Darwin for 1964-76. El Niño type events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

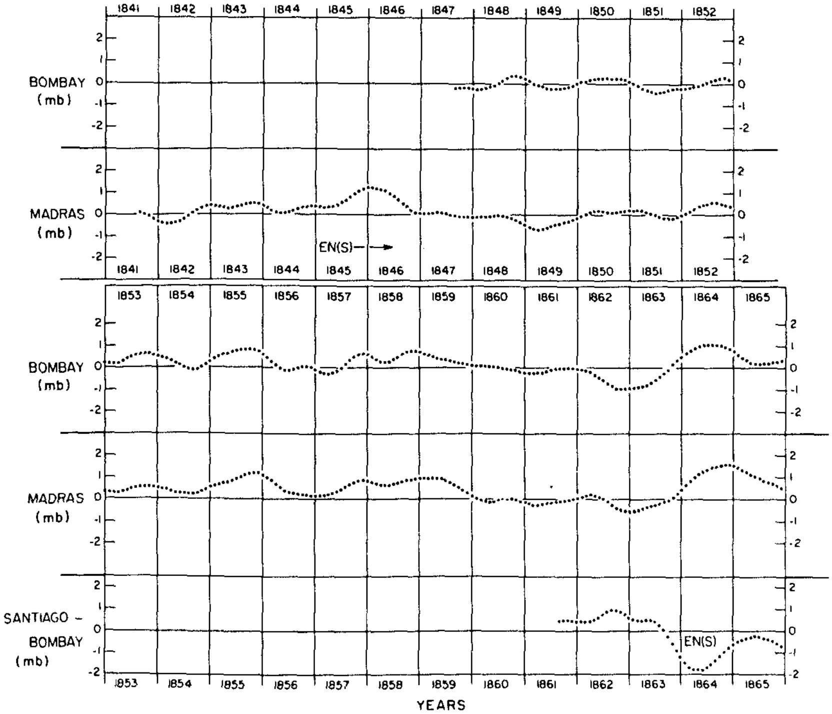

FIGURE 3a.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay (18°54′N, 72°49′E), India (1847-65) and for Madras (13°00′N, 80°11′E), India (1841-65); also triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago (33°27′S, 70°42′W), Chile and Bombay (1861-65). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

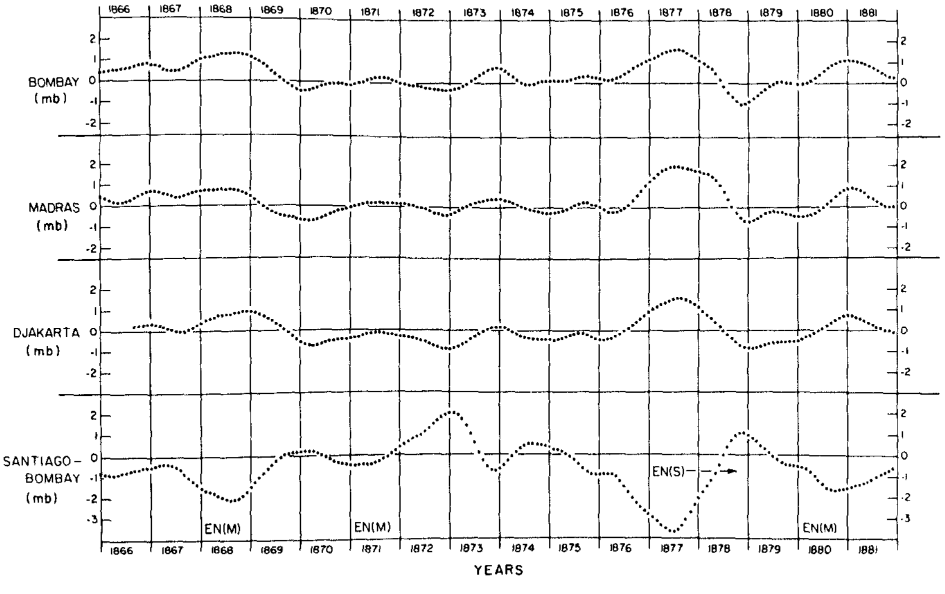

FIGURE 3b.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay and Madras, India, and Djakarta (06°11′S, 106°51′E), Indonesia (1866-81); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Bombay (1866-81). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

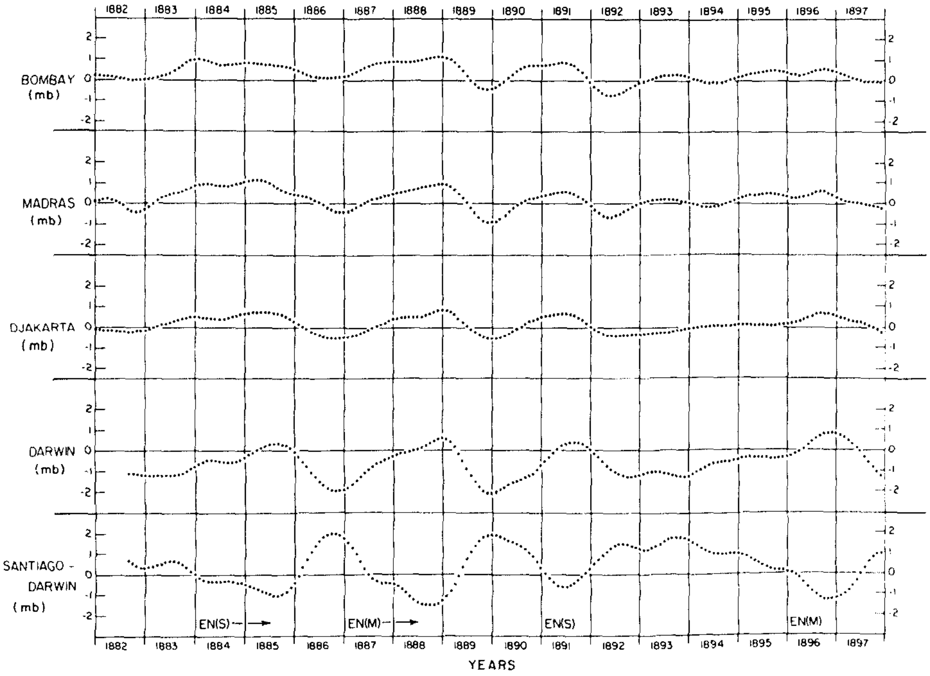

FIGURE 3c.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (12°26′S, 130°52′E), Australia (1882-97); also triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1882-97). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

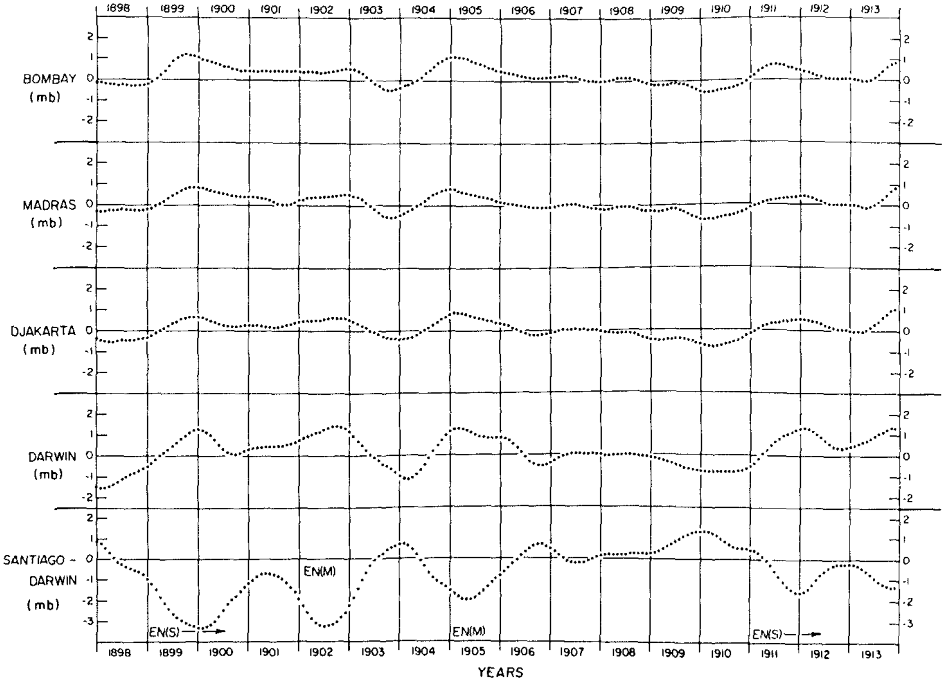

FIGURE 3d.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (1898-1913); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1898-1913). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

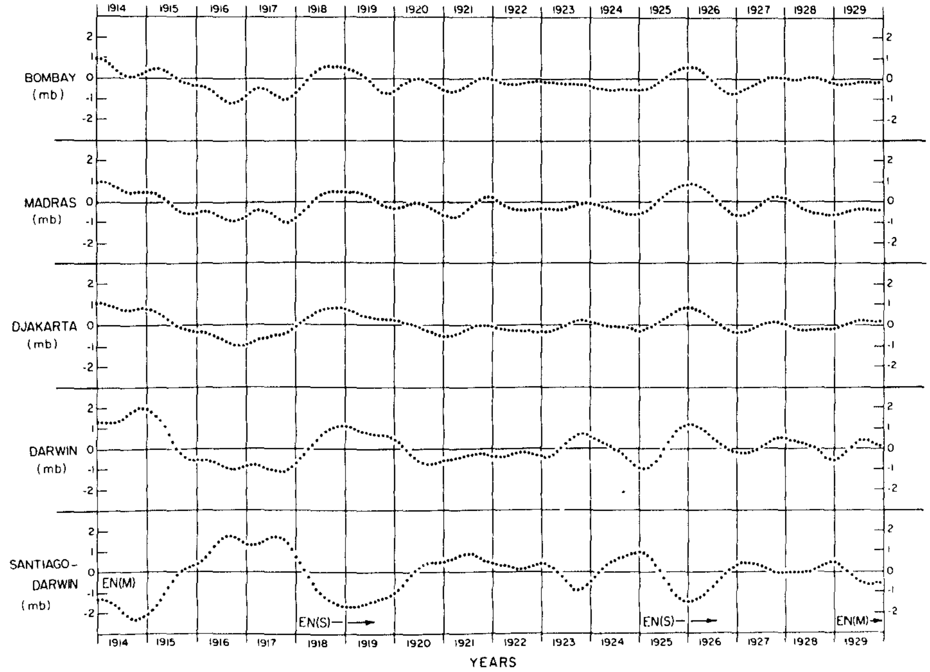

FIGURE 3e.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (1914-29); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1914-29). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

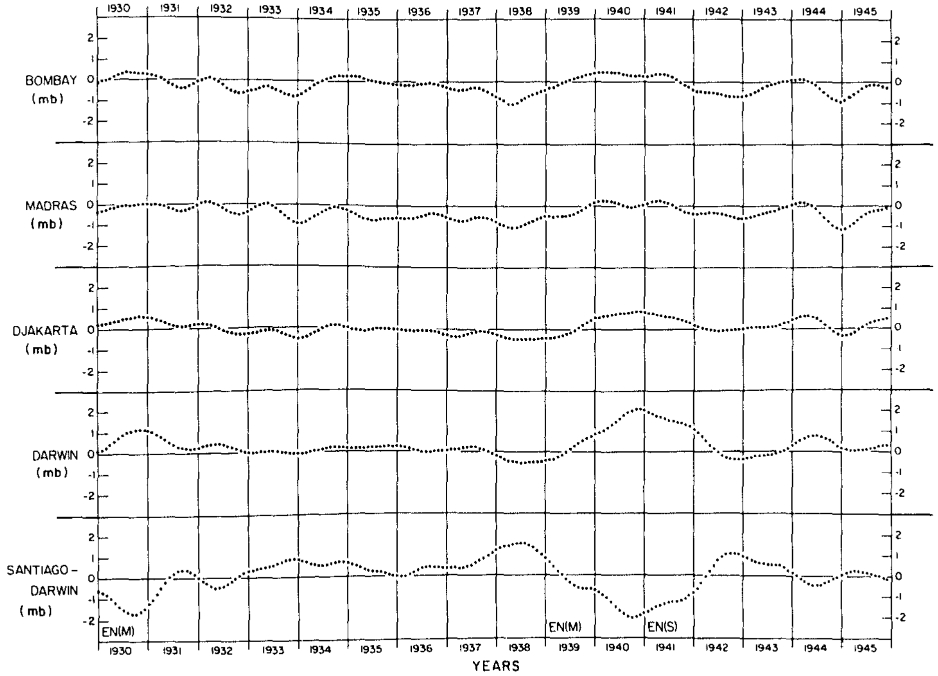

FIGURE 3f.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (1930-45); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1930-45). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

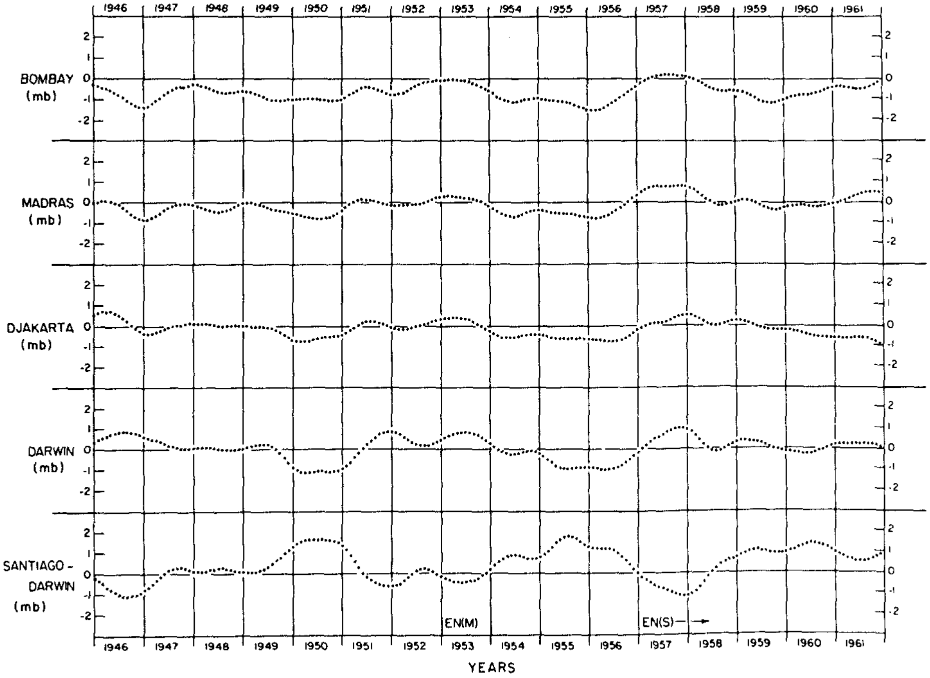

FIGURE 3g.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (1946-61); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1946-61). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

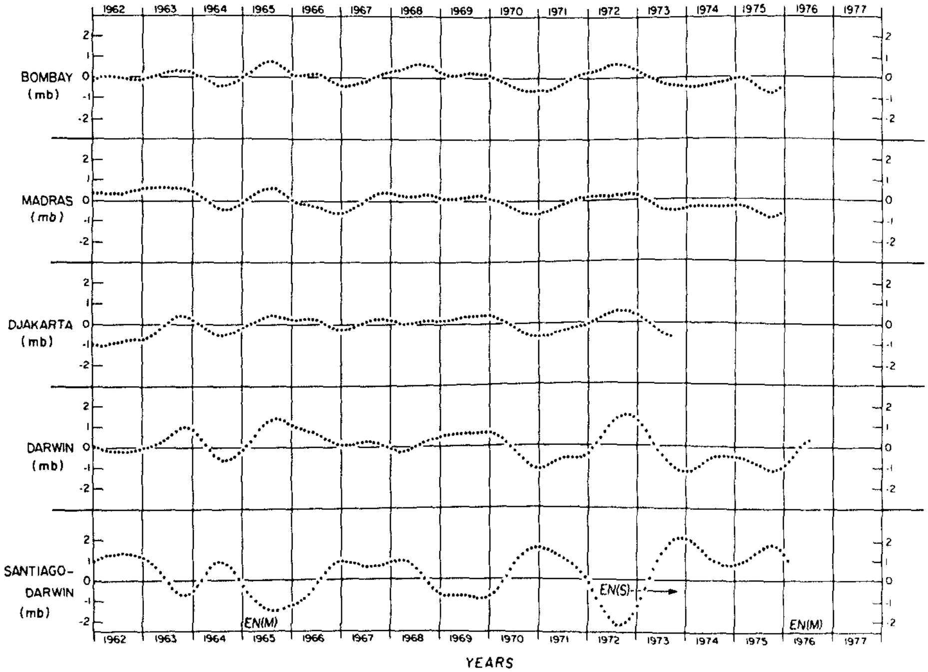

FIGURE 3h.—Triple 6-mo running mean plots of sea level atmospheric pressure anomalies (millibars) for Bombay, Madras, Djakarta, and Darwin (1962-76); also, triple 6-mo running mean plot of difference in atmospheric pressure anomalies between Santiago and Darwin (1962-76). El Niño type events (EN) are indicated in strong (S) or moderate (M) intensity.

affected (e.g., the 1957-58 and 1972-73 cases of recent years). Moderate cases are recognized as El Niños by most investigators, and display typical El Niño features to a lesser degree; maximum monthly sea-surface temperature anomalies along the coast usually peak in the 2.0°-3.5°C temperature range (e.g., the 1953, 1965-66, and 1976-77 cases of recent years). The effects of a moderate El Niño on the anchoveta fishery are considerable, but less serious than for the strong category.

Weak events may or may not be recognized as El Niños by investigators; maximum monthly sea-surface temperature anomalies along the coast usually peak in the 1.0°-2.5°C temperature range, but may appear relatively late in the year (e.g., the 1951 and 1969 cases of recent years). Very weak events are not considered to be El Niños; maximum sea-surface temperature anomalies, if they penetrate into the coast, are in the 0°-2°C range (e.g., the 1963 and 1975 events). The weak and very weak categories are included in this discussion because the difference between weaker and stronger events depends not only on the height of the preevent index anomaly peak and the subsequent degree of relaxation reflected in the southeast trade strength, but also on the timing of this interannual relaxation. If the timing is in phase with the regular annual relaxation (Southern Hemisphere summer and early fall), a moderate or strong event is likely to occur; if they are out of phase, a weak or very weak event is likely. Relaxation troughs that occur near the end of the year are usually associated with high Peruvian coastal sea temperature anomalies in the latter half of the year. The weak and very weak events may not be of significance to the Peruvian anchoveta fishery, but they do show up in the western equatorial Pacific rainfall and their larger scale aspects may be significant from the standpoint of associated global fluctuations. Figure 4 shows an example of how the recent events were reflected in the Tarawa rainfall.

The weaker events were included as EN(W) in Figure 2a, b, since we have a fairly large amount of evidence available from 1950 on. They were not included in Figure 3a-h due to the decreasing availability of evidence as we reach further back in time. However, these weaker events, ascertained to the best of our ability from available data

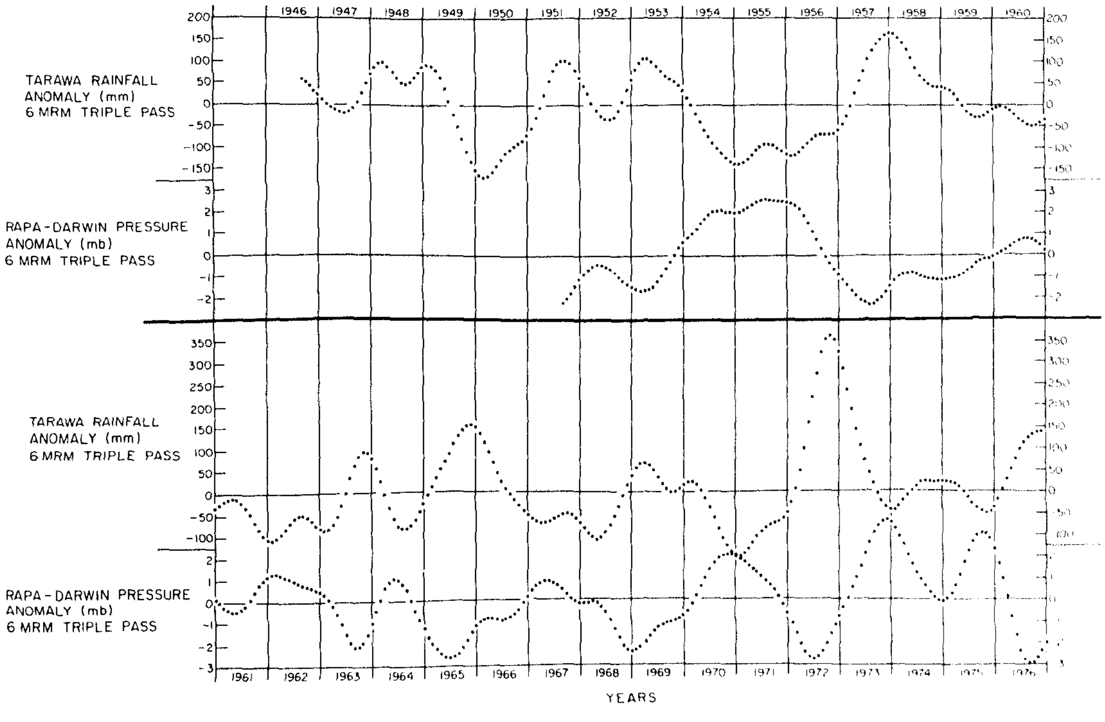

FIGURE 4.—Triple 6-mo running mean plot of anomalies of the difference in sea level atmospheric pressure (millibars) between Rapa (27°37'S, 144°20'W) (Austral Is.) and Darwin (12°26'S, 130°52'E), Australia compared with a similarly filtered plot of Tarawa (01°21'N, 172°55'E) (Gilbert Is.) rainfall anomalies (millimeters).

and literature, are included in Table 1; and, the typical index and index component trends associated with them can be noted in Figure 3a-h.

Eguiguren's (1894) data were evaluated to extend the record back even further. He classified rainfall at Piura, Peru (lat. 5°5′S, long. 80°38′W) into five categories: dry (0), light (1), moderate (2), good (3), and extra ordinary (4). Considering the distribution of events over the period 1891-1976 in relation to Eguiguren's rainfall category distribution for 1791-1890, it appeared that we could relate his category 4 to a strong El Niño, category 3 to a moderate El Niño, and categories 2 and 1 to weak and very weak events respectively. One must realize that for this Peruvian desert area long-term average rainfall values have little meaning, since averages combine data from the more-frequent drought years with data from the smaller number of event years when significant rainfall may occur. A year when an average amount of rain fell is likely to have been a year when an event occurred. Whereas the categories 3 and 4 rainfall situations were likely to have been associated with El Niño, there is no assurance that the categories 1 and 2 rainfalls were associated with the oceanic events.

A study of presumed event occurrences (based on Eguiguren's information) in relatiion to trends of the Southern Oscillation indices and index components for a period when overlapping data records were available (1841-90) showed a high degree of compatibility. Table 1 lists years in accordance with Eguiguren's rainfall classification as well as our interpretation of event intensity after considering his indications, the index and index component trends, and the various data and information sources listed early in this section.

After 1790 and prior to 1841, when no pressure records were available for a cross-check, we avoided the weak event category, but accepted Eguiguren's stronger categories 3 and 4 events. Events occurring prior to 1791, as reported by Frijlinck (1925), were considered to be of the strong variety. Sources for each event are listed in Table 1.

STATISTICAL STUDY OF EL NINO TYPE EVENTS

From a practical standpoint, we were concerned with the question of when the next event is likely to occur and what its intensity might be. Therefore, this study referred to the onset times for separate events and the interval between onset times. When the year immediately following the year of onset reflected an event of equal or lower intensity, it was assumed that the initial event extended into this next year or that the effects of the initial event held over into the early part of the next year; and, the whole situation was treated as a single event. However, when a weaker initial event preceded a stronger event in a following year they were treated as two separate events,

TABLE 1.—Year of onset of El Niño type events, 1726-1976, as classified according to event intensity by Eguiguren (1894), left, and the present authors, right (events below intensity 3 were not accepted prior to 1841 when pressure data became available). Numbers refer to event intensity: 1, very weak; 2, weak; 3, moderate; and 4, strong. Asterisks indicate onset of events considered separate (see text).

Year	Event intensity		Key to source	Year	Event intensity		Key to source	Year	Event intensity	Key to source	Year	Event intensity	Key to source
*1726		(3)	G	*1852	2	(2)	B, PC	*1896	(3)	PI, R	*1943	(2)	G, T, R
*1728		(4)	A, G	1854	2		B	*1899	(4)	D, PI, R	1944	(2)	PI, T
*1763		(4)	A	*1855		(2)	PC	1900	(3)	PI, R	*1946	(1)	PI, R
*1770		(4)	A	*1857	2	(2)	B, PC	*1902	(3)	PI, R	*1948	(1)	PI, T, R
*1791	4	(4)	A, B	1862	2		B	*1905	(3)	PI, R	*1951	(2)	G, PI, T
*1803	2		B	*1864	4	(4)	A, B, PI	*1911	(4)	F, E, PI	*1953	(3)	G, E, T
*1804	4	(4)	B	1866	2		B	1912	(3)	F, PI	*1957	(4)	G, L, PI
*1814	4	(4)	B	*1868	1	(3)	B, C, PI	*1914	(3)	G, PI, R	1958	(4)	G, L, PI
*1817	3	(3)	B	*1871	4	(3)	A, B, C	*1917	(2)	H	*1963	(1)	PI, R
*1819	3	(3)	B	*1873		(2)	PI	*1918	(4)	C, D, PI	*1965	(3)	M, PI, T
*1821	3	(3)	B	*1875	1	(1)	B, PC	1919	(3)	D, PI, R	*1969	(2)	PI, T, R
*1824	3	(3)	B	*1877	4	(4)	A, B, PI	*1923	(2)	H, PI	*1972	(4)	N, O, PI
*1828	4	(4)	A, B	1878	4	(4)	A, B, PI	*1925	(4)	D, E, PI	1973	(4)	N, O, T
1829	1		B	*1880	2	(3)	B, PI	1926	(4)	I, PI, T	*1975	(1)	P, PI, T
*1832	3	(3)	B	*1884	4	(4)	A, B, PI	*1929	(3)	G, I, PI	*1976	(3)	Q, PI, T
*1837	3	(3)	B	1885		(3)	PI	1930	(3)	G, PI, T			
*1844	3	(2)	B, PC	*1887	2	(3)	B, PI	*1932	(2)	E, I, J			
*1845	4	(4)	B, C, PC	1888	2	(3)	B, PI	*1939	(3)	E, J, T			
1846	2	(3)	B, PC	1889	1	(1)	B, PI	1940	(2)	C, PI, T			
*1850	2	(2)	B, PC	*1891		(4)	D, E, PI	*1941	(4)	E, K, T			

Key	Source	Key	Source	Key	Source
A	Frijlinck (1925)	H	Lavalle (1917, 1924)	O	Caviedes (1975)
B	Eguiguren (1894)	I	Shepard (1930, 1933)	P	Wyrtki et al. (1976)
C	Hutchinson (1950)	J	Mears (1944)	Q	Quinn (1976)
D	Murphy (1923, 1926)	K	Lobell (1942)	R	Rainfall (equatorial and/or Peruvian)
E	Sears (1954)	L	Wooster (1960)	T	Sea-surface temperature off Peru
F	Forbes (1914)	M	Guillén (1967)	PC	Pressure component of Southern Oscillation index
G	Schweigger (1961)	N	Idyll (1973)	PI	Southern Oscillation pressure index

since an additional contribution was introduced in the following year. The foregoing assumptions were based on findings from a study of the Southern Oscillation index trends and associated events over recent decades when more data were available for case history studies.

Our study of strong events was limited to the period 1763-present (Table 2, Figure 5), since the break of 35 yr between 1728 and 1763 was 14 yr longer than the longest subsequent break between events, and there was no way of eliminating the possibility that one or more strong events might have gone unreported over the 35-yr gap. These data indicate that given a strong El Niño, there is a 35% probability of having another strong event in 7-8 yr, and an 82% probability of having one within the next 15-16 yr. Considering all available data, the time between onsets of separate strong events was never <7 yr.

For strong and moderate events (Table 3, Figure 5) the record was limited to the period 1791-present when data for both categories were available. For strong, moderate, and weak events (Table 4, Figure 5) the record was limited to 1842-present, so we would have at least one index component trend available for cross-checking the less prominent weak events. (Madras pressure data became available in 1841.) With the addition of very weak events (Table 5, Figure 5), we limited our record to 1862-present in order to have an index trend available for cross-checking the more obscure very weak events. (The Santiago-Bombay index became available in 1861.)

Cases were noted where relaxation from a large preevent index anomaly peak appeared to be a two or more stage process. [This type development was

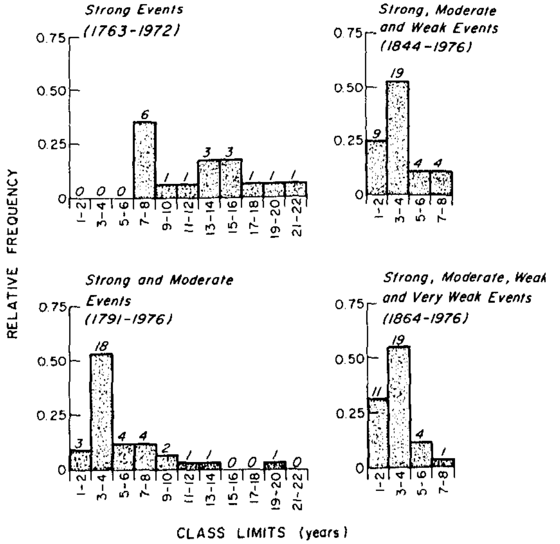

FIGURE 5.—Histograms of frequency distributions for El Niño type events by intensity. Number of occurrences within class intervals is indicated.

TABLE 2.—Strong El Niños, with intervals between events from onset to onset.

Onset year	Onset year	Years between onsets	Onset year	Onset year	Years between onsets
1763	1770	7	1884	1891	7
1770	1791	21	1891	1899	8
1791	1804	13	1899	1911	12
1804	1814	10	1911	1918	7
1814	1828	14	1918	1925	7
1828	1845	17	1925	1941	16
1845	1864	19	1941	1957	16
1864	1877	13	1957	1972	15
1877	1884	7			

209 (cumulative years between onsets) ÷ 17 (number of intervals) = 12.3 yr, average time interval between onsets of strong El Niños.

TABLE 3.—Strong and moderate El Niños with intervals between events from onset to onset.

Onset year	Onset year	Years between onsets	Onset year	Onset year	Years between onsets
1791	1804	13	1887	1891	4
1804	1814	10	1891	1896	5
1814	1817	3	1896	1899	3
1817	1819	2	1899	1902	3
1819	1821	2	1902	1905	3
1821	1824	3	1905	1911	6
1824	1828	4	1911	1914	3
1828	1832	4	1914	1918	4
1832	1837	5	1918	1925	7
1837	1845	8	1925	1929	4
1845	1864	19	1929	1939	10
1864	1868	4	1939	1941	2
1868	1871	3	1941	1953	12
1871	1877	6	1953	1957	4
1877	1880	3	1957	1965	8
1880	1884	4	1965	1972	7
1884	1887	3	1972	1976	4

185 (cumulative years between onsets) ÷ 34 (number of intervals) = 5.4 yr, average time interval between onsets.

TABLE 4.—Strong, moderate, and weak El Niños with intervals between events from onset to onset.

Onset year	Onset year	Years between onsets	Onset year	Onset year	Years between onsets
1844	1845	1	1905	1911	6
1845	1850	5	1911	1914	3
1850	1852	2	1914	1917	3
1852	1855	3	1917	1918	1
1855	1857	2	1918	1923	5
1857	1864	7	1923	1925	2
1864	1868	4	1925	1929	4
1868	1871	3	1929	1932	3
1871	1873	2	1932	1939	7
1873	1877	4	1939	1941	2
1877	1880	3	1941	1943	2
1880	1884	4	1943	1951	8
1884	1887	3	1951	1953	2
1887	1891	4	1953	1957	4
1891	1896	5	1957	1965	8
1896	1899	3	1965	1969	4
1899	1902	3	1969	1972	3
1902	1905	3	1972	1976	4

132 (cumulative years between onsets) ÷ 36 (number of intervals) = 3.7 yr, average time interval between onsets.

TABLE 5.—Strong, moderate, weak, and very weak El Niños with intervals between events from onset to onset.

Onset year	Onset year	Years between onsets	Onset year	Onset year	Years between onsets
1864	1868	4	1923	1925	2
1868	1871	3	1925	1929	4
1871	1873	2	1929	1932	3
1873	1875	2	1932	1939	7
1875	1877	2	1939	1941	2
1877	1880	3	1941	1943	2
1880	1884	4	1943	1946	3
1884	1887	3	1946	1948	2
1887	1891	4	1948	1951	3
1891	1896	5	1951	1953	2
1896	1899	3	1953	1957	4
1899	1902	3	1957	1963	6
1902	1905	3	1963	1965	2
1905	1911	6	1965	1969	4
1911	1914	3	1969	1972	3
1914	1917	3	1972	1975	3
1917	1918	1	1975	1976	1
1918	1923	5			

112 (cumulative years between onsets) ÷ 35 (number of intervals) = 3.2 yr, average time interval between onsets.

first mentioned in Quinn and Zopf (1975).] In some cases there was an initial fall from a large preevent (primary) peak which was not fully in phase with the seasonal relaxation (Southern Hemisphere summer and early fall) and the result was a relatively weak event; then, there was the 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. The length of time between the two troughs was generally 18-22 mo and it is our opinion that situations of this type may account for many of the event-to-event intervals that fall in the short 1-2 yr category. Examples of such developments can be noted in 1950-53, 1962-65, and 1973-76 (Figure 2a, b). Preevent peaks occurred 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. Then, there were rises to 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 for these latter years. We must be aware that these situations can arise and should be particularly wary when a large preevent peak is followed prematurely by a weak or very weak event. (One must not lose sight of the fact that these interannual fluctuations in the index anomaly trends were used to represent the interannual fluctuations in southeast trade and equatorial easterly strength as affected by the Southern Oscillation.) Figure 6 demonstrates the similarity of the three two-stage developments discussed above; a particularly obvious index trend was selected to represent each case.

The index trend between late 1872 and 1877 indicates a possible three stage development (Figure 3b), with a weak event in 1873, a very weak event in 1875, and a strong event in 1877 (Table 1). It is noteworthy that Indonesian droughts, which are usually associated with El Niño, occurred in 1873, 1875, and 1877 (Berlage 1957).

The preevent index anomaly peak has been reported to be a reliable indicator for subsequent El Niño type activity, and our long index record substantiates this viewpoint. We compiled statistics on the climb time from trough to peak and fall time from peak to trough from our long index anomaly record to provide some general guidance for event predictions. Figure 7 shows the applicable statistics. Events usually set in while the index is falling and prior to the index trough inflection point. Therefore, the contents of Table 6 and Figure 8, which pertain to time between index peak and subsequent event onset, can be used to further refine event predictions. We assumed a March onset time for all cases in arriving at values in the column headed "Peak to event onset" (Table 6). This assumption was made since month of onset was not available for most of the early cases, and a study of recent cases showed onset times to range from January to May.

INDONESIAN DROUGHTS

What happens over Indonesia relates to the Southern Oscillation (Berlage 1957) and is, therefore, an integral part of the activity affecting the

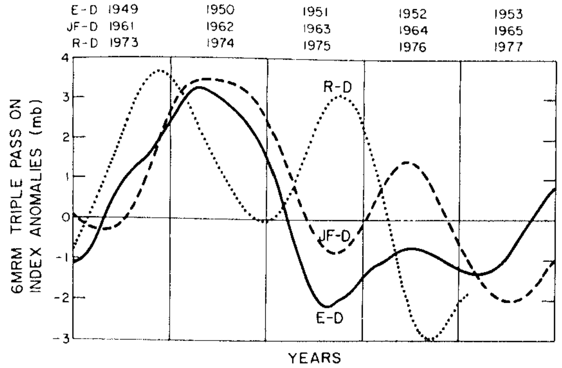

FIGURE 6.—Recent examples of two stage developments using triple 6-mo running mean plots of: 1) Easter-Darwin (E-D) index anomalies (1949-53); 2) Juan Fernandez-Darwin (JF-D) index anomalies (1961-65); 3) Rapa-Darwin (R-D) index anomalies (1973-77).

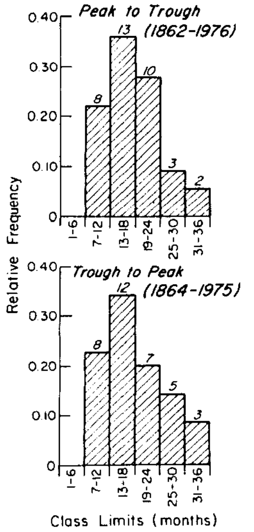

FIGURE 7.—Frequency distributions of rise time from trough to peak and fall time from peak to trough (in months) for the triple 6-mo running mean plots of Southern Oscillation index anomalies (see text). The number of cases falling within a class interval is entered at the top of the relevant histogram element.

equatorial Pacific and the oceanic region off northwestern South America. In general, years when the index is low and El Niño type activity occurs are also years of drought in Indonesia (particularly during the east monsoon season, May-October).

Using sea salt production on the Island of Madura (near Java), which is a very sensitive indicator of drought and precipitation, as well as some administration reports from Java estates, compiled by Van Bemmelen (1916), Berlage (1957) drew up a complete series of east monsoons drier than normal, from 1830 to 1953. Although 93% of the drought periods occurred during years when El Niño type events were under way (Table 7), only 77% of the periods when El Niño type events were underway were also designated as periods of east monsoon drought (Table 8). Nevertheless, the association between occurrences of these two phenomena and changes in the Southern Oscillation index trends are close enough in either case to indicate common relationships with the large-scale ocean-atmosphere changes over the Indo-

TABLE 6.—Time (in months) between index peak and El Niño type event onset (assuming onset is in March of indicated year), and time between index peak and associated Indonesian drought onset (assuming onset is in May of associated year). Pressure indices (see text) used to determine time of preevent peak were: S-B, Santiago-Bombay; S-D, Santiago-Darwin; JF-D, Juan Fernandez-Darwin; E-D, Easter-Darwin; T-D, Totegegie-Darwin; and R-D, Rapa-Darwin. In last column ND indicates no associated drought.

El Niño type event	Preevent index peak		Peak to event onset	Peak to drought onset
Year of onset	Month of peak	Index used	No. of Months	No. of months
1864	Aug.-Sept. 1862	S-B	18.5	20.5
1868	Mar.-Apr. 1867	S-B	11.5	ND
1871	Jan.-Feb. 1870	S-B	13.5	ND
1873	Jan. 1873	S-B	2.0	4.0
1875	Aug.-Sept. 1874	S-B	6.5	8.5
1877	Feb. 1876	S-B	13.0	15.0
1880	Nov. 1878	S-B	16.0	30.0
1884	May 1882	S-B	22.0	12.0
1887	July-Aug. 1886	S-B	7.5	21.5
1891	Nov.-Dec. 1889	S-B	15.5	17.5
1896	Oct. 1893	S-D	29.0	31.0
1899	Nov.-Dec. 1897	S-D	15.5	ND
1902	May 1901	S-D	10.0	12.0
1905	Sept.-Oct. 1903	S-D	14.5	16.5
1911	Jan.-Feb. 1910	S-D	13.5	ND
1914	Sept.-Oct. 1912	JF-D	17.5	7.5
1917	Aug.-Sept. 1916	S-B	6.5	ND
1918	Aug.-Sept. 1917	S-D	6.5	8.5
1923	Aug. 1921	JF-D	19.0	21.0
1925	May-June 1924	S-B	9.5	11.5
1929	Dec.-Jan. 1928/29	JF-D	2.5	4.5
1932	Aug.-Sept. 1931	S-D	6.5	8.5
1939	June-July 1938	JF-D	8.5	22.5
1941	Jan.-Feb. 1940	JF-D	13.5	15.5
1943	July-Aug. 1942	JF-D	7.5	21.5
1946	Dec.-Jan. 1944/45	S-B	14.5	4.5
1948	Aug. 1947	JF-D	7.0	ND
1951	Apr.-May 1950	E-D	10.5	ND
1953	Apr.-May 1952	R-D	10.5	12.5
1957	July-Aug. 1955	E-D	19.5	↑
1963	May 1962	JF-D	10.0	
1965	June 1964	JF-D	9.0	Data not
1969	Mar.-Apr. 1967	T-D	23.5	available
1972	Oct.-Nov. 1970	R-D	16.5	
1975	Nov.-Dec. 1973	R-D	15.5	↓
1976	Sept.-Oct. 1975	R-D	5.5	7.0

Pacific region. Based on the association between El Niño type events, drought years and index features, and also an assumption that the drought will set in during May of involved drought years, we arrived at values in the column headed "Peak to drought onset" (Table 6). Figure 8 shows the resulting statistics which could be applied to Indonesian drought predictions.

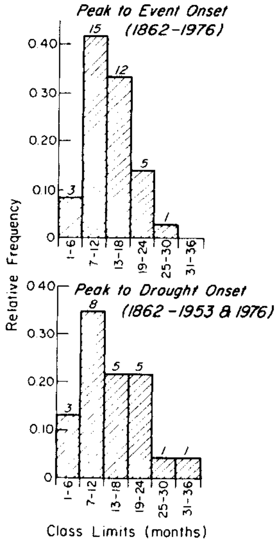

FIGURE 8.—Frequency distributions of time (in months) between preevent peaks in triple 6-mo running mean plots of Southern Oscillation index anomalies (see text) and: 1) the onset of subsequent El Niño type events (assuming onset is in March of involved years); 2) the onset of associated Indonesian droughts (assuming onset is in May of involved years). The number of cases falling within a class interval is entered at the top of the relevant histogram event.

TABLE 7.—Association of east monsoon droughts in Java with El Niño type events.

Drought years	El Niño type event years	Notes
1844	1844	
1845	1845-46	
1850	1850	
1853	None	Event in 1852
1855	1855	
1857	1857	
1864	1864	
1873	1873	
1875	1875	
1877	1877-78	
1881	1880	Index low 1880-81
1883		
1884)	1884-85	
1885		
1888	1887-89	
1891	1891	
1896	1896	
1902	1902	
1905	1905	
1913 1914	1914	
1918 1919	1918-19	
1923	1923	
1925 1926	1925-26	
1929	1929-30	
1932	1932	
1935	None	Slight lowering of index
1940	1939-40	
1941	1941	
1944	1943-44	
1945 1946	1946	
1953	1953	
Drought data unavailable 1954-75		
1976	1976	

28 (separate events) ÷ 30 (east monsoon drought situations) = 0.93.

93% of east monsoon droughts can be associated with El Niño type events.

TABLE 8.—Association of El Niño type events with east monsoon droughts in Java.

El Niño type event years	Drought years	Notes
1844	1844	
1845-46	1845	
1850	1850	
1852	None	Drought in 1853
1855	1855	
1857	1857	
1864	1864	
1868	None	
1871	None	
1873	1873	
1875	1875	
1877-78	1877	
1880	1881	Index low 1880-81
1884-85	1883-85	
1887-89	1888	
1891	1891	
1896	1896	
1899-1900	None	
1902	1902	
1905	1905	
1911-12	None	
1914	1913-14	
1917	None	
1918-19	1918-19	
1923	1923	
1925-26	1925-26	
1929-30	1929	
1932	1932	
1939-40	1940	
1941	1941	
1943-44	1944	
1946	1945-46	
1948	None	
1951	None	
1953	1953	
Drought data unavailable 1954-75		
1976	1976	

28 (east monsoon drought situations) ÷ 36 (separate events) = 0.78.

78% of El Niño type events can be associated with east monsoon droughts.

DISCUSSION

Over the past 116 yr (1861-1976), for which we have adequate data on the occurrence of El Niño type events of weaker intensity, there were decades of minimal activity (e.g., 1901-10, 1931-40, 1961-70), but no decade without such activity. There is no reason to expect any significant change in the amount of El Niño activity in the foreseeable future over that experienced in the past century. Therefore, it would appear that our data (e.g., Tables 2-5) might eventually be used in conjunction with associated catch data and biological findings for effective long-range planning in the management of the anchoveta fishery. For example, assessment of maximum sustainable yields under various environmental conditions ranging from the favorable extended anti-El Niño condition (when there are two or more consecutive years with high Southern Oscillation indices) to the El Niño situation (when there are rapidly falling and low Southern Oscillation indices) might prove useful for determining the optimum size and flexibility of the fishing fleet and fish processing facilities. A key element to such assessments will be a knowledge of the required biological recuperation time following cessation of an unfavorable physical environmental condition.

Such data could also be used for speculative long-range outlooks. For example, if we had just experienced a strong El Niño, our results suggest that there is a near-zero probability that we would experience another strong event in <7 yr after the onset of the recent situation. However, there would be an 86% probability that an event in the very weak, weak, or moderate category would occur within 3-4 yr after the strong El Niño onset. Considering the current situation, and recognizing that a moderate event set in during 1976 and held over into early 1977, there is a 54% probability (based on our data) that another event of unknown intensity would set in during 1980. It would not be reasonable to go beyond statistical estimates until we find we are approaching a peak in the Southern Oscillation index anomalies.

When we are nearing a preevent peak and can assess its height and time of occurrence, then we can use peak to trough statistics (e.g., Figure 7) to advantage in forecasting onset time and likely intensity of the coming El Niño type event. The intensity would be based on the height of the index anomaly peak and the time of year when the subsequent trough was expected to occur. Event onset time can be further refined by considering Figure 8 statistics. It is also essential in the prediction procedure to realize that some developments may involve two or more stages. In cases of this type, forecast lead times for the separate stages will often be greatly reduced (to 1-6 mo in advance), unless historical analogies lead to pattern recognition as the situation evolves.

ACKNOWLEDGMENTS

We thank the Chief of the Naval Weather Service and the Director of the Hydrographic Institute of the Armada de Chile; the Director of the Civil Aviation Service and Chief of the Meteorological Service of Polynesie, Francaise; the Director of the Meteorological and Geophysical Institute, Djakarta, Indonesia; the President of the Instituto del Mar del Peru; Ramon Mugica, Universidad de Piura, Peru; the Director of the Australian Bureau of Meteorology; and, the National Climatic Center, Environmental Data Service, NOAA, for their support of this study. We are indebted to Forrest R. Miller of the Inter-American Tropical Tuna Commission and Richard Evans of the Southwest Fisheries Center, National Marine Fisheries Service, NOAA, for their timely information on sea temperatures and weather conditions over the eastern tropical Pacific. We also thank Clayton Creech for his support in data processing. Support by the National Science Foundation under the North Pacific Experiment of the International Decade of Ocean Exploration through NSF Grant No. OCE 75-21907 A01, and under the Climate Dynamics Program of the Division of Atmospheric Sciences through NSF Grant No. ATM77-00870 is gratefully acknowledged.

LITERATURE CITED

BERLAGE, H. P.
1957. Fluctuations of the general atmospheric circulation of more than one year, their nature and prognostic value. K. Ned. Meteorol. Inst., Meded. Verh. 69, 152 p.
1966. The Southern Oscillation and world weather. K. Ned. Meteorol. Inst., Meded. Verh. 88, 152 p.
BJERKNES, J.
1969. Atmospheric teleconnections from the equatorial Pacific. Mon. Weather Rev. 97:163-172.
CAVIEDES, C. N.
1975. El Niño 1972: Its climatic, ecological, human, and economic implications. Geogr. Rev. 65:493-509.
CLAYTON, H. H.
1927. World weather records. Smithson. Inst. Misc. Collect. 79, 1199 p.

1934. World weather records, 1921-1930. Smithson. Inst. Misc. Collect. 90, 616 p.

CLAYTON, H. H., AND F. L. CLAYTON.

1947. World weather records, 1931-1940. Smithson. Inst. Misc. Collect. 105, 646 p.

EGUIGUREN, D. V.

1894. Las Nuvias de Piura. Bol. Soc. Geogr. Lima 4(7-9):241-258.

FORBES, H. O.

1914. Notes on Molina's pelican *(Pelecanus thagus)*. Ibis, Ser. 10, 2:403-420.

FRIJLINCK, C. P. M.

1925. Bijdrage tot het probleem der Klimatwisselingen. Nat. Utr. 45:372-374.

GUILLÉN, O.

1967. Anomalies in the waters off the Peruvian coast during March and April 1965. Stud. Trop. Oceanogr. (Miami) 5:452-465.

HUTCHINSON, G. E.

1950. Survey of existing knowledge of biogeochemistry. 3. The biogeochemistry of vertebrate excretion. Bull. Am. Mus. Nat. Hist. 96, 554 p.

IDYLL, C. P.

1973. The anchovy crisis. Sci. Am. 228(6):22-29.

JOHNSON, J. H., AND G. R. SECKEL.

1977. Use of marine meteorological observations in fishery research and management. U.S. Dep. Commer., NOAA, Environ. Data Serv., p. 3-12.

LAVALLE, Y GARCIA, J. A., DE.

1917. Informe preliminar sobre la causa de la mortalidad anormal de las aves ocurida en el mes de marzo del presente ano. Mem. Cia. Adm. Guano, Lima 8.

1924. Estudio de la emegracion y mortalidad de las aves guaneras. Mem. Cia. Adm. Guano, Lima 15.

LOBELL, M. G.

1942. Some observations on the Peruvian coastal current. Trans. Am. Geophys. Union 23:332-336.

MEARS, E. G.

1944. The ocean current called "The Child." Annu. Rep. Smithson. Inst., 1943, p. 245-251.

MILLER, F. R., AND R. M. LAURS.

1975. The El Niño of 1972-73 in the eastern tropical Pacific Ocean. Inter-Am. Trop. Tuna Comm. Bull. 16:403-448.

MURPHY, R. C.

1923. The oceanography of the Peruvian littoral with reference to the abundance and distribution of marine life. Geogr. Rev. 13:64-85.

1926. Oceanic and climatic phenomena along the west coast of South America during 1925. Geogr. Rev. 16:26-54.

NATIONAL MARINE FISHERIES SERVICE.

1977. Industrial fishery products, market review and outlook, June 1977. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Curr. Econ. Anal. I-29, 27 p.

PANOFSKY, H. A., AND G. W. BRIER.

1965. Some applications of statistics to meteorology. Pa. State Univ. Press, University Park, 224 p.

QUINN, W. H.

1971. Late Quaternary meteorological and oceanographic developments in the equatorial Pacific. Nature (Lond.) 229:330-331.

1974. Monitoring and predicting El Niño invasions. J. Appl. Meteorol. 13:825-830.

1976. Use of Southern Oscillation indices to assess the physical environment of certain tropical Pacific fisheries. *In* Proceedings of the NMFS/EDS Workshop on Climate and Fisheries, Columbia, Mo., April 26-29, 1976, p. 50-70. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv./Environ. Data Serv.

QUINN, W. H., AND D. O. ZOPF.

1975. The Southern Oscillation, equatorial Pacific anomalies and El Niño. Geofis. Int. 15:327-353.

SCHWEIGGER, E. H.

1961. Temperature anomalies in the eastern Pacific and their forecasting. Soc. Geogr. Lima, Bol. 78:3-50.

SEARS, M.

1954. Notes on the Peruvian coastal current. 1. An introduction to the ecology of Pisco Bay. Deep-Sea Res. 1:141-169.

SHEPARD, G.

1930. Notes on the climate and physiography of southwestern Ecuador. Geogr. Rev. 20:445-453.

1933. The rainy season of 1932 in southwestern Ecuador. Geogr. Rev. 23:210-216.

TROUP, A. J.

1965. The 'southern oscillation.' Q. J. R. Meteor. Soc. 91:490-506.

U.S. DEPARTMENT OF COMMERCE.

1959. World weather records, 1941-1950. Wash., D.C., 1361 p.

1961-76. Monthly climatic data for the world, Vol. 14-29. Wash., D.C., var. pag.

1966-68. World weather records, 1951-1960, Vol. 3, 4, and 6. Wash., D.C., var. pag.

VAN BEMMELEN, W.

1916. Droogte-jaren op Java. Nat. Tijdschr. Ned.-Indië 75:157.

WALKER, G. T.

1924. World Weather II. Mem. India Meteor. Dep. 24:275-332.

WOOSTER, W. S.

1960. El Niño. Calif. Coop. Oceanic Fish. Invest. Rep. 7:43-45.

WYRTKI, K., E. STROUP, W. PATZERT, R. WILLIAMS, AND W. QUINN.

1976. Predicting and observing El Niño. Science (Wash., D.C.) 191:343-346.