LONG-TERM VARIATIONS IN THE SOUTHERN OSCILLATION, EL NIÑO, AND CHILEAN SUBTROPICAL RAINFALL

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ABSTRACT

A 120-year record of Southern Oscillation-related activity along the west coast of South America was studied in order to better understand the causes and variations in this activity with time. Significant decreases in the frequency of occurrence of moderate/strong El Niños and the related abnormally heavy amounts of Chilean subtropical rainfall were noted over the past half century. Work done by Berlage on the Southern Oscillation and findings here concerning the above decreases in activity indicate a significant change took place between 1927 and 1931. A significant decrease in average annual rainfall was noted over subtropical Chile after 1944.

Below normal pressures in the southeast Pacific subtropical high over the past 6 years coincide timewise with generally above normal sea surface temperatures over this region. An associated weakening of the southeast trade system is hypothesized to be responsible for environmental changes that contribute to the large alteration in composition of the pelagic biomass in both the Peruvian and northern Chilean fishery regions over recent years.

Recent findings on large-scale climatic fluctuations over a large part of the tropical and subtropical Pacific (Quinn et al. 1978, 1981), the availability of additional sources of corroborative evidence of these changes (Chilean subtropical rainfall data), and the establishment of an unusual trend in the Southern Oscillation indices over the past 6 yr led to our further investigation of the long-term climatic changes and their causes.

In Quinn et al. (1978) we compiled evidence on El Niño developments, their intensities, and their frequency of occurrence. However, at that time we did not consider the possibility of long-term variations in El Niño intensity with time. In Quinn et al. (1981) we found the Chilean subtropical rainfall amounts to be closely associated with the El Niño (low Southern Oscillation index anomaly)/anti-El Niño (high Southern Oscillation index anomaly) type conditions for 1875-1930. Here we have extended the rainfall records from Taulis (1934) up through 1980 (Table 1) for a study of the changes in activity with time.

In the past we noted a relationship between the Southern Oscillation indices and the productivity of the Peruvian anchoveta fishery (Quinn 1976; Quinn et al. 1978). Ordinarily when a moderate/strong El Niño occurred, the fishery suffered a significant setback, but following such events there was usually a prolonged anti-El Niño period during which the fishery recuperated. However, since the 1976 El Niño the index has remained unusually low (Fig. 1), and coincidentally there has been a startling change in the makeup of the pelagic biomass in the fishery. This change was reported in a Cerescope item (Ceres 1981) from the FAO/Norway Regional Acoustic Centre (the Centre) for Latin America in Lima, Peru. (The Centre became operational in May 1975 under

TABLE 1.—Annual rainfall amounts (in mm) at Santiago (lat. 33°26′S, long. 70°50′W) and Valparaiso (lat. 33°01′S, long. 71°39′W), Chile, for 1931-80.

Year	Santiago	Valparaiso	Year	Santiago	Valparaiso
1931	321.2	470.3	1960	193.0	208.6
1932	351.0	498.3	1961	270.0	442.0
1933	316.1	293.4	1962	210.0	228.3
1934	519.2	486.5	1963	440.0	452.9
1935	252.5	325.0	1964	160.0	261.0
1936	377.3	439.0	1965	400.0	811.0
1937	346.2	391.9	1966	434.0	450.0
1938	202.0	289.4	1967	172.0	248.0
1939	322.6	382.0	1968	70.0	89.0
1940	339.7	529.0	1969	175.0	194.0
1941	674.0	796.0	1970	325.0	229.0
1942	402.0	397.0	1971	253.0	237.9
1943	204.0	327.2	1972	574.0	443.6
1944	494.0	604.0	1973	171.0	217.8
1945	247.0	194.6	1974	417.0	391.7
1946	127.0	222.6	1975	149.0	362.8
1947	253.0	317.0	1976	189.0	299.3
1948	367.9	336.6	1977	333.0	405.2
1949	306.5	255.2	1978	403.0	472.1
1950	292.8	358.4	1979	166.0	295.6
1951	323.0	429.8	1980	292.0	440.1
1952	335.0	350.1			
1953	584.0	488.9			
1954	317.0	392.8			
1955	196.0	255.6			
1956	264.0	281.4			
1957	309.0	461.1			
1958	335.0	394.8			
1959	321.0	234.1			

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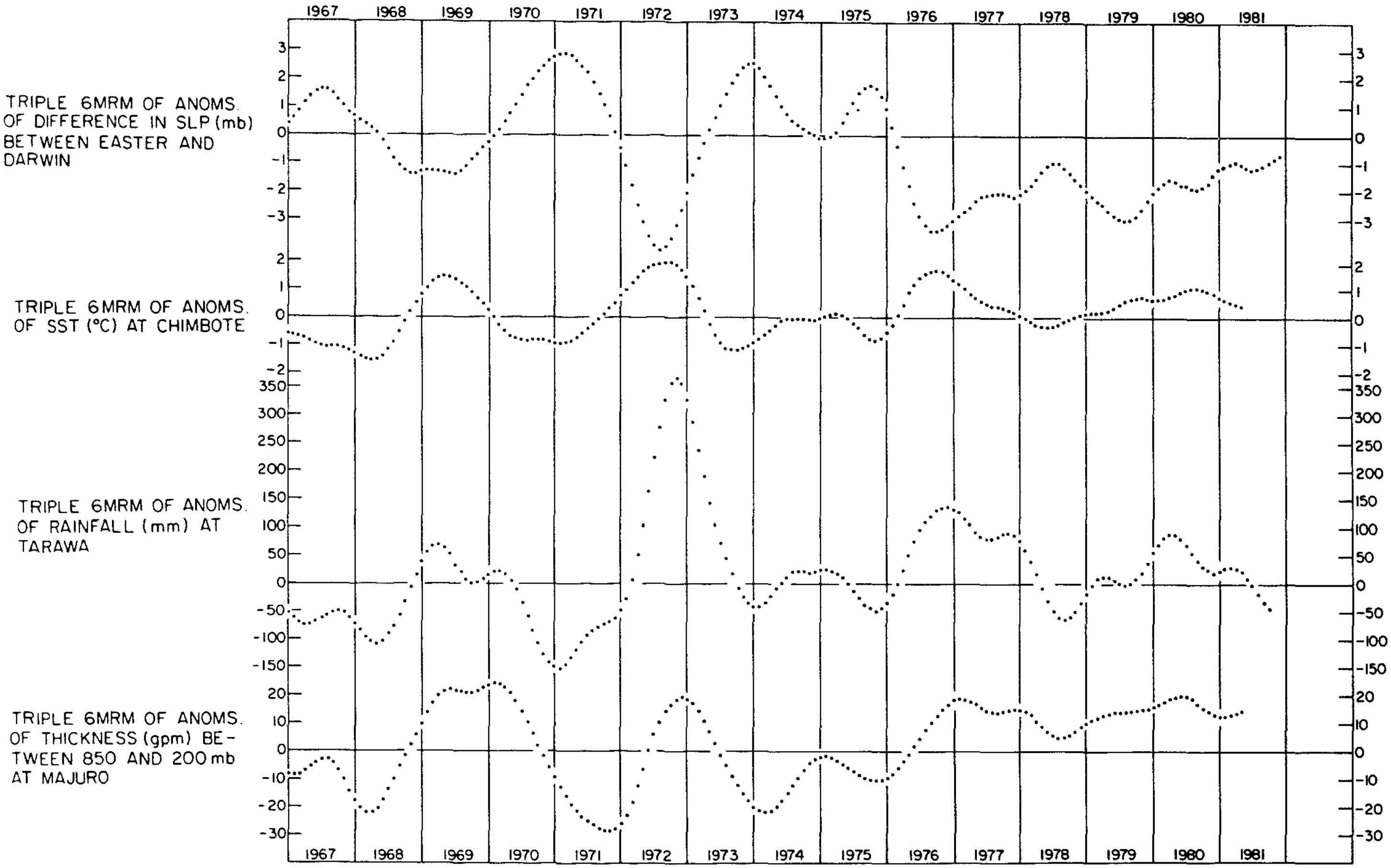

FIGURE 1.—Triple 6-mo running mean (6 MRM) plots of anomalies of the difference in sea level atmospheric pressure (millibars) between Easter Island (lat. 27°10′S, long. 109°26′W) and Darwin (lat. 12°26′S, long. 130°52′E), Australia; anomalies of sea surface temperature (°C) for Chimbote (lat. 09°10′S, long. 78°31′W), Peru; anomalies of rainfall (millimeters) for Tarawa (lat. 01°21′N, long. 172°55′E), Gilbert Islands; and anomalies of 200-850 millibar atmospheric thickness (geopotential meters) for Majuro Island (lat. 07°05′N, long. 171°23′E) for 1966-81.

a 5-yr research and training project that developed and passed on the technique for hydroacoustic surveying of fishery stocks.) Karl Johannesson, FAO team leader at the Centre during the project, mentioned that one would only have to go back to 1973 to find that about 95% of the total pelagic biomass off Peru was anchoveta, but by the end of the project it was about 30% or less. He noted that the whole ecological system had been changed after a brief recovery of the stock in early 1976. It was also noted in the Peruvian fishery that at the same time the decline in the anchoveta stock was being observed, other species, such as sardine and mackerel, began to grow (Ceres 1981). The Centre calibrated its equipment for these species, and after several surveys estimated stocks at between 5 and 8 million tons. Vondruska (1981) noted the sharp fall in Peru's production and exportation of fishmeal in 1977 and attributes it to the adverse effects of both heavy fishing and El Niño in 1976. Over the past 5-6 yr Ceres (1981) reported that the Peruvian anchoveta fishery has operated under a set of regulations covering length of season, size of individual fish taken, and maximum allowable catch.

The fisheries along the north Chilean coast, like those off Peru, are sensitive to environmental disturbances (Brandhorst et al. 1968; Cañon 1978; Quinn 1980b; Caviedes 1981). The Southern Oscillation-related El Niño type conditions affect both fisheries. Table 3 of Vondruska (1981), which extends through 1979, shows the combined Peru plus Chile fishmeal production to be particularly low in 1973, 1975, and 1977. In both fishery areas, species other than anchoveta (e.g., mackerel, sardines) have become more important over recent years. Off northern Chile there has been a decline in the anchoveta catches since 1970, but there was an extremely steep decline after 1976 (figure 4 of Caviedes 1981). Since recent environmental changes, as represented by the Southern Oscillation index trend (Fig. 1), may have played a significant part in the recent unusual west coast South American fishery changes, we wish to consider them in the light of past history and to determine the cause for the persistently low indices since 1976.

Background and definition of terms frequently used in this article follow. Southern Oscillation indices (differences in sea level atmospheric pressure between sites located in the South Pacific subtropical high pressure region and the Indonesian equatorial low region) are used to represent the Southern Oscillation (Quinn 1974; Quinn et al. 1978). In this respect it was proposed that they be used to monitor and predict Southern Oscillation-related, short-term climatic changes over the equatorial Pacific, the oceanic region off the northwest coast of South America, and the Indonesian region. Although we have used many different indices in our studies, we find the Easter-Darwin, Totegegie-Darwin, and Rapa-Darwin indices to be most effective for following and assessing developments. Details concerning processing of the index data are included in the following section.

Hushke (1959) defined El Niño as a warm ocean current setting south along the coast of Ecuador, so called because it generally develops after Christmas. In exceptional years, concurrent with a southerly shift in the tropical rain belt, he stated that the current may extend southward along the coast of Peru to lat. 12°S. When this occurs, he reported that plankton and fish are killed in the coastal waters and a phenomenon somewhat like the red tide of Florida results. Through common usage, most publishers and scientists now refer to El Niño as the exceptional year event of Hushke. Also, on learning more about El Niño and the fishery it affects, the definition has been altered accordingly, since it not only involves the thin southward flowing equatorial surface water layer but an influx of waters from the west and northwest beneath this surface layer. The invading thin surface layer has a significantly lower salinity than the subtropical surface water further to the west of the Peru coast, and it is nutrient depleted unlike the cool, highly productive Peru current and its coastal upwelled waters that usually prevail along the Peruvian coast. These infrequent invasions ordinarily set in during the Southern Hemisphere summer season, when sea temperatures are at a seasonal high, but they may set in well into the fall; and the effects may persist for a year or more. Additional symptoms of the stronger El Niño, some or all of which may be noted, are torrential downpours, flood, and erosion in the normally arid coastal lowlands of northern Peru; red tide; invasion by tropical nekton; and mass mortality of various marine organisms, including guano birds, sometimes with subsequent decomposition and release of hydrogen sulphide (Wooster 1960). It occurs at irregular intervals—may appear 2 yr in succession and then not reappear for another 3-12 yr [refers to the moderate and strong categories of Quinn et al. (1978) which seriously affect the fishery]. El Niño is the regional manifestation of a large-scale ocean-atmosphere fluctuation (Southern Oscillation), and it is brought about by relaxation from a prolonged period of strong southeast trades (represented by rising and high Southern Oscillation indices) (Quinn 1974; Wyrtki 1975). The magnitude of the southeast trade relaxation (as indicated by falling and low Southern Oscillation indices) and its timing in relation to the regular regional seasonal relaxation determine the strength of the resulting El Niño (Quinn 1979). During the period of prolonged strong southeast trades and equatorial easterlies, the south equatorial current is intensified, coinciding with an east-to-west buildup in sea level and an accumulation of warm water in the western Pacific; and, as soon as the wind stress relaxes, the accumulated water flows eastward, probably in the form of an internal equatorial Kelvin wave (Wyrtki 1975). This wave leads to the accumulation of warm equatorial undercurrent water off Ecuador and Peru and to a depression of the usually shallow thermocline there. In addition to the generation of internal Kelvin waves and Rossby waves, as discussed by Hurlburt et al. (1976) and McCreary (1976), it is assumed that the eastward-flowing currents (i.e., the North Equatorial Countercurrent, South Equatorial Countercurrent, and Equatorial Undercurrent) are intensified, and the westward-flowing South Equatorial Current is weakened when the relaxation occurs (Wyrtki et al. 1976). Hydrographic data off the coasts of Ecuador and Peru confirm the thermal structure depression and poleward spreading during El Niño (Enfield 1981); although upwelling may continue, it is from the accumulated warm water above the base of the thermocline, and this too causes coastal surface waters to be much warmer and less productive than water from the usual source, the Peru Current.

At times we use the broader connotation "El Niño type" when describing events, in order to avoid arguments as to what is and what is not an El Niño; in this way, we can account for events that evolve in a similar manner (associated with falling and low Southern Oscillation indices), but which vary in timing, intensity, and extent (Quinn et al. 1978). We will also at times refer to the contrasting anti-El Niño phase where a strengthening and strong southeast trade and equatorial easterly system prevails (associated with rising and high Southern Oscillation indices) (Quinn et al. 1978). It appears that most of the large short-term climatic changes, and their characteristic current and weather patterns over the lower latitudes of the Pacific, are associated with either El Niño or anti-El Niño phases of the Southern Oscillation.

METHODS

Data Processing

Rainfall data for Santiago and Valparaiso prior to 1931 were obtained from Taulis (1934). Rainfall data for Valparaiso 1931-80 were obtained from the Servicio Meteorologico, Armada de Chile. Rainfall data for Santiago 1931-80, La Serena 1869-1980, and Tarawa 1966-81 were obtained for applicable years from the World Weather Records (Clayton 1927, 1934; Clayton and Clayton 1947; U.S. Department of Commerce 1959, 1968) and the Monthly Climatic Data for the World (U.S. Department of Commerce 1961-81). The sea level atmospheric pressure data and upper level pressure versus geopotential height data (used to obtain atmospheric thickness data between the 850 and 200 mbar levels in Figure 1) were obtained for applicable years from previously listed U.S. Government sources. Sea surface temperature (SST) data for Chimbote were obtained from the Instituto del Mar del Peru. SST analyses for the southeast Pacific were obtained from Fishing Information (National Marine Fisheries Service 1976-80) and a continuation of those analyses for 1981-82 by Forrest Miller of the Inter-American Tropical Tuna Commission at the Southwest Fishery Center, National Marine Fisheries Service, NOAA, in La Jolla, Calif.

The use of the triple 6-mo running mean filter on monthly anomalies of various atmospheric and oceanic variables (i.e., Fig. 1) has been discussed in Quinn et al. (1978). An 11-yr running mean filter was used on the longest annual rainfall records available for Santiago and Valparaiso (Fig. 2). Our selection of the 11-yr running mean for smoothing the data was based in part on the desire for a decadal filter and in part on the sunspot cycle having an average length of 11.1 yr. Although 11-yr cycles have been suggested for various tropospheric phenomena, none of these has been substantiated (Hushke 1959).

Classifications of Activity

The classification of El Niño events by intensity was accepted from Quinn et al. (1978). Since we had a Southern Oscillation index and more reliable information concerning El Niño intensities available after 1860, our study concerning El Niño intensities, event frequencies, and the corroborative subtropical Chilean rainfall data was limited to the period from 1861 on (see Tables 2-6).

In Tables 3, 4, and 5 the rainfall classifications of <200 mm for Santiago and <300 mm for Valparaiso were selected to represent unusually dry years; and the classifications of ≥500 mm for Santiago and ≥ 600 mm for Valparaiso were selected to represent unusually wet years.

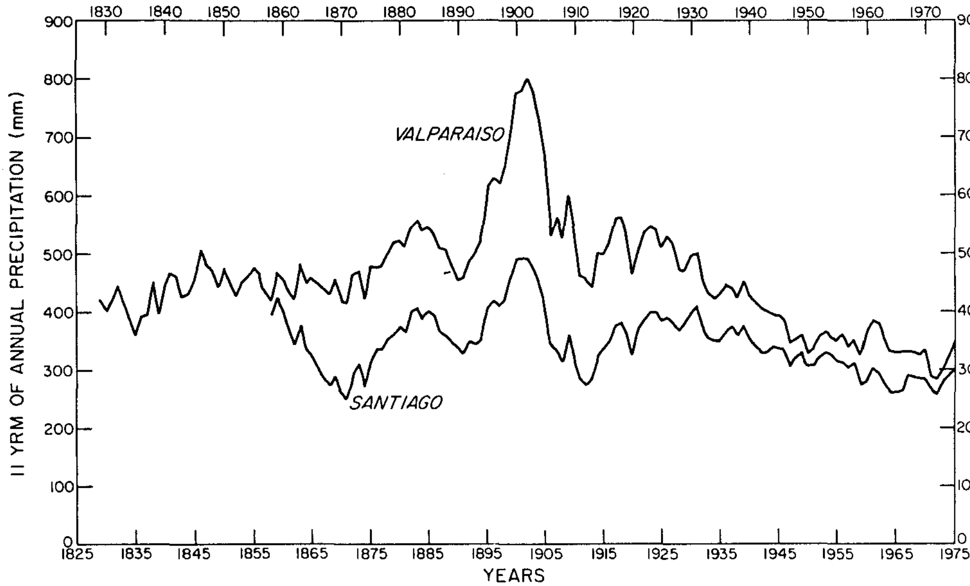

FIGURE 2.—Eleven-year running mean (11-YRM) plots of annual precipitation amounts (millimeters) for Santiago (lat. 33°26'S, long. 70°50'W) and Valparaiso (lat. 33°01'S, long. 71°39'W), Chile, for 1853-1980 and 1824-1980, respectively.

LONG-TERM VARIATIONS

Southern Oscillation-Related Activity

Large demands on the Peruvian anchoveta fishery over the past couple of decades to support fishmeal production have caused increasing concern over El Niño occurrences, since they adversely affect this fishery. As a result, many articles on El Niño, both scientific and popular, have appeared in periodicals and other news media over recent years. So much emphasis has been placed on recent El Niño-type events, regardless of intensity, that those without the historical background on this subject might think this type of activity has increased in frequency and intensity over recent years. Our findings indicate this is definitely not the case.

It was Berlage's (1957) opinion that the Southern Oscillation (the large-scale atmospheric circulation fluctuation with which El Niño is associated) was less regular and less intensively developed after 1925 than it was before. Accepting Berlage's breakpoint after the 1925 El Niño and using tables 3 and 5 in Quinn et al. (1978) to obtain times between onsets of moderate/strong events and between onsets of all events (very weak, weak, moderate, and strong), respectively, we derived the data in Table 2. The average time between event onsets, regardless of intensity, was the same for 1925-76 as it was for 1864-1925. However, the average time between onsets of the significant (moderate/strong) El Niños was much less for 1864-1925 (4.1 yr) than it was for 1925-76 (6.4 yr). Therefore, it appears that the average frequency of occurrence of the irregular atmospheric circulation fluctuations, known as the Southern Oscillation, has not changed significantly over the past 120 yr; but the number of those fluctuations resulting in moderate/strong El Niños has decreased considerably over the past half century.

In our investigation of this intensity shift, we followed up on findings in Quinn et al. (1981) which showed the Chilean subtropical rainfall fluctuations (for Santiago and Valparaiso) to be closely related to the El Niño/anti-El Niño conditions for 1875-1930.

TABLE 2.—Statistical information pertaining to the frequency of occurrence of the highly significant moderate/strong El Niño (Case I) and all events regardless of intensity (Case II) (from Quinn et al. 1978).

Period considered	No. of events[1]	No. of periods between events	Average time (yr) between events
Case I	strong/moderate		
1864-1925	16	15	4.1
1925-1976	9	8	6.4
Case II	all intensities		
1864-1925	20	19	3.2
1925-1976	17	16	3.2

[1]Here we refer to separate events, the onset times for separate events, and the interval between onset times (e.g., the 1925-26 El Niño was a single event with onset in 1925, the 1957-58 El Niño was also a single event with onset time in 1957).

The large rainfall amounts occurred in those years when moderate/strong El Niños were setting in or occurring. The frequency of occurrence of years with abnormally heavy rainfall at Santiago and Valparaiso appeared to decrease significantly after 1930 (based on contents of table IIIB of Taulis 1934 and Table 1 here). At Santiago about 23% of the years 1861-1930 had rainfall amounts ≥500 mm, whereas only 8% of the years 1931-80 had rainfall amounts in this category; and at Valparaiso 30% of the years 1861-1930 had rainfall amounts ≥600 mm, but only 6% of the years 1931-80 had rainfall amounts in this category (Table 3). Tables 4 and 5 show the rainfall category breakdown by decade for Santiago and Valparaiso, and substantiate the decrease in wet years over the past 5 decades when significant (moderate/strong) El Niños were less frequent.

The smoothed rainfall plots for Santiago and Valparaiso (Fig. 2) show prominent rainfall peaks near and shortly after the turn of the century. Over the 7-yr period 1899-1905 the average annual rainfall was extremely high at La Serena, Santiago, and Valparaiso (Table 6). During this period there were three moderate/strong El Niños (Quinn et al. 1978) which resulted in very large rainfall amounts in 5 of the 7 yr (table 5 of Quinn et al. 1981).

The prominent El Niño/anti-El Niño-related rainfall departures are primarily confined to the Chilean subtropics. Data from stations near lat. 40°S, at

TABLE 3.—Percentage of years with annual rainfall (in millimeters) in designated categories over indicated periods for Santiago (lat. 33°26'S, long. 70°50'W) and Valparaiso (lat. 33°01'S, long. 71°39'W), Chile.

Stations	Percentage of years in indicated categories							
	1861-1930		1931-1980		1861-1944		1945-1980	
Santiago	<200 mm	—500 mm	<200 mm	—500 mm	<200 mm	—500 mm	<200 mm	—500 mm
	17.1%	22.9%	22.0%	8.0%	14.3%	21.4%	30.6%	5.6%
Valparaiso	<300 mm	—600 mm	<300 mm	—600 mm	<300 mm	—600 mm	<300 mm	—600 mm
	12.9%	30.0%	38.0%	6.0%	13.1%	27.4%	47.2%	2.8%

TABLE 4.—Number of years per decade that annual rainfall was within indicated categories, the average rainfall by decade, and similar data for the 7-yr peak rainfall period (1899-1905) at Santiago (lat. 33°26'S, long. 70°50'W), Chile.

Decade	Rainfall categories in mm			Decadal annual average
	<200	200-499	≥500	
1861-1870	3	5	2	304.4
1871-1880	3	5	2	352.2
1881-1890	1	7	2	371.3
1891-1900	1	6	3	422.1
1901-1910	2	5	3	360.6
1911-1920	1	7	2	341.2
1921-1930	1	7	2	393.6
1931-1940	0	9	1	334.8
1941-1950	1	8	1	336.8
1951-1960	2	7	1	317.7
1961-1970	4	6	0	265.6
1971-1980	4	5	1	294.7
Peak period				Peak period annual average
1899-1905	1	1	5	568.5

TABLE 5.—Number of years per decade that annual rainfall was within indicated categories, the average rainfall by decade, and similar data for the 7-yr peak rainfall period (1899-1905) at Valparaiso (lat. 33°01'S, long. 71°39'W), Chile.

Decade	Rainfall categories in mm			Decadal annual average
	<300	300-599	≥600	
1861-1870	2	6	2	451.7
1871-1880	0	5	2	484.2
1881-1890	1	6	3	504.6
1891-1900	1	5	4	639.1
1901-1910	1	5	4	597.7
1911-1920	3	5	2	498.7
1921-1930	1	5	4	534.2
1931-1940	2	8	0	410.5
1941-1950	3	5	2	380.9
1951-1960	4	6	0	349.7
1961-1970	6	3	1	340.5
1971-1980	4	6.	0	356.6
Peak period				Peak period annual average
1899-1905	0	2	5	906.9

TABLE 6.—Average annual rainfall and departure from overall average (DA) (in millimeters) for indicated periods at three subtropical Chilean stations: La Serena (lat. 29°54'S, long. 71°15'W), Santiago (lat. 33°26'S, long 70°50'W), and Valparaiso (lat. 33°01'S, long 71°39'W).

Period	La Serena[1]		Santiago		Valparaiso		Notes
	Avg.	DA	Avg.	DA	Avg.	DA	
1861-1930	137.0	+20.2	359.8	+20.8	530.0	+67.6	
1931-1980	91.8	−25.0	309.9	−29.1	367.6	−94.8	
1861-1944	133.9	+17.1	360.8	+21.8	515.8	+53.4	
1945-1980	80.8	−36.0	288.2	−50.8	337.6	−124.8	
1899-1905	224.9	+108.1	568.5	+229.5	906.9	+444.5	Peak period average
1861-1980	116.8		339.0		462.4		Overall average

[1]For La Serena the precipitation record is limited to 1869-1980.

times, register these Southern Oscillation-related changes, but to a lesser degree.

Additional Considerations

Although a decrease in frequency of occurrence of moderate/strong El Niños might be expected to have some affect on average annual rainfall, the rainfall records for recent decades show a sizeable decrease in amounts for El Niño, anti-El Niño, and intermediate years as well for subtropical Chile. Rainfall data (table 5 in Quinn et al. 1981 and Table 1 here) show that a significant decrease in average annual rainfall at Santiago and Valparaiso occurs after 1944. Table 6 shows large negative departures from the long-term averages at La Serena, Santiago, and Valparaiso for 1945-80. This climatic change, which is also primarily noted over subtropical Chile, indicates another source for change. It appears that the desert conditions that have prevailed over northern Chile have been spreading further southward into subtropical Chile for several decades. Discussions with Chilean scientists confirm that this is occurring.

This decrease in rainfall over the arid region between the west coast and the westernmost ranges of the high Andes also appears to be affecting western Peru. Santiago E. Antuñez[2] stated that his 70-yr regression analysis of river runoff in western Peru showed that a very serious decrease in runoff was occurring. The extremely arid zone between the west coast of South America and the westernmost ranges of the high Andes and extending from about lat. 30°S almost to the Equator (as described in Lettau and Lettau 1978) appears to be becoming increasingly arid and slowly extending southward.

Obviously the heavy rainfall that occasionally occurs over the usually arid coastal lowlands of Peru during significant El Niños cannot be directly related to the heavy rainfall occurrences over subtropical Chile, although a superficial overview of statistics from year-to-year rainfall records might so indicate. Rainfall sources for these two areas, and times of year the rainfall occurs in each, differ. The association between these occurrences is indirect; the weakening of the southeast Pacific subtropical high (as represented by low Southern Oscillation indices) with a resulting slackening in the southeast trades facilitates both developments.

Abnormal southward advances of the intertropical convergence zone over the invading warm El Niño surface waters along the coasts of southern Ecuador and northern Peru cause the heavy rainfall over the usually dry coastal lowlands. This El Niño-related rainfall occurs during the Southern Hemisphere summer and/or fall, a time when the regular annual weakening of the trades augments this irregular interannual slackening (Caviedes 1975).

Years of abnormally heavy rainfall in subtropical Chile result when storms of the westerly belt penetrate further to the north than usual into subtropical Chile during the Southern Hemisphere winter (sometimes including late fall and/or early spring) months, as a result of degeneration of the southeast Pacific high and/or displacement of the weakened high center. This is similar to what happens north of the Equator when the northeast Pacific subtropical high breaks down, and we get unusually heavy rainfall down into the southwestern United States and northwestern Mexico during the Northern Hemisphere winter.

RECENT CHANGES IN THE PERUVIAN AND NORTHERN CHILEAN ANCHOVETA FISHERIES

Up through a little beyond the first half of this century, the principal drain on the Peruvian anchoveta fishery at shallow depths was the heavy consumption by guano birds, on which Peru's guano industry depends. Demands of the fishermen over these earlier years were quite modest, and their catches extended to depths to which the birds could not reach. During significant El Niños the anchoveta were no longer abundant at shallow depths, and large numbers of guano birds died of starvation along the Peruvian coast while others left the affected area. Yet, limited demands of fishermen at that time and the great reduction and slow recovery in bird populations following El Niños permitted a suitable recovery of the fishery during the subsequent anti-El Niño periods. However, by the late 1950's the growing fishmeal industry was placing increasingly large demands on the anchoveta fishery to meet fishmeal production quotas. The anchovy fishery made Peru the leading fish-producing nation from the late 1960's through 1971 (Idyll 1973). The record catches of 1970-71 followed by the strong 1972-73 El Niño led to a precipitous drop in fishmeal production through 1973 (Fig. 3), from which there has never been a significant recovery. In 1972 and 1976, fishing continued through the principal fishing season (March-May) without taking into account the El Niños already underway. In retrospect, for these

[2]Santiago E. Antuñez, Universidad Mayor de San Marcos at Lima, Peru, pers. commun. 14 August 1978.

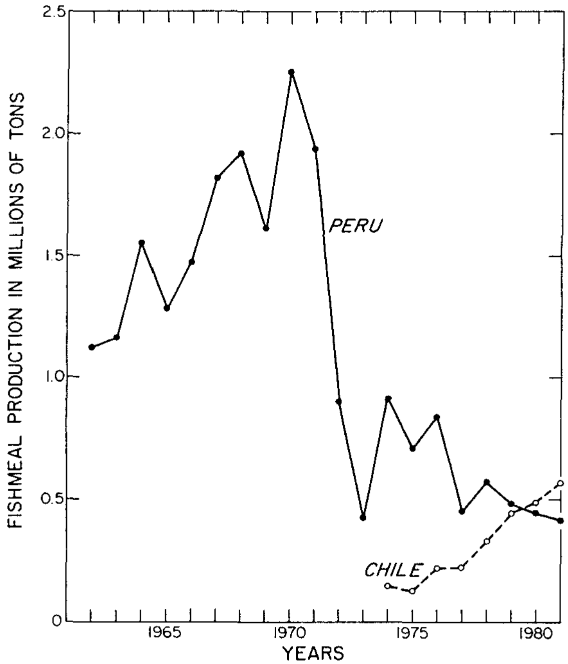

FIGURE 3.—The Peruvian fishmeal production for 1962-81 and Chilean fishmeal production for 1974-81 in millions of metric tons as obtained from National Marine Fisheries Service (1977, 1979, 1981, 1982).

cases it might have been advantageous to conserve reproductive stocks (ban fishing) in order to minimize subsequent recruitment failures. It appears that the operating regulations since the 1976 El Niño, as reported in the introductory section, were initiated much too late to benefit the anchoveta.

Available information on the fishery off northern Chile, along with the El Niño-related effects on it, is quite limited; nevertheless, contents of the introductory section and the previous section indicate it should be included in this discussion. Over the past 2 decades the fisheries off the coast of northern Chile, although not as productive formerly as those off Peru, have been likewise exploited most of this time without regard for conservation of the fish population. However, we must realize that whereas anchoveta, as a percentage of the catch, was still at the 95% level in 1973 in the Peruvian fishery (Ceres 1981), it declined from a level of 70-80% of the catch off northern Chile before 1970 to a little over 30% by 1973; and after the 1976 El Niño the percentage dropped precipitously to <10% of the northern Chilean catch for 1977, with sardines, jurel, and other fish making up the rest of the catch (figure 4 of Caviedes 1981). This would indicate that the decline in anchoveta, as a percentage of catch, showed up several years earlier off the coast of northern Chile than it did off the coast of Peru. Also, the substantial increase in other fish (e.g., jurel, sardines) was noted earlier off northern Chile than was the increase in sardines and mackerel off Peru (Ceres 1981; Caviedes 1981). It is interesting that Caviedes (1981) reported the largest jurel catches off northern Chile during the El Niño-related years of 1973, 1975, and 1977, the same years that Vondruska (1981) in his table 3 showed the combined Peru plus Chile production of fishmeal to be at its lowest levels.

Since 1976 the SST's over the tropical and subtropical southeast Pacific, as evidenced in the Fishing Information (National Marine Fisheries Service 1976-80) and Forrest Miller's continuation analyses, have remained near or above normal; and sea level pressures in the South Pacific subtropical ridge, as represented by pressures at Easter, Totegegie, and Rapa Islands, have averaged below normal over this same period. An indication that this was taking place was shown earlier in figure 7 of Quinn (1980b). Instead of having a compensating prolonged rise in the Easter-Darwin index to high positive anomalies following the deep index anomaly trough of the 1976-77 event, as one would ordinarily expect after an El Niño, the index has remained unusually low. It has averaged about 2 mbar below normal over the past 75 mo (April 1976-June 1982), and 78% of this abnormally low value was caused by the contribution of the Easter Island pressure component. In the past, it was usually during the high index anti-El Niño periods that the Peruvian anchoveta fishery recuperated. During this extended low index period the Peruvian fishmeal production has continued its pattern of decline (Fig. 3) to the extent that Peru has fallen from its position of leading fishmeal producer in the Fishmeal Exporters Organization to a number two position behind Chile for 1980 and 1981. Although Peruvian fishermen modified their efforts so as to also catch the types of fish which have recently become more numerous (e.g., mackerel and sardines), this modification was necessitated by the change in composition of the pelagic biomass (which showed a drastic reduction in the anchoveta). As mentioned before, a similar change in biomass with a drastic reduction in anchoveta also occurred in the fisheries off northern Chile, although this change off northern Chile started setting in earlier. How much of the change in fishery composition has been the result of fishing practices (e.g., overfishing) and how much can be attributed to environmental change or other ecological factors is questionable; however, it is our opinion that the recent unusual climatic trend, as represented by the abnormally low Southern Oscillation index and the greatly reduced amplitude in index fluctuations (Fig. 1), has played a significant part in bringing about this change.

DISCUSSION

Thermal and Pressure Changes and Their Effects

We were interested in determining the cause for the persistent abnormally low sea level pressures in the southeast Pacific subtropical anticyclone over the past 6 yr. Petterssen (1940) explained that in the central parts of anticyclones, or belts of high pressure, the air is stagnant or slowly moving, and it therefore has sufficient time to adjust its temperature and moisture content to the underlying surface. The circulation around anticyclones is divergent, and properties absorbed in the central parts are, therefore, spread over large areas, while turbulence and convective currents gradually distribute the absorbed properties to higher levels (Petterssen 1940). Our limited studies at other marine locations illustrate this adjustment of properties in the overlying atmosphere to changes in the underlying ocean surface (Quinn 1977, 1980a, b; Quinn et al. 1981). Rises in SST relate to rises in surface air temperature, falls in sea level pressure, and increased thicknesses between pressure levels aloft. Falls in SST relate to falls in surface air temperature, rises in sea level pressure, and decreased thicknesses between pressure levels aloft. Talara data in figure 13 and table 4 of Quinn (1980a) show close correlations between SST, surface air temperature, and sea level pressure; however, on the average there is about a 1 mo lead on the part of SST changes over the associated changes in air temperature and sea level pressure. (Changes in sea level on the average lead changes in SST by 1 mo at Talara.) Figures 6 and 7 of Quinn et al. (1981) show close associations between SST and thickness changes between pressure levels aloft, and Table 2 of this article indicates thickness changes between pressure levels near the surface precede related changes in thickness between pressure levels at higher altitudes.

In our opinion, it is primarily the relatively persistent in-sync relationship over the past 6 yr, between the generally above normal SST's and the generally below normal sea level pressures over the subtropical southeast Pacific, which has caused the below normal Southern Oscillation index and the reduced amplitude of fluctuations in this index. As a representation of the Southern Oscillation, the index trend would indicate a significant reduction in amplitude of the Southern Oscillation over this period. How much longer this low index condition will prevail and what will cause a return to the large fluctuations of the past are not apparent at this time. However, a slow occasionally interrupted rise in the index has been noted over the past several years.

The below normal pressures in the subtropical high signify a generalized weakening of the associated southeast trades and equatorial easterlies, and the reduced amplitude of the index fluctuations signifies a reduction in the El Niño/anti-El Niño extremes in Southern Oscillation-related activity.

It appears to us that the generally weaker southeast trades and their reduced fluctuations in strength, which have prevailed over the past 6 yr, would not be capable of building up to the type of relaxation response called for by Quinn (1974), Wyrtki (1975), and Wyrtki et al. (1976), where Wyrtki's so-called "back sloshing" of the built-up water accumulation in the western Pacific produces a significant El Niño. Under existing conditions we would expect weaker responses to the smaller buildups, such as the 1979-80 event reported by Donguy et al. (1982). This event would be considered a relaxation response to the small 1978 anti-El Niño buildup. (Note the 1978 index peak in Figure 1.)

Changes in strength of the southeast trades and equatorial easterlies bring about changes in the Peru (offshore and coastal) current and equatorial current systems, and the Peru-Chile undercurrent, as discussed in the introductory section; and they, in turn, cause environmental changes in the Peruvian and north Chilean coastal fisheries. In addition to the generally above normal subtropical surface water temperatures, we also note that the Chimbote SST anomalies remain generally high during this period of low index anomalies (Fig. 1). One cannot fail to note the sharp drop in the anchoveta contribution to the overall catch after the 1976 El Niño in both the Peruvian and north Chilean fisheries; also, in both of these fishery areas the catch of other types of fish increased over this same period (Ceres 1981; Caviedes 1981).

Monitoring and Predicting the Changes

Considering the monitoring and prediction of El Niño, it must be realized that when the use of the Easter-Darwin index was initially proposed (Quinn 1974), it was intended for use on large interannual fluctuations leading to the onset of relatively strong events (e.g., 1957, 1972). This was particularly true for purposes of prediction, since the time involved in relaxation from a pre-event index peak to a projected index trough determines to a large extent how far in advance of event occurrence the outlook can be given (Quinn 1978). Nevertheless, we did find the indices useful in predicting the very minor 1975 event and moderate 1976 event. And, when we look at Figure 1, we can see that even the very small changes in index anomaly trends are reflected in the trends of other variables over various parts of the tropical Pacific. Additional Southern Oscillation-related changes in other variables over the tropical and subtropical region are shown in more detail in Quinn (1980a, b) and Quinn et al. (1978, 1981). Since Berlage (1957, 1966) and Troup (1965) indicated that the Southern Oscillation was not only involved with the South Pacific subtropical high, but also to some extent with the North Pacific subtropical high region, we monitor a Ship N-Darwin index (Quinn 1979). (With the demise of Ship N, we started using data obtained for its former coordinates: lat. 30°N, long. 140°W.) The northeast trades can contribute significantly to the equatorial easterly flow.

When one considers the nature of the short-term climatic changes and the time leads/lags in the involved variable changes, as shown in the articles referenced in the previous paragraph, one realizes that the significant changes in the atmospheric centers of action (the semipermanent highs and lows that appear on mean charts of sea level pressure; e.g., the South Pacific subtropical high, the Indonesian equatorial low, the North Pacific subtropical high) take place more nearly on the time scale of the oceanic circulation and thermal pattern changes. Therefore, the centers of action are more likely to respond measurably to significant oceanic changes and vice versa; it is through monitoring and projecting these involved large-scale, long-term changes that we are most likely to have a suitable basis for our short-term climatic outlooks. Results will be reflected in the influence these slower changing, large-scale features exert on the developments and trajectories of the rapidly moving transient storms that affect our day-to-day weather and sea conditions.

Significant changes in fishery populations also take place on the time scales of the large changes in atmospheric centers of action, oceanic circulation, and oceanic thermal anomaly patterns. In our opinion, through the monitoring and projection of appropriate pressure and circulation indices and other related variables such as sea level, SST, etc., a suitable basis for outlooks on fishery environmental changes and fishery catches could be provided. For the north Chilean fishery, in addition to the Southern Oscillation indices, we would also recommend use of the Easter-Quintero and Easter-Antofagasta 850 mbar height difference indices of Quinn (1980b). They can be used to represent interannual changes in strength of the low level flow (south to north components) over that part of the southeast Pacific with which we would be concerned. In the case of fisheries we will not only be concerned with interannual changes, but also the longer term changes such as those noted in the previous section.

CONCLUDING REMARKS

After seeing what has been happening to the Peruvian and north Chilean fisheries over the past decade or more, and how they are similarly affected by large-scale ocean/atmosphere changes, the need for a well-coordinated study of this west coast South American fishery region as a whole becomes apparent. In the past, investigations have been limited by the areas covered and the objectives of scientists involved. Most of the studies have been concentrated on the Peruvian coastal region. Investigations should cover an area extending in length from near the Equator to lat. 30°-35°S, and in width from the coast out to about 600 km seaward. Participants should include fisheries biologists, marine ecologists, physical oceanographers, meteorologists, and chemical oceanographers.

We will be interested in monitoring the current climatic situation to see what brings about an emergence from the extended period of abnormally low Southern Oscillation indices and the greatly reduced amplitudes in fluctuations of these indices.

We will also be interested in further investigation of the very long-term climatic changes that have been occurring over western South America between the coast and the westernmost ranges of the Andes. This will include further study of the following noted changes in rainfall characteristics over subtropical Chile: 1) The decrease in frequency of abnormally heavy El Niño-related rainfall after 1930, and 2) the sizeable decrease in average annual rainfall after 1944.

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