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INFLUENCE OF EL NINOS ON CALIFORNIA'S WAVE CLIMATE

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ABSTRACT

Waves with exceptional height and periods caused severe damage along the coast of California in 1982-83. Because these large wave events coincided with a strong El Nino-Southern Oscillation (ENSO) climatic anomaly, which occurs 20-25 times per century, there was interest in determining if the extreme waves resulted from the ENSO or its related features. The meteorological setting featured a very large and intense low pressure zone over the north-central Pacific. Associated with this Pacific-wide pattern, a series of large mid-latitude storms developed at about weekly intervals and produced exceptionally long fetchs directed at the California Coast.

Two time series of extreme wave events, using buoy data after 1981 and hindcasts before, were used covering the period from 1900 to 1984. One series considered waves with significant heights greater than 3 m (10 ft) and the second for those greater than 6 m (20 ft.) These were compared with a time history of ENSOs for the same period. A strong association was established between northern hemisphere winters during ENSO years and large wave events in Southern California. Strong ENSO winters had the largest storm waves, moderate ENSOs less intense waves, and weak ENSOs tended not to have storm waves greater than the threshold value used in this study. The correlation between large waves and ENSO years is significant at the 1% level. The correlation between lack of large waves and non-ENSO years is significant at the 0.5% level.

Because of the great southerly extent of the most energetic storms, a large number of energetic wave trains approach the coast from the west, rather than the northwest, as previously assumed by many. ENSO winters are responsible for producing all of the wave events in this study with both heights greater than 6 m and periods of peak energy longer than 19 seconds.

Five out of nine eastern Pacific tropical storms making landfalls on California in the 85 year period occurred during the late northern summer of ENSO years.

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INTRODUCTION

During the Winter of 1982-83, a series of extraordinary storms attacked the coast of California. Shoreline damage was severe, particularly in Southern California, and was accompanied by unusual coastal plain flooding in many areas. The extreme sea levels causing this flooding and an assessment of the nearshore waves and their impacts are discussed in two papers in these proceedings (see Flick and Cayan,1984 and Walker,Nathan,Strange and Seymour,1984.) The wave fields associated with these storms attracted particular attention because of the extremely long peak periods as well as the great wave heights. To many observers, the number and intensity of these storms exceeded that of any winter within memory.

The year 1982, which immediately preceeded the most intense storms during January-March of 1983, was climatologically exceptional. We now know that a very strong El Nino - Southern Oscillation (ENSO) event began in the late spring of 1982. At the time, the time sequence of equatorial oceanic warming and trade wind reversal was several months later than most previous ENSOs, causing lively debate among oceanographers and climatologists as to whether there really was an ENSO occurring (see Kerr, 1983.) The impact of ENSOs on productivity in South American coastal waters has been well studied for many years. Only recently, motivated in part by the extreme nature of the 82-83 ENSO. have scientists understood the global impacts of the event, including droughts and excessive rainfall over large areas outside of the tropics. (For a review of ENSO see Philander, 1983.) There was a second major climatological perturbation almost coincident with the onset of the ENSO - the eruption of the Mexican volcano, El Chichon. Although its total ejected mass was much smaller than, say, Mount St. Helens, it was one of those rare eruptions that results in very large quantities of sulfuric acid in the stratosphere. This contaminant, with a long persistence, spread completely around the globe in a broad band straddling the equator. There is evidence from historical climate records that this kind of eruption can have pronounced effects on global climate (see Sigurdsson, 1982.) The superposition of the strong ENSO and El Chichon makes it very difficult to sort out the climatic effects of each event. The severity of the 1982 ENSO may even have been augmented by the influence of the El Chichon cloud, but our present level of understanding of climatology does not allow us to confirm or reject such interactions.

Volcanos rarely vent sulfides all the way to the stratosphere, but ENSOs occur perhaps 20 times in a century. It is therefore important, from a wave climatology standpoint, at the least to determine if ENSOs are likely to have been paramount in driving these severe storms. Therefore, the authors decided to test the relationship between ENSOs and large wave events by comparing time series from historical records.

THE 1982-83 LARGE WAVE EVENTS OFF CALIFORNIA

The NOAA observation buoy moored at approximately 35 N latitude and 121 W longitude measured six large wave events, each related to a massive storm in the Pacific Basin, that occurred in the period from December,1983 to March,1983. The significant wave height exceeded 6 m (20 ft) in each of these events, as shown in Table I. These observations were made in deep water in unsheltered offshore locations.

The storm of 10 February, 1983, which produced the longest periods of this series, was studied in detail (see Earle et al., 1984.) Using all of the NOAA buoy data, this work showed that the significant wave height at the site closest to the storm was 12.9 m (43 ft) and that there was considerable energy up to periods as long as 25 seconds. This energy level would predict a maximum wave height of about 24 m (79 ft.)

In later sections of this paper, it will be shown that these storms rank as very extreme events in recent history.

THE METEOROLOGICAL SETTING

From a meteorological standpoint, the 1982-83 ENSO winter was most extraordinary, especially over the Pacific and adjacent continental margins. Not only was the Gulf of Alaska-Aleutian low pressure center unusually deep (as is often the case with northern hemisphere ENSO winters), but the low was, on average, large enough in areal extent and displaced eastward sufficiently to affect the West Coast and particularly California. This has not always been the case with ENSO winters (see Namias and Cayan, 1984.) Figure 1 shows the departure from normal of the 700 millibar (mb) height surface for winter, which is nearly equivalent to the anomalous pressure pattern at about 3 km (10,000 ft) aloft. It is shown to be abnormally low (negative) in a broad region centered in the southern Gulf of Alaska, and very high (positive) in the central Pacific subtropics. Symptomatic of this pressure distribution were the frequent massive and vigorous storms that tracked across the central North Pacific to make landfall along virtually the entire West Coast of the United States. In a more ususal winter, storms would be confined to landfalls at latitudes much further north.

The anomalous atmospheric angular momentum associated with these wind fields was studied by Rosen et al., (1984). This work shows that the transfer of angular momentum between the earth and the atmosphere was sufficient to change the length of the day by a few milliseconds during the winter of 1982-83.

Note that, although these storms were associated with an ENSO (a tropically based phenomenon), they were definitely extratropical disturbances. This is shown in Figure 2 by the cyclone tracks for March 1983. Figure 3 shows an infrared satellite image of two of the March 1983 storms. The storm fronts show greater development and a more southerly displacement than usual. Also note that there is no obvious connection of these storm systems with the tropics.

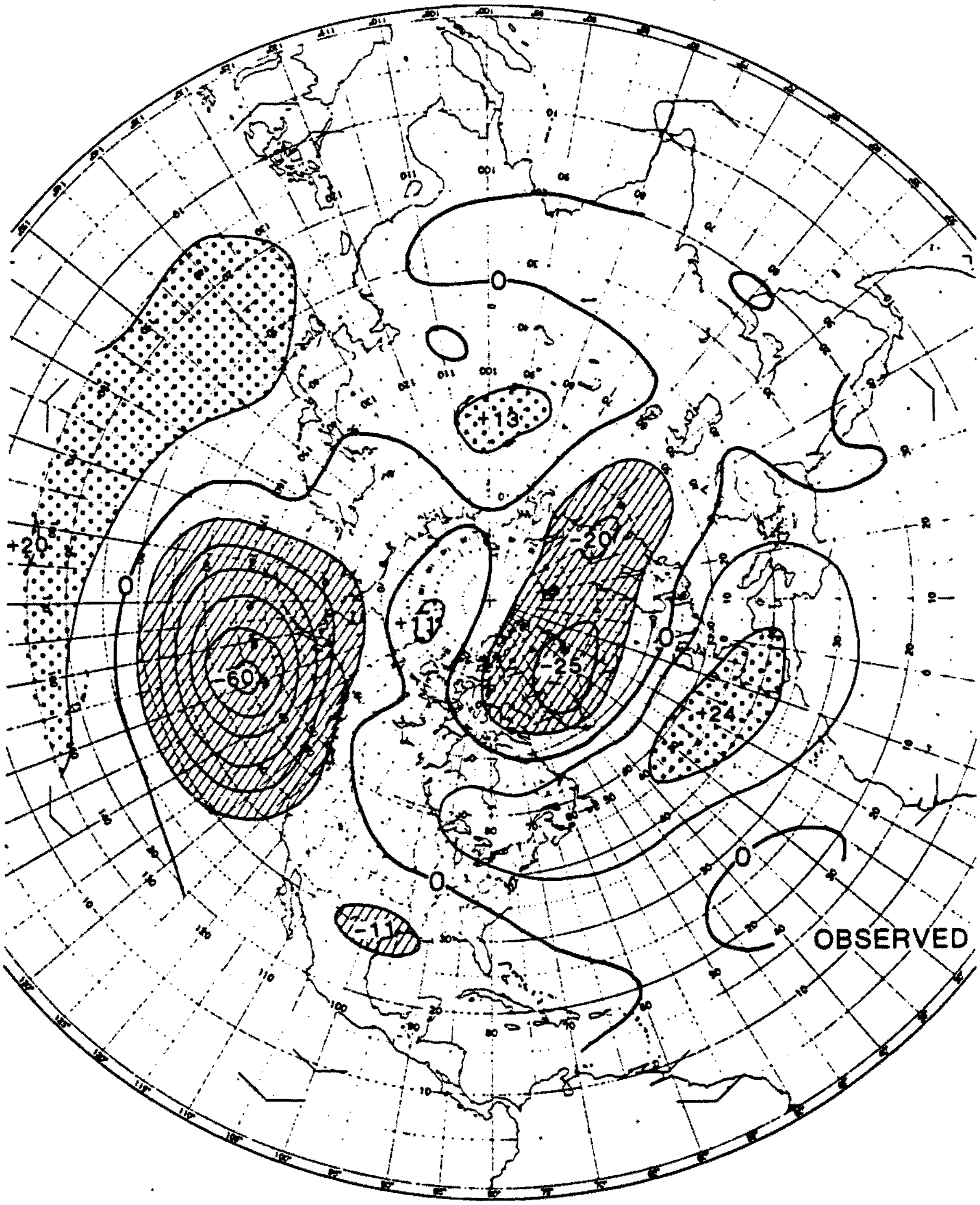

FIGURE 1

Winter 1982-1983 mean 700 mb. height anomaly in tens of feet. This is roughly analogous to the sealevel pressure anomaly. Winter is defined as December through February. Anomaly calculated against mean of 1947-1972 winters.

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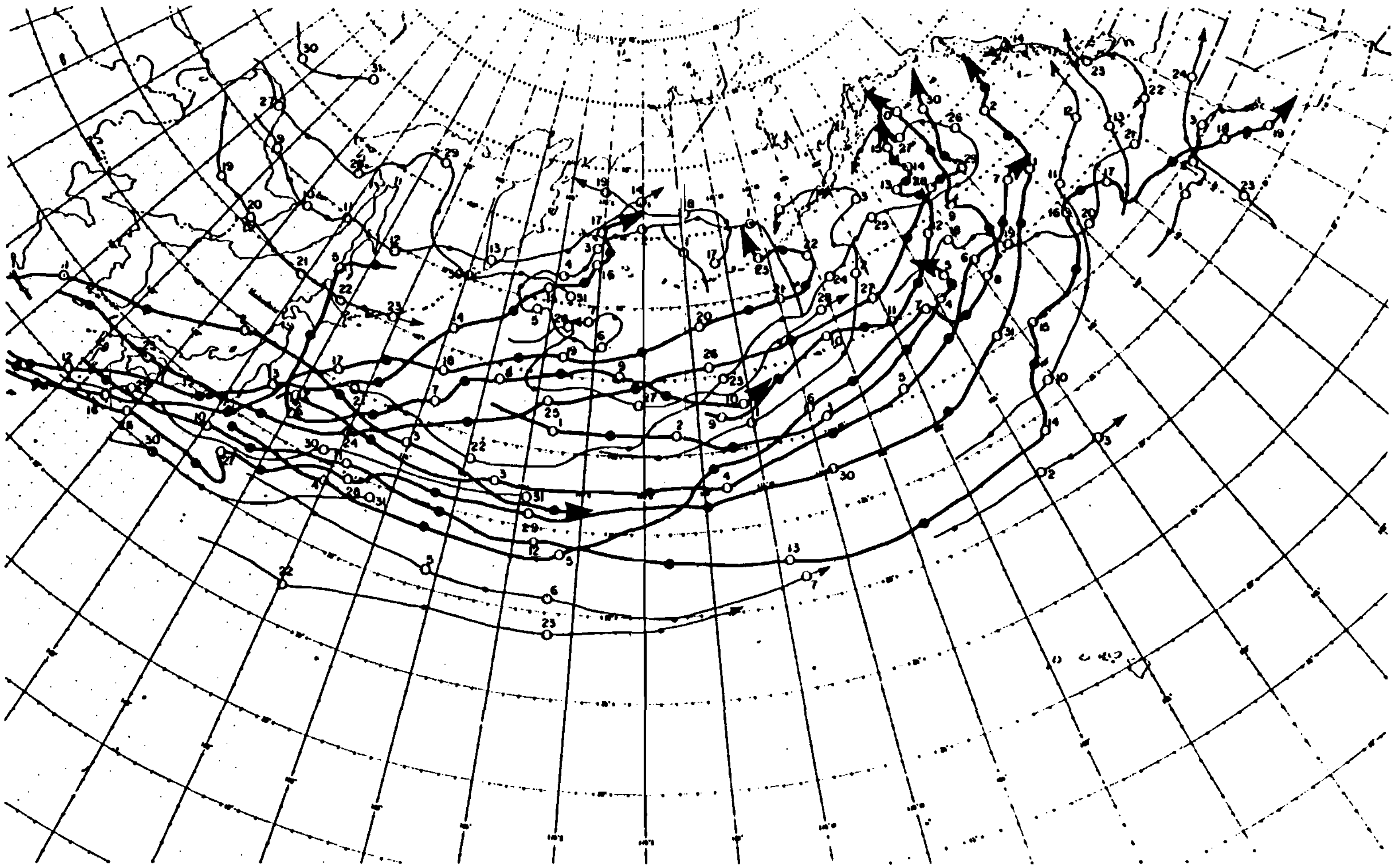

FIGURE 2

North Pacific cyclone (extratropical storm) tracks for March, 1983.
[From NOAA Mariner's Weather Log,:27, p182]

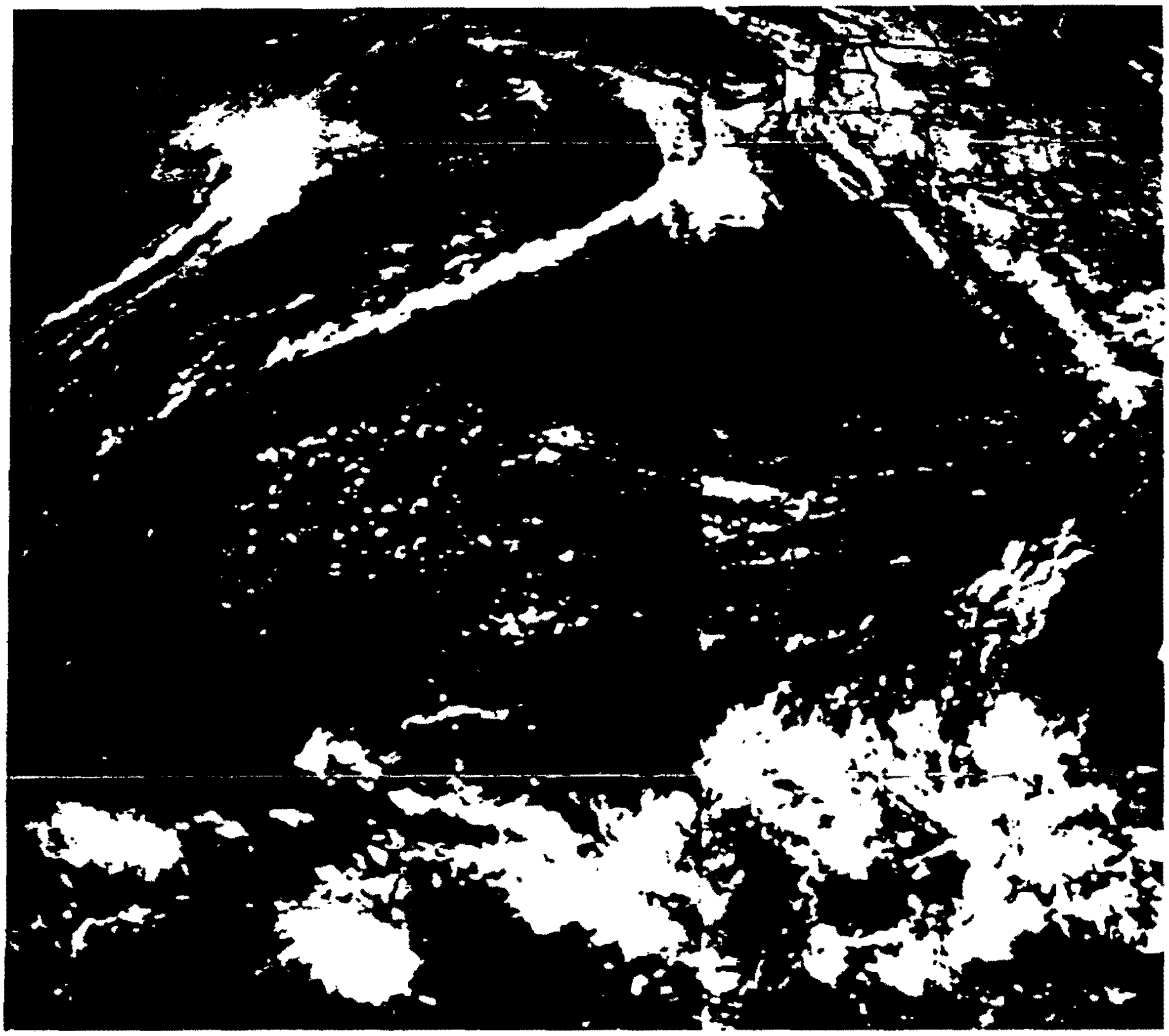

FIGURE 3

Satellite infrared image over North Pacific, March 4, 1983. High clouds (coldest) are shown in white. Low clouds (warm) are not distinguishable here. Note extensive frontal systems extending southward to 30 deg N, and lack of connection to intertropical convergence zone near equator.

TABLE I

NOAA BUOY OBSERVATIONS OF WAVES FROM MAJOR STORMS
WINTER 1982-83

DATE	SIG.HT. (m)	MAX. PERIOD	DIRECTION
01 DEC 82	6.4	14	295
18 DEC 82	6.4	20	288
25 JAN 83	6.1	17	278
27 JAN 83	7.3	22	279
10 FEB 83	6.7	25	281
01 MAR 83	8.2	20	258

These very large and intense low pressure centers resulted in fetchs on the order of 1000 km (550 nm) and wind speeds up to 30 m/s (60 kts.) Previous empirical models, still widely used today, would predict peak periods of only about 17 seconds for such conditions. Contemporary spectral wave generation models containing nonlinear wave interaction terms, however, are capable of predicting the very long periods actually generated in these storms.

It can be seen from Figure 1 that the wind vectors can be expected to rotate to the north as the storms approach the continent. In typical winters, this northward shift occurs (on avearge) about 2200 km (1200 nm) offshore. At this point, the winds no longer continue to increase wave height. Dispersion causes the swell to decay over these long distances, reducing the height of the waves as they approach the shore. During the winter of 1982-83, because of the very large size of the low pressure zone and the increased strength of the westerlies, the average decay distance was reduced to about 1600 km (900 nm.) These factors account for the increase in the swell height during these storm wave events. It should also be noted that the locally generated waves may be travelling north almost orthogonally to the swell, producing a very confused sea state in deep water.

HISTORICAL WAVE DATA FOR THE CALIFORNIA COAST

Systematic wave measurements in deep water off the West Coast of the United States have been available only since 1980. Therefore, any meaningful historical assessment must depend largely upon wave hindcasts. Contemporary hindcasts, based upon reliable pressure field data and satellite imagery, can provide wave energy spectra and directional estimates with satisfactory accuracy for engineering analyses. However, for pre-satellite years, and particularly prior to the mid-1940's, the meteorological data become less satisfactory and the accuracy of the wave hindcasts is degraded. There are a number of storm hindcast studies that have been performed for the California

Coast (e.g., see Marine Advisers, 1960 and Meteorology International, 1977.) These works suffered from short observation periods and, in at least one case, from serious methodological problems. The earlier works used a singular wave approximation, compared with the spectral approach now employed by contemporary hindcasters. Rather than attempting to patch together the work of several hindcasting studies in an attempt to acquire a long enough time history, we decided to use the work of a single hindcaster which spanned the whole interval from the inception of meteorological data (approximately 1900) to the advent of continuous deep water measurements in late 1980. One of us (RRS) has prepared such a series. It was hindcast for a location in Southern California at a latitude of about 35 N. This series was an attempt to identify wave trains expected to have a significant impact on the shoreline. Therefore, it included only those events with deep water approach directions in the zone between SW and WNW. Waves approaching more obliquely would be diminished considerably by refraction as they approached the shore. Further, the waves were ranked by their power (energy multiplied by period.) This resulted in a list of 59 storms in which the resulting offshore significant wave height exceeded 3 m (10 ft), all having periods equal to or exceeding 12 seconds. The tropical cyclone of September, 1939, a major wave event in Southern California, was added for a total of 60 storms. These storms are listed in Table II.

A second series was obtained by considering only the very largest events. The threshold significant wave height was raised to 6 m (20 ft.) The second series contains only 18 storms because of its higher limit value, as shown in Table III.

It should be clearly recognized that the possible quality of hindcast decreases with the age of the data, particularly prior to the 1950's. It is likely that some major storms in the early years were excluded because there was insufficient pressure field resolution and accuracy to estimate the real wind speeds. This is particularly true for small, intense storms like tropical cyclones. It is almost impossible to hindcast these storms prior to the availablity of satellite imagery. However, since no series of this length had previously been published, and since the work used a consistent methodology throughout, we felt that they would make a valuable contribution to our knowledge of the wave climate off California.

HISTORICAL RECORDS OF ENSO CONDITIONS

Using anomalies in the surface barometric pressure in the Indian and Pacific Oceans, combined with observations of fisheries in Peru and other similar data, Quinn et al. (1978) were able to develop a series of ENSO events covering more than 200 years. They also rated each event as strong, moderate or weak. The ENSOs since 1900 from this record are shown in Table IV. Quinn et al's ENSO series identifies events according to their onset years. For our purposes, it is the winter following the onset, when the mid-latitude connections are strongest, that would have possible consequences for Pacific waves.

TABLE II

EXTREME WAVE EPISODES EXCEEDING 3 M. (BASIC SERIES)
1900 - 1984

DATE	SIG.HT. (m)	MAX. PERIOD	DIRECTION
13 MAR 05	8.8	15	247
17 NOV 05	3.3	17	286
31 DEC 07	5.3	16	282
12 MAR 12	3.2	12	220
26 JAN 14	5.8	13	223
03 FEB 15	7.5	14	235
01 JAN 18	3.7	16	280
12 FEB 19	5.3	12	299
20 DEC 20	4.7	13	301
15 OCT 23	3.7	16	296
01 FEB 26	6.9	15	257
03 JAN 27	5.8	20	287
06 NOV 28	4.0	17	294
01 JAN 31	3.9	16	276
28 DEC 31	7.4	18	288
19 DEC 35	4.7	16	267
13 DEC 37	4.5	16	272
06 JAN 39	7.9	19	285
25 SEP 39	4.5	15	205
24 JAN 40	4.3	16	267
25 DEC 40	5.7	16	270
20 OCT 41	3.3	17	294
30 DEC 45	3.9	19	285
13 FEB 47	3.9	16	265
04 NOV 48	4.7	18	300
15 NOV 53	5.7	17	269
15 JAN 58	3.1	22	280
26 JAN 58	6.8	14	259
05 APR 58	7.7	18	289
16 FEB 59	5.1	14	244
09 FEB 60	8.1	19	295
22 DEC 60	3.4	17	276
31 JAN 63	4.2	16	260
10 FEB 63	5.9	15	256
19 NOV 65	4.0	15	277
07 DEC 67	4.0	15	298
06 FEB 69	4.7	13	222
04 DEC 69	3.6	17	278
06 DEC 69	4.9	22	274
14 DEC 69	5.7	17	290
19 DEC 69	4.7	18	281
26 DEC 72	4.1	15	289
21 FEB 77	5.2	18	280
29 OCT 77	5.5	20	299
16 JAN 78	6.0	13	240

TABLE II (cont.)

01 JAN 80	4.7	20	272
17 FEB 80	6.1	18	249
22 JAN 81	4.3	20	258
28 JAN 81	7.0	17	262
13 NOV 81	4.9	18	284
01 DEC 82	6.4	14	295
18 DEC 82	6.4	20	288
25 JAN 83	6.1	17	278
27 JAN 83	7.3	22	279
10 FEB 83	6.7	25	281
13 FEB 83	4.9	17	268
01 MAR 83	8.2	20	258
14 NOV 83	5.0	17	290
03 DEC 83	7.0	17	285
25 FEB 84	6.4	17	300

TABLE III

EXTREME WAVE EPISODES EXCEEDING 6 M.
1900 - 1984

DATE	SIG.HT. (m)	MAX. PERIOD	DIRECTION
13 MAR 05	8.8	15	247
03 FEB 15	7.5	14	235
01 FEB 26	6.9	15	257
28 DEC 31	7.4	18	288
06 JAN 39	7.9	19	285
26 JAN 58	6.8	14	259
05 APR 58	7.7	18	289
09 FEB 60	8.1	19	295
17 FEB 80	6.1	18	249
28 JAN 81	7.0	17	262
01 DEC 82	6.4	14	295
18 DEC 82	6.4	20	288
25 JAN 83	6.1	17	278
27 JAN 83	7.3	22	279
10 FEB 83	6.7	25	281
01 MAR 83	8.2	20	258
03 DEC 83	7.0	17	285
25 FEB 84	6.4	17	300

In four cases, one year adjustments were made in the onset years suggested by Quinn et al. The 1929 onset was changed to 1930 and the 1905, 1914 and 1939 onsets were changed to two year spans (1904-05, 1913-14, and 1939-40, respectively.) The basis for this was the timing of the peak of the Southern Oscillation (as determined from the Santiago-Darwin anomaly.) The onset year was adjusted to provide a uniform condition throughout the series in which the peak of the pressure anomaly occurred in the Spring or Summer. In addition, the

TABLE IV

ONSET YEARS OF ENSOS, 1900-1984
(From Quinn et al., 1978)

ONSET YEAR	SEVERITY
1902	Moderate
* 1904-05	Moderate
1911	Strong
* 1913-14	Moderate
1917	Weak
1918	Strong
1923	Weak
1925	Strong
* 1930	Moderate
1932	Weak
* 1939-40	Moderate
1941	Strong
1943	Weak
1951	Weak
1953	Moderate
1957	Strong
1965	Moderate
1969	Weak
1972	Strong
1976	Moderate
* 1982	Strong

* Modified from Quinn et al.

1969 ENSO was reclassified from weak to moderate, in the context of this study, because the pressure anomaly persisted for more than a year. The 1982 ENSO, which occurred after the Quinn et al. paper, was classified by us as strong. The ENSO predictions for the first half of the century are expected to be of higher quality than the wave hindcasts, since they did not depend upon the density of pressure measurements.

CORRELATIONS BETWEEN ENSO YEARS AND LARGE WAVE EVENTS

As was observed in 1982-83, increased storminess as a result of an ENSO condition would likely occur during the winter following onset. Therefore, storms in January through April of the year following the onset could be assumed to have been influenced by the ENSO.

Applying this criterion to the time series of ENSOs and of large wave events produces the following results. For the basic wave series, 32 of the 60 wave events were associated with ENSOs. For the series of very large waves, 12 of the 18 wave events were associated with ENSOs.

Not all ENSOs resulted in large wave events. Table V shows a comparison between the occurrence of large storms and the ENSO strength categories of Quinn et al.

Table V shows that all seven strong ENSOs resulted in a wave event where the height exceeded 3 m (10 ft) with an average of 2.1 such events per ENSO. Three out of seven of these strong ENSOs produced wave heights over 6 m (20 ft) for an average of 1.3. All but one of the nine moderate ENSOs yielded waves above 3 m, with an average of 1.7 events per ENSO. Only two of these produced waves above 6 m and the average dropped to 0.3. Two of the five weak ENSOs met the lower height limit with an average of 0.4 occurrences per ENSO. Weak ENSOs produced no wave events exceeding the 6 m limit.

Table V shows a consistent series of relationships between ENSOs and large wave events. Strong ENSOs result in significant numbers of storms with waves exceeding both the 3 m and the 6 m thresholds. Moderate ENSOs produce storms with waves exceeding the 3 m limit, but not the 6 m value. Weak ENSOs have only a slight tendancy to produce storm waves that exceed the 3 m threshold.

Eliminating the weak ENSOs, a total of 16 strong and moderate events were recorded in the 85 year period considered. Allowing for the three multi-year events, there were 19 ENSO years during the 85 year interval that would be classified as greater than weak events. Considering the 3 m (10 ft) threshold wave events, there was an average of 0.71 events per year over all years. During the moderate or strong ENSO years, there was an average of 1.58 events per year. Applying the Student's t test to determine the probability of the mean during these ENSO years exceeding the mean over all years by this amount, the probability was shown to be about 0.01 (one chance in a hundred.) The mean value of large wave events during non-ENSO years was found to be 0.45. The probability of the mean being this much lower than the mean over all years was found, by Student's t test, to be less than 0.005 (five chances out of a thousand.) Thus, the incidence of large wave events in association with ENSOs and the reduction in large storm waves during non-ENSO years are established statistically with little question.

WAVE APPROACH DIRECTIONS AND CHARACTERISTIC PERIODS

Because of the frequent winter storms that are spawned by the Aleutian Low during most years, it has generally been assumed that the track for major storms affecting California is usually out of the northwest. Table II shows, however, that a large number of severe storm waves come out of the west. This is shown in Figure 4, which plots the incidence of wave approach directions for the Table II series. A strong peak is found at about 285 deg. for both the total data set and also the ENSO year subset. The ENSO year occurrences also are observed to fall off rapidly at approach directions slightly north of this peak.

TABLE V

ASSOCIATION OF ENSOS AND LARGE WAVES

ONSET YEAR	NUMBER OF LARGE WAVE EVENTS Central California	Southern California
STRONG ENSOS		
1911	1	0
1918	1	0
1925	1	1
1941	1	0
1957	3	2
1972	1	0
1982	7	6
MODERATE ENSOS		
1902	0	0
1904-05	2	1
1913-14	2	1
1930	1	0
1939-40	3	0
1953	1	0
1965	1	0
1969	4	0
1976	1	0
WEAK ENSOS		
1917	1	0
1923	1	0
1932	0	0
1943	0	0
1951	0	0

Conventional wisdom has also suggested that severe storms along the California Coast produced periods of peak energy of no greater than about 19 seconds. The storms of 1982-83 showed very clearly that this limit was much too low. Figure 5 depicts the incidence of peak periods in the very large wave events contained in the Southern California series. It can be readily seen from Figure 5 that all storms that produced peak energy wave periods greater than 20 seconds were associated with ENSO years. This is, of course, consistent with the meteorological setting during most ENSO events in which there are very long fetchs directed at the California Coast.

TROPICAL STORMS

The pronounced warming of the surface waters along the California Coast during a strong El Nino condition could be expected to allow the northward excursion of tropical cyclones (hurricanes) in late summer and early fall to latitudes excluded in non-ENSO years. As previously noted, it is not generally possible to develop a wave hindcast series

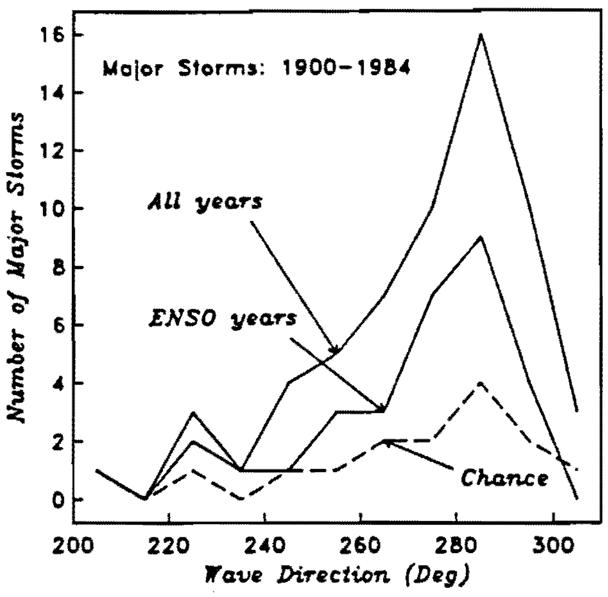

FIGURE 4

Number of occurrences of major wave events from various approach directions for events in Table II.

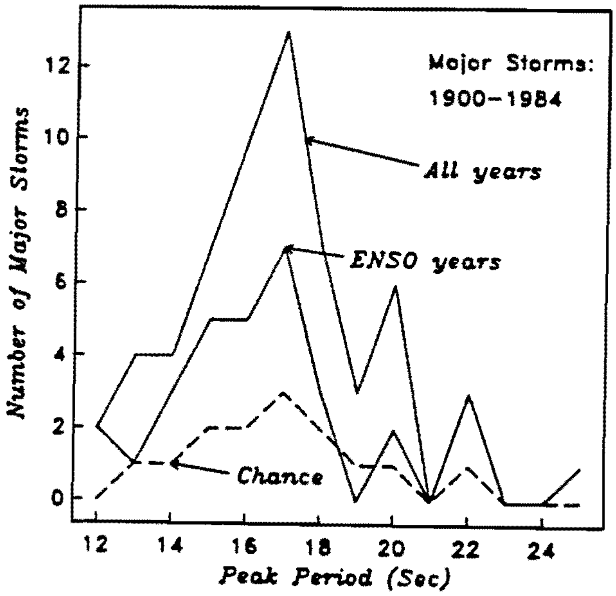

FIGURE 5

Number of occurrences of major wave events with the energy spectra peaked at various wave periods. Events are from Table II.

for these storms which are so small in diameter compared to a typical extra-tropical cyclone. However, Court (1980) has compiled a record of hurricane tracks since 1900. This was extended through 1983 using DeAngelis (1983). The tracks of these storms are shown in Figure 6. Of all of the hurricanes observed in this period, only nine made landfalls in California. Five of these nine were in ENSO initiation years, when warm water would be expected along the West Coasts of Mexico and California during the Fall hurricane season. One of these was the storm of 25 September, 1939, which is one of the events in the basic series. Therefore, the data suggest that late summer and fall hurricane-driven wave events in Southern California are much more likely in ENSO years than during the intervening periods.

DISCUSSION AND CONCLUSIONS

A very convincing statistical relationship has been demonstrated between ENSOs and the large wave events that dominate the wave climate of Southern California. Because ENSOs also tend to increase sea level along the California Coast in rough proportion to their intensity, the coastal damage resulted from large waves will be exacerbated during ENSO events.

The scheme adopted by Quinn et al. (1978) for designating the intensity of the ENSOs is in good qualitative agreement with the number and intensity of large hindcast wave events in California.

ENSOs appear to be among the more predictable of the major global climate events. Therefore it may be possible to forecast severe winter wave climates with some skill for the California Coast.

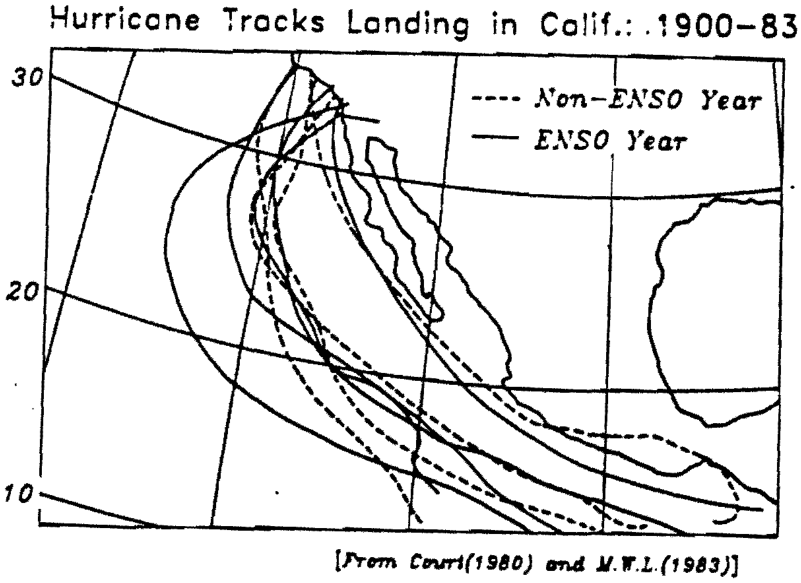

FIGURE 6

Tracks of tropical cyclones (hurricanes) that made landfalls in Southern California during the period 1900-1983.

Wave periods much longer than typically assumed for this coast were recorded. These very long periods have particular significance both for wave runup intensity and for drastic intensification of mooring loads on large floating structures with the potential for reaching a near-resonant condition at approximately 0.04 hz.

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