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WAVE CLIMATE VARIABILITY IN SOUTHERN CALIFORNIA

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ABSTRACT: The incidence of major wave events is investigated for the Southern California offshore region for the period from 1984 to 1995. The significant influence of the world climate event popularly known as El Niño, which had been shown in an earlier study of the first 83 yr of the century, is seen to be a major influence in the recent decade. Although the overall wave intensity (as measured by the median wave height for all observations during a year) has decreased for the most part in the last 20 yr, the number of large wave events has been very much increased. An averaged sea surface temperature anomaly in the tropics is shown to be well correlated with the increases in large wave events.

INTRODUCTION

In Seymour, Strange, Cayan, and Nathan (1984) (hereinafter referred to as SSCN), a significant correlation was demonstrated between the world climate events called ENSOs (El Niño—Southern Oscillation) and the occurrence of storms involving large waves along the coast of Southern California. That work was motivated by the co-occurrence during the winter of 1982–83 of a number of very large wave events and a particularly well-developed ENSO. During certain intense ENSO periods, very large atmospheric lows develop north of the Hawaiian Islands resulting in extremely long west-to-east fetches and high winds. These wind fields generate large amplitude, long-period waves out of the west that result in the impacting of exceptional swell on the southern and central coasts of California. Two time series, one involving major waves events and the other the existence of ENSO conditions and their relative intensities, was presented in SSCN. The series covered the period from 1900 to 1983.

More than a decade has passed since the great ENSO of 1982–83. During the intervening period there have been three other ENSOs, an occurrence rate slightly higher than anticipated from the historical record. The ENSO of 1986–87 could be characterized as strong, following the rating system of Quinn et al. (1978), as modified in SSCN. There was a nearly continuous, moderate to strong ENSO condition from the winter of 1990 to the spring of 1993. The ENSO of the winter of 1994–95, at this time, is considered moderate to strong. As anticipated from the findings of SSCN, the period from 1984 to 1995 has been marked by many events of large waves. In this work, the wave climate over the most recent decade is compared with the earlier results, with emphasis on the occurrence of large wave events. The investigation of the influence of ENSOs is extended, on both the intensity and the direction of major wave storms. An attempt is made to develop a predictor for severe winter storm conditions by considering the warming of the Pacific tropical surface waters that is a precursor to ENSOs.

WAVE OBSERVATIONS

Data Series

For convenience, the two major tables in SSCN have been repeated here in a slightly different form and extended to include the next 12 yr of observations. The basic series (Table 2 in SSCN) has been changed by raising the threshold significant wave height from 3 to 4 m. This resulted in removing about 18% of the storms reported prior to February 1984. All of the removed storms were earlier than 1970. The new basic series is shown here as Appendix I. The newer entries were developed using data from the Begg Rock buoy from March 1984 until December 1986. From 1987 on, they were based upon measurements from the Harvest Platform. The locations of these measurement sites is shown in Fig. 1. Entries prior to March 1984 are from SSCN as discussed earlier. These earlier entries employed a blend of hindcasts and observations (observations limited to the late 1970s and beyond). To prepare a comparable series for the present paper, the following methodology was employed:

1. Extreme wave episodes were defined as periods in which the significant wave height remained at 3 m or greater for a period of at least 9 h. Some of these episodes lasted for more than one week and may have involved more than a single storm, although it was not possible to unequivocally sort out multiple sources.
2. To insure that the events were indicative of what could

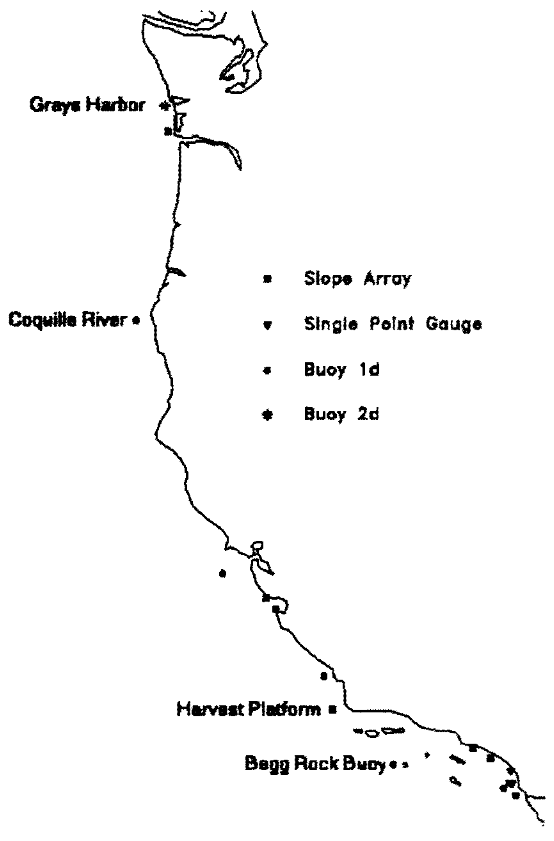

FIG. 1. Locations of Measurement Sites since 1984

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be expected throughout the Southern California Bight (i.e., broad area storms) events with wave periods restricted to the wind-wave regime were excluded and only those episodes where the maximum energy occurred at a period of 12 s or more were included. This procedure eliminated 25 storms, which appeared to be locally generated, including five which had over 5 m significant heights.

3. The SSCN series included events with significant heights over 3 m. A significantly increased incidence of these events was found in the present study, suggesting that the methodology employed in the earlier work may have underestimated these smaller events. Therefore in the present work the lower limit was raised to 4 m to allow a more meaningful comparison.
4. Directions listed in SSCN were taken from hindcasts. No hindcasts were available for those events added in this paper, but mean overall measured directions, a comparable statistic, are available from December 1992 onward from the array installed on the Harvest Platform that year.
5. The Begg Rock buoy results are expected to be biased below the true offshore wave heights, because of the shoals in the vicinity, such that the record in Table 1 between the Fall of 1984 and the end of 1986 may contain fewer (or lower) values for the extreme wave episodes.
6. In all of the tabulations, significant wave heights are reported to 0.1 m precision and directions to the nearest degree. The significant wave heights, in all cases, refer to the maximum values measured (or hindcast) for that event in deep water offshore of the islands in Southern California. The 0.1 m accuracy implied is probably reasonable for measurements and not for hindcasts, but rounding was avoided to preserve the information obtained from the measurements. In the same fashion, the mean directions are shown with a precision of 1° and are those directions that occur at the peak of the large wave event. The Harvest array is capable of resolution of this order; the hindcasts most likely were not. Again, for uniformity, no binning of the directions was done in the tables. Users are cautioned that the accuracy of many of the data entries are less than implied by the precision of the data.

TABLE 1. Extreme Wave Episodes Exceeding 6 m H_s, 1900–1995

Date (1)	Significant height (m) (2)	Maximum period (s) (3)	Direction (°*T* from) (4)
13 Mar 05	8.8	15	247
3 Feb 15	7.5	14	235
1 Feb 26	6.9	15	257
28 Dec 31	7.4	18	228
6 Jan 39	7.9	19	285
26 Jan 58	6.8	14	259
5 Apr 58	7.7	18	289
9 Feb 60	8.1	19	295
17 Feb 80	6.1	18	249
28 Jan 81	7.0	17	262
1 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
1 Mar 83	8.2	20	258
3 Dec 83	7.0	17	285
25 Feb 84	6.4	17	300
03 Dec 85	6.5	17	—
02 Jan 87	6.6	22	—
18 Jan 88	10.1	15	—
22 Jan 95	6.2	20	267

Following the methodology of SSCN, a second series showing only those wave events where the significant wave height was equal to or greater than 6 m is shown in Table 1.

Associations with ENSOs

The association between ENSOs and large wave events was established in SSCN by correlation between an arbitrary rating system for ENSO intensity and the number of wave events exceeding various threshold significant wave heights. In the present study, the ENSO potential is established in a more objective manner. Time series of sea surface temperature anomalies (SSTs) have been established to assist in the study of ENSO onsets and decays. A sustained positive (warmer) anomaly in the eastern tropical Pacific is generally considered to indicate the establishment of an ENSO condition. The wave data were re-examined for the period from 1974 to 1995, when measurements were available, and compared to the ENSO potential signal from the SSTs. The SST anomalies were estab-

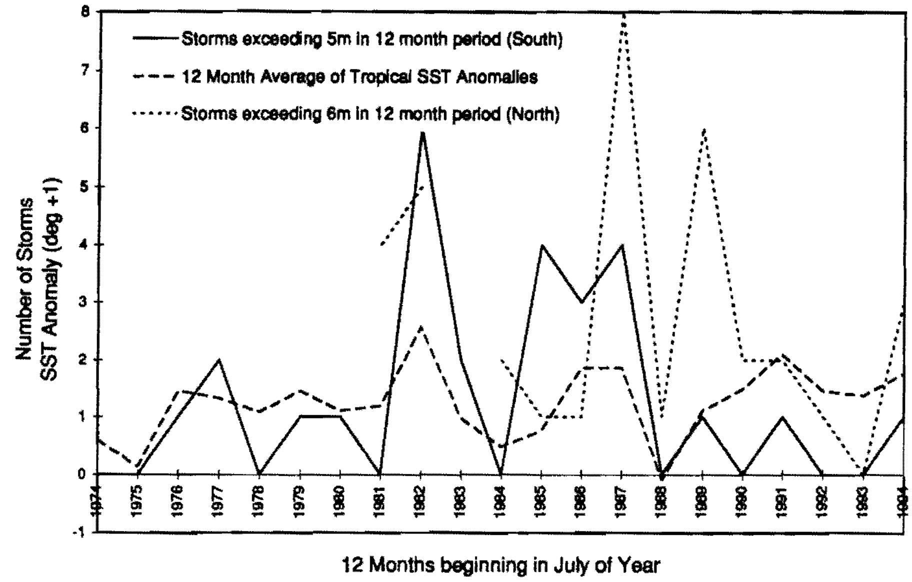

FIG. 2. Influence of El Niños on Number of Wave Events over Threshold H_s

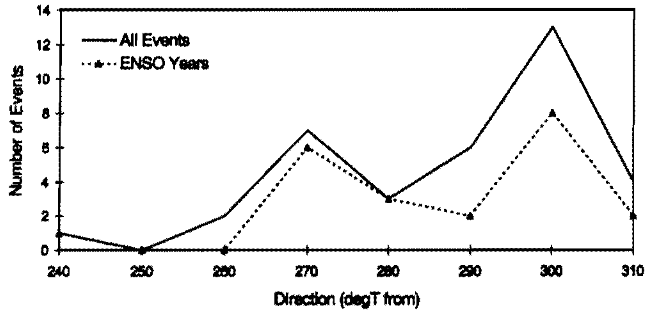

FIG. 3. Directions of Major Wave Events, 1992–1995

lished by averaging the monthly averages of the N3 and N4 zones, which extend approximately 5° north and south of the equator from 180W to 90W, over a 12 month period. These averages were established for the winter periods starting in July and ending in June. The large wave events were filtered to include only those with significant wave heights over 5 m, which occur less than 1% of the time. The numbers of these events in a July-June winter season were counted and displayed with the composite SST anomaly in Fig. 2.

Fig. 2 shows a pronounced signal of the ENSO condition in the wave event record for Southern California (solid line). The squared correlation coefficient r^2 is 0.55. Wave records are also available from the North Coast (Oregon and Washington) for much of this period. The records for two deep water sites shown in Fig. 1 (Coquille River, Oregon and Grays Harbor, Washington) were investigated. The two stations were found to agree almost exactly (20 out of 21 events) on the occurrence of waves larger than 6 m. Also, the 6 m threshold was exceeded with the same probability (0.008) as the 5 m limit in Southern California. The events at Grays Harbor were plotted in Fig. 2 and show a signal of the ENSO but are less well correlated with it than the California waves.

The largest wave height occurring in Table 1 was the storm of January 18, 1988, with an observed significant height of 10.1 m. The next largest was 8.8 m in 1905. Although the 1988 storm occurred in an ENSO period, the meteorological event that produced it was very different from the large-scale Central Pacific lows that are characteristic of many ENSO disturbances. The storm of 1988, a very intense, fast-moving and compact event, was sufficiently unique to have an entire edition of *Shore & Beach* devoted to it (Seymour 1989).

Periods and Direction

The SSCN paper showed that wave spectra could be peaked at very long periods, as great as 22 s, during ENSO periods. In the new series in Appendix I. there are five entries with peak periods of 20 s and one peaked at 22 s. The 22 s event and three of the five 20 s events occurred during ENSOs.

In SSCN, it was shown that the directions from which major wave events approached offshore Southern California were centered on 285° *T*, both for ENSO years and for the full record. The new series contains less than 3 yr of directional data so that it is not possible to make significant comparisons. The distribution of directions for the 1992–95 entries from Table 1 is shown in Fig. 3.

From this shorter series it can be seen that there are two peaks, one directly out of the west (270) and a second from the northwest (300). During ENSO years, the westerly direction becomes relatively more important, as would be predicted by the SSCN findings.

Decadal Wave Climate Variability

In the slightly more than 11 yr encompassed by the Appendix I. entries from 1984 to the present, there have been 69 large wave events—an average of over six per year. In the previous 84 yr, a total of only 48 were recorded—or slightly more than one event every two years. Some significant portion of this discrepancy can certainly be ascribed to poor weather data early in the century and the inability to hindcast intermediate size storms. However, the interval from 1974 through 1983, during which there were continuous wave measurements starting in 1976 to clearly identify major storms, produced only 17 significant events—an average of less than two per year. Therefore, the present decade resulted in major wave storms at a rate of more than three times that of the previous decade, even though the earlier period included those major events in 1982–83 that were the motivation for the SSCN paper.

These data suggest the possibility of a general rise in the wave intensity along the West Coast. To test this, the median annual wave significant wave heights for nine sites were taken from the annual reports of CDIP (Seymour et al. 1994). The values are plotted in Fig. 4.

As illustrated in Fig. 4, the trend lines appear to decrease with time in most cases. Least squares regression lines were calculated for all long data runs in this series. Scripps Pier and

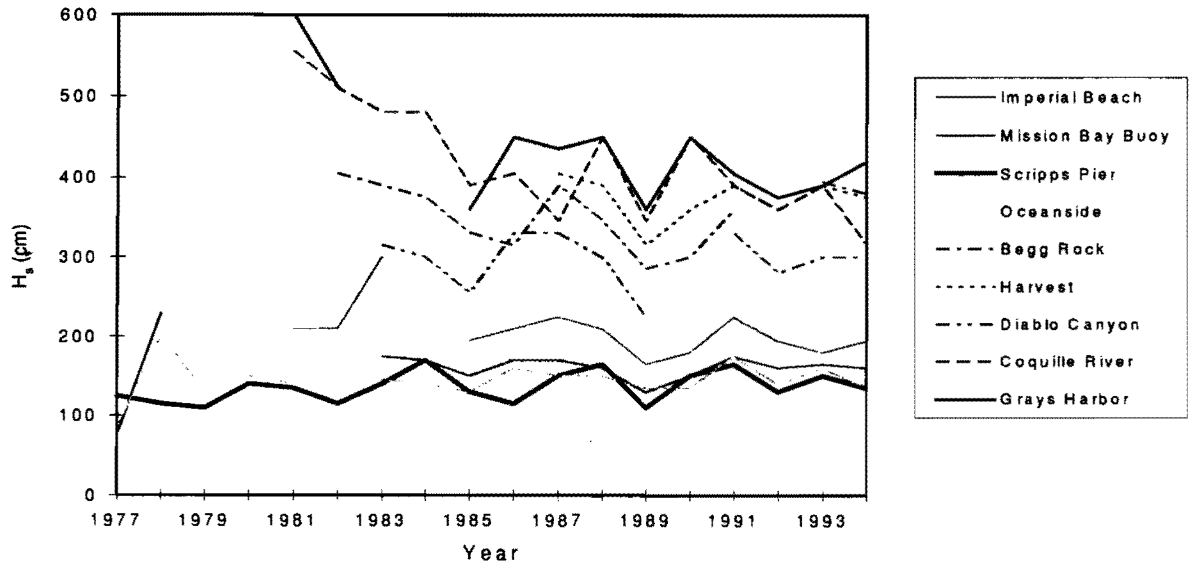

FIG. 4. Median H_s for Selected Sites

TABLE 2. Extreme Wave Episodes Exceeding 4 m H_s (Basic Series) 1900–1995

Date (1)	Significant height (m) (2)	Maximum period (s) (3)	Direction (°T from) (4)
13 Mar 05	8.8	15	247
31 Dec 07	5.3	16	282
26 Jan 14	5.8	13	223
03 Feb 15	7.5	14	235
12 Feb 19	5.3	12	299
20 Dec 20	4.7	13	301
01 Feb 26	6.9	15	257
03 Jan 27	5.8	20	287
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
04 Nov 48	4.7	18	300
15 Nov 53	5.7	17	269
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
31 Jan 63	4.2	16	260
10 Feb 63	5.9	15	256
06 Feb 69	4.7	13	222
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
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
09 Mar 84	4.2	20	—
20 Apr 84	4.2	15	—
25 Apr 84	4.6	13	—
04 Nov 84	4.7	17	—
13 Dec 84	4.3	13	—
25 Apr 85	4.5	13	—
3 Dec 85	6.5	17	—
2 Jan 87	6.6	22	—
25 Jan 87	4.3	17	—
31 Jan 87	5.2	17	—
23 Feb 87	5.4	13	—
2 Dec 87	5.8	15	—
7 Dec 87	5.5	15	—
18 Jan 88	10.1	15	—
15 Nov 88	4.1	15	—
24 Nov 88	4.3	15	—
21 Dec 88	4.7	13	—
31 Dec 88	4.6	15	—
3 Dec 89	4.6	17	—
31 Jan 90	5.4	20	—
7 Feb 90	4.1	17	—
3 Feb 91	4.2	15	—
2 Mar 91	4.9	17	—
21 Mar 91	4.5	13	—
5 Apr 91	4.8	20	—
19 Nov 91	4.5	15	—
29 Nov 91	5.2	13	—

TABLE 2. (Continued)

(1)	(2)	(3)	(4)
29 Dec 91	4.6	13	—
6 Jan 92	4.0	13	—
29 Jan 92	4.5	17	—
11 Feb 92	4.2	13	—
31 Oct 92	4.4	15	—
8 Dec 92	4.9	17	300
14 Jan 93	4.7	13	260
9 Feb 93	4.1	13	270
4 Mar 93	4.7	15	287
24 Mar 93	4.2	15	300
1 Apr 93	4.7	15	297
10 Apr 93	4.8	15	292
16 Apr 93	4.7	17	295
18 Apr 93	4.5	17	289
4 May 93	4.7	15	307
12 Nov 93	4.1	13	307
2 Dec 93	4.3	17	300
11 Dec 93	4.2	17	289
15 Dec 93	4.9	17	267
25 Jan 94	4.9	17	298
18 Feb 94	4.5	13	272
23 Mar 94	4.1	15	301
26 Apr 94	4.6	13	300
10 Nov 94	4.9	17	298
16 Nov 94	6.0	13	307
18 Nov 94	4.6	13	307
26 Nov 94	5.2	15	302
19 Dec 94	4.8	15	285
21 Dec 94	4.5	17	280
2 Jan 95	4.1	20	282
5 Jan 95	6.0	13	272
7 Jan 95	5.7	15	271
11 Jan 95	5.6	17	271
16 Jan 95	4.5	15	298
22 Jan 95	6.2	20	267
2 Feb 95	4.7	17	271
6 Feb 95	4.2	15	284
10 Mar 95	4.8	17	238
14 Mar 95	4.5	15	287
23 Mar 95	5.0	15	299
1 Apr 95	4.2	15	304

Oceanside had positive slopes while the other seven stations showed negative slopes.

ANALYSIS AND CONCLUSIONS

The influence of strong ENSOs on the wave climate of Southern California that was identified in SSCN for the first 80 plus yr of the 20th century has continued into the decade following. The nearly continuous incidence of the ENSO condition from 1984 through 1995 has resulted in a marked increase in the number of broad-area wave events exhibiting very high waves. The period of this study, slightly more than a decade, yielded more than three times as many events with significant wave heights exceeding 4 m than the previous decade—even though that earlier period had been similarly more energetic than the decades preceding it. When the threshold is raised to >6 m (Table 1), however, a different picture emerges. The last decade in SSCN produced more than twice as many very large wave events as the comparable interval since that work. Thus the most recent decade produced many more wave events at the >4 m level than any other decade this century, but failed to match the number of >6 m events engendered by the super-ENSO of 1982–83.

A predictor based upon averaging tropical sea surface temperature anomalies over a 12 month period beginning in July was shown to have useful skill in predicting the climate of severe waves for Southern California during the same period.

Although the rate of incidence of large wave events (>4 m) increased over the last decade, the trend indicated by the median height of all wave observations during the year has been downward for the majority of the Southern California stations. This would indicate that there is no general trend towards increasing wave intensity, but that the ENSO influence has continued to result in more severe winter storms.

ACKNOWLEDGMENTS

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APPENDIX I.

Table 2 shows the extreme wave episodes from 1900 to 1995. This includes the original SSCN basic series of 83 years plus the next 12 years of observation. The threshold significant wave height has been raised from 3 to 4 m.

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