CHAPTER 65

MONTE CARLO SIMULATION FOR NEARSHORE WAVE STATISTICS IN SOUTHERN CALIFORNIA

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ABSTRACT

To develop the nearshore wave condition in Southern California, six meteorological weather patterns including extratropical cyclones of the northern hemisphere, northwest winds in the outer coastal waters, west to northwest local sea, pre-frontal local sea, tropical storm swell and extratropical cyclones of the southern hemisphere were identified and classified. Wave characteristics in deep water, corresponding to the categorized weather patterns, were computed and then transferred to the nearshore target sites via a spectral back-refraction transformation model. A Monte Carlo simulation technique was applied to generate a synoptic atlas of the nearshore wave climate in this region.

INTRODUCTION

Waves, currents and water levels are the dominant oceanographic forces that control the movement of sediment and determine, in part, the potential for coastal flood damage exposure. Waves that impinge on the shoreline perhaps more than any other oceanographic factor, determine the fate of sediment movement and the associated impacts to coastal development. An understanding of the temporal and spatial variation of waves is critical to the formulation of effective shoreline erosion management plans. Although wave hindcast and measurement data are currently available in Southern California, existing databases are sparse and lack sufficient detail of important information. For example, wave direction data, important in the understanding of sediment transport processes, are limited; and most of the hindcast wave data exclude waves generated in the southern hemisphere ocean (southerly swell). This study was therefore performed to address data gaps and to develop a practical database that can characterize the wave climate for the Orange County shoreline in Southern California.

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METHODOLOGY

The technical approach taken in this study is unique and represents a significant departure from previous wave studies within Southern California. In general, the following procedures were adopted.

1. Local, regional and hemispheric meteorological weather systems which influence the wave climate within this region were identified. In this manner, the local and distant origins of ocean wave generation patterns and their recurrence frequencies were defined.

2. A state-of-art spectral transformation numerical model was applied to characterize how the offshore waves will change in height and angle of shoreline approach as they propagate into the nearshore water area.

3. A synthetic nearshore wave database was compiled by using a Monte Carlo simulation technique based on the probable sequential and combined occurrences of different meteorological events and their associated wave generation patterns.

Pattern Identification

Waves that impact the Southern California coastline, as shown in Figure 1, are generated by any one or more of the following meteorological patterns:

I. Extratropical cyclones of the northern hemisphere (northwest to west-southwest swell);
II. Northwest winds in the outer coastal waters (wind swell);
III. West to northwest local sea (west sea);
IV. Pre-frontal local sea (southeast sea);
V. Tropical storm swell ;
VI. Extratropical cyclones of the southern hemisphere (southerly swell).

Low pressure centers which develop along the polar front are the source of the predominant wave action along the Southern California coast during the winter half of the year. Storm swell is generated at some distance from the Southern California coastline in the North Pacific. Most commonly these storms will traverse the mid-Pacific before turning northeastward toward the Gulf of Alaska with swell decaying on the average of 2,400 kilometers to the coast of Southern California. However, under some meteorological conditions, storms can move in much closer to the coast; and on rare occasion these storms may move directly across Southern California, following either a northeast, east or southeast trajectory. In general, the modal deep water approach directions range between 275° and 285°. However, these North Pacific low pressure systems exhibit great variations from year to year such that wave approach directions and amplitudes will show a corresponding degree of variation. Years when the storm centers follow a more northerly route in the eastern Pacific will result in extremely quiet conditions in Southern California, whereas more southerly storm tracks through the mid and/or eastern Pacific will result in frequent periods of high wave conditions.

The predominant swell along the Southern California coast in spring and summer is generated by the prevailing northwest winds north and west of this area. Wave heights are usually low, less than one meter; but on occasion, with superposition of a strong surface high and an upper level trough, the northwesterlies increase, becoming very strong from north of Point Conception to San Nicolas Island. Waves traveling at a variance to the mean wind direction reach Southern California with periods on the order of 6 to 10 seconds. Moderate northwesters will produce breaker heights of one to two meters, while strong events can give two to 3 meters.

Seas generated by westerly winds can be divided into two types: 1) temperature-induced sea breezes, and 2) gradient winds. The strong sea breezes occur during the late spring and summer months, while the lightest winds are during December and January. The sea breezes usually set in during the morning and peaks in the mid-afternoon. Gradient winds are confined largely to the months of November through May with the peak in March and early April.

Pre-frontal winds blow strongly from the southeast along the coast but turn toward the south to southwest a short distance offshore. Significant wave heights are generally in the range of one to 2.5 meters. Westerly swells tend to follow the frontal passage, when southeast seas are well on the way down, but on occasion the two wave trains overlap.

Tropical cyclones form regularly along the intertropical convergence zone west of Mexico from early July to early October. On the average, about 15 of them are to be expected each year. Most of them take a westerly track, and swells generated by these storms will have little or no effect on Southern California. Some, however, take a more northerly track and swells off Southern California may reach 2 to 4 meters.

Southerly swells occur primarily between April and October and to a lesser extent the remainder of the year. Large South Pacific storm systems traversing the ocean between 40° and 60° south from Australia to South America send swells northward to the west coast of Central and North American. Great circle approach directions off Southern California range from about 215° for storms near New Zealand to 170° for South American storm system. The decay distance ranges from 7,200 to 11,200 kilometers. Swells in deep water off Southern California are generally about one meter, but breaker height may be 3 to 4 meters or more.

To better distinguish the wave conditions generated from the aforenamed meteorological patterns, each weather type was further classified according to wind speed, effective fetch, decay distance and storm duration. Table 1 tabulates the meteorological criteria for the classified categories within each generated wave pattern. The destructive storms of March 2, 1983 and January 17, 1988 are examples of the storm swells of Category 4a.

Pattern Recurrence

The meteorological characteristics, which produce various wave generation patterns, change seasonally. Four meteorological seasons were defined according to weather characteristics instead of the traditional calendar seasons. The discrete meteorological seasons have a two-month spring (April and May), a three-month summer (June to August) and fall (September to November), and a four-month winter (December to March). Observed storm swells or seas between 1974 to 1993 were reviewed from the Pacific Weather Analysis' daily logged data bank. Seasonal recurrence of the classified wave generation patterns was then derived to characterize the probability of occurrence for each classified category. Table 2 shows the resultant seasonal occurrence for each wave generation pattern. For example, the occurrence of northwest to west swells (Pattern I) has its peak frequency in winter, while observations of long-period southerly swells (Pattern VI) have a summer peak.

The possible wave approach directions generated from all six weather patterns were also evaluated from the historical data between 1974 to 1993. Wave directions with a 5-degree increment were discretized for the northwest or west storm swells (Pattern I). Table 3 lists the discretized ranges of deep water wave approach directions and their probability of occurrence for each category. Three discretized wave directions were designated for the tropical storm (Pattern V) and the southerly swell (Pattern VI). Tables 4 and 5 show the directional occurrence probability for the tropical storm and the southerly swell respectively. The prevailing deep ocean approach direction is from west (270°) for both the wind swell and west to northwest local sea, and southeast (160°) for pre-frontal local sea (southeast sea).

Deep Water Wave Characteristics

Based on the aforedefined meteorological parameters such as wind speed, effective fetch, decay distance and storm duration, the deep water wave characteristics were computed from a PWA wave generation model. The PWA hindcast method is based on the principles set forth by Pierson, Newmann, and James (1955) wherein the energy in each frequency band of the wave spectrum, propagating at group velocity with angular spreading, is generated and recombined with other frequency bands at the hindcast point to give the predicted spectrum.

The PWA model, which is proprietary, has been developed through analysis of wave data taken from several locations along the California coast. The hindcasted spectral form is quite wide during the early stages of development; but as the wind speed, fetch or duration increases the spectrum narrows, with the front face becoming steeper. The wind speed is the most critical as compared to the effect due to the fetch. The spectral area does increase as the fetch increases, and the peak energy shifts toward longer periods but at a decreasing rate. Although there is no fully developed absolute condition for this spectrum, the spectral curves flatten out to such an extent at low frequencies that maximum periods have been assigned as the criterion for the "fully developed" sea. The approximate areas where the hindcast deep water wave characteristics were performed are indicated in Figure 1.

Nearshore Wave Transformation

The wave characteristics derived from the meteorological weather patterns, described in the last section, all represent deep water environments. To determine the wave conditions within the Southern California coast, it is necessary to transform the predicted deep water wave conditions to the nearshore water area. The transformation process consists of adjusting deep water wave heights and approach directions due to the effects of island sheltering, shoaling, refraction and diffraction. In this study, a spectral back-refraction model (O'Reilly & Guza, 1991) was selected as the tool to transfer the deep water wave environments into the nearshore water area.

O'Reilly's spectral back-refraction model performs a linear spectral refraction transformation in which the transferred spectrum is established from the incident wave spectrum by back-refracting rays from the target site. The model accounts for island blocking, wave refraction, and wave shoaling. It is typically used to model waves with periods between 8 and 25 seconds. The model includes deep ocean swell directions ranging from 150 to 335 degrees. Unlike more traditional forward ray refraction methods, O'Reilly's model back-refracts wave rays from the site of interest, therefore eliminating caustics which plague forward ray tracing schemes. As a result, the spectral transformations are robust (finite solutions are always obtained), easily interpreted, and more realistic than those obtained using forward ray tracing and the assumption of unidirectional, monochromatic deep ocean waves.

For a known deep water wave condition including both energy and directional spectra, the transformation is performed by :1) decomposing the deep water energy spectrum and the deep water directional spectrum into 1-second and 1-degree increments, respectively; 2) obtaining the transformed energy at the target point for each component from the transformed and normalized coefficients; 3) assembling the transformed wave components to form an energy spectrum and a directional spectrum at the target point; and 4) determining the significant wave height, the wave period and the approach direction from the transferred spectra.

In this study, the nearshore wave conditions transformed from the hindcasted deep water wave characteristics in spectrum form were computed every three hours to describe the temporal variability of the wave condition. The significant wave height was determined from the spectrum computed every three hours; and the significant wave period and the predominant wave direction correspond to the period and the direction at the peak wave energy component. Approximately, 5,800 wave event data sets were computed and cataloged, including all classified categories and different wave approach directions for each nearshore site of interest. This wave information provides the data bank necessary for the characterization of long-term wave statistics.

Monte Carlo Simulation

A Monte Carlo simulation technique was applied to generate a synthetic practical data base to characterize the Orange County nearshore wave climate. This technique recreates a stochastic process to solve a problem which can not be easily evaluated by a direct analytic or a standard numerical analysis procedure. In this study, a computer code was written in accordance with the probability occurrence scenarios derived from the 20-year daily recorded weather patterns, as previously described.

In addition to the individual seasonal probability distribution related to each wave pattern, the 20-year statistics of the recorded wave patterns also provide a basis for assessing the coupling (coincident events) and the likely sequential order among different wave patterns. A few principles were derived and implemented in the computer code. These are:

1. The recurrence for each weather pattern varies seasonally in accordance with the derived probabilities of occurrence.

2. The occurrence of southerly swells and tropical storms were treated independently since their meteorological characteristics are not related to the remaining weather patterns. Also, there is no intercorrelation between southerly swells and tropical storms.

3. There is a 30% chance in which the coupling between two northwest to west-southwest extratropical storm swells occurs in winter. The occurrence distribution for each storm category is listed in Table 6.

4. After a west local sea, there is a 50% chance that a wind swell follows for all seasons.

5. After a southeast local sea, there is a 30% chance that a category 4 northwest to west storm swell or a 30% chance of a west sea follows in winter.

6. A background noise is selected if no wave event occurs in each simulated day. The noise can be either a weak northwesterly swell, a light wind swell, a slight southerly swell or a sea breeze only occurring in the afternoon.

In the Monte Carlo simulation, numbers between 1 and 100 were randomly generated. The model performed the wave event selection in accordance with the sequence of the random numbers. For example, if the first random number implies a storm event is evident, the following random numbers would determine the wave pattern, intensity category and incoming direction. The model then determines if another wave pattern occurs simultaneously. After the end of all possible coincident or subsequent events which may be a few simulated days later, the model reselects a random number and repeats the same procedure. On the other hand, if the random number implies a no-storm event, the model would generate a background noise for the particular simulated day and selects a new random number the next day to proceed the simulation. The simulated daily nearshore wave environment may be composed of a single, multiple wave events or no event with a background noise only.

RESULTS

The recurrence probability of the identified weather patterns was compiled on a season-by-season basis. Therefore, the simulation can be used to statistically characterize the seasonal and annual nearshore wave environments. Figure 2 illustrates one of the simulated wave environments for a winter month at San Clemente, where a California Data Information Program (CDIP) gage station is located. For a multiple-wave-event selection, the significant wave height was computed from the superposition of all the wave energy spectra, and its associated wave period and approach direction was defined as the period and direction of the peak energy component.

In order to be statistically significant, it was necessary to perform replicate simulations so that the statistical moments such as the mean and deviation can be derived. The trial and error process was conducted to determine the required number of simulations to yield a valid record of data for one year. It was found that approximately 10 simulations were adequate to provide a statistical significance of the results. Figure 3 presents the average annual statistics of significant wave height and period at the San Clement gage station obtained from the Monte Carlo simulation compared to the average field measurements recorded over 6 years (US Army and State of California, 1984, 1985, 1986, 1987, 1992 and 1993). It is noted that no complete annual wave measurements were collected at the San Clemente gage from 1988 to 1991.

As seen in Figure 3, the majority of observed wave heights (about 88% of time) ranges from 0.4 to 1.3 meters, while an occurrence of about 73 % was estimated from the simulated results. The model overpredicts the occurrence of lowest significant wave height (16% for Hs < 0.4 meter). The difference may be attributed to the following reasons.

1. In the field condition, the background noise is always present. This noise would contribute additional wave energy to the total spectrum, thereby increasing the resultant significant wave height. However, in the model simulation, no background noise was introduced as long as a wave event was selected. A test simulation was conducted to incorporate the background noise on a daily basis. The resultant statistics shows the reduced occurrence of low wave events (Hs < 0.4 meter) and more frequent recurrence of high wave event (Hs > 1.6 meters). This implies that incorporated background noise combined with the selected wave patterns will overmagnify the storm events. The model result can be improved with the development of an improved background noise incorporated in the simulation.

2. The El Nino effect, which occurs every 3 to 7 years, was not implemented in the model simulation. Approximately two to three El Nino scenarios of different severities (Seymour et al, 1984) may occur over 10 simulations (10-year span). During an El Nino year, the frequency of storm events occurring in winter may increase, which would result in occurrence of more intermediate wave events (0.4 meter < Hs < 1.3 meters) and a reduction in the average percentage of occurrence for low wave events (Hs < 0.4 meter).

In the statistical representation, the wave period selected only represents a peak energy component of the combined wave trains. Other components are not included in the statistical count. For example, if two wave trains with different significant periods of 11 and 15 seconds are simulated and the wave energy for the 11-second wave train is slightly higher, the statistics only count for the period of 11 seconds. The wave train with a 15-second significant wave period is as important, but is not counted in the annual statistics. Thus, comparisons of significant wave period, based solely on the peak energy period without further evaluating the combined wave trains, may be somewhat misleading. The discrepancy of annual statistics for wave period may not be as significant as that for wave height.

CONCLUSIONS

The Monte Carlo simulation method presented in this study provides an alternative to characterize a long-term (annually or seasonally) synoptic nearshore wave climate within Southern California. For each simulated daily wave environment, the influencing weather patterns originating from distant or local areas can easily be identified. Also, the spatial variation of wave climate can be evaluated as the simulation is applicable to any selected nearshore location. Further studies in better quantifying the specified background noise and including the El Nino effect are suggested.

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Table 1: Classification of Meteorological Patterns

Weather Pattern	Category	Decay Distance (kilometer)	Duration (days)	Wave Direction (degrees)	Sub-Category	Wind Speed (m/sec)
Extratropical Cyclone of Northern Hemisphere	1	>2,880	4	265-305	a	24.7
					b	21.6
					c	18.5
	2	1,920-2,880	3	260-305	a	24.7
					b	21.6
					c	18.5
	3	960-1,920	3	240-305	a	24.7
					b	21.6
					c	18.5
					d	16.5
					e	14.4
	4	<960	2	185-305	a	24.7
					b	21.6
					c	18.5
					d	16.5
					e	14.4
					f	12.4
Northwest Winds in Outer Coastal Waters	1	192	1	270	-	15.5
	2	192	2	270	-	15.5
	3	192	2	270	-	16.5
	4	192	3	270	-	15.5
	5	192	3	270	-	16.5
	6	192	3	270	-	17,5
	7	192	4	270	-	17.5
	8	192	5	270	-	16.5
	9	192	6	270	-	17.5
West to Northwest Local Sea	1	0	1	270	-	11.6
	2	0	1.5	270	-	14.2
	3	0	2	270	-	18.0
Pre-frontal Local Sea	1	0	1	160	-	11.6
	2	0	2	160	-	14.2
	3	0	3	160	-	18
Tropical Storm	1	1,440	2.5	165-190	-	25.8
	2	1,120	2.5	165-190	-	25.8
	3	800	2.5	165-190	-	25.8
Extratropical Cyclones of Southern Hemisphere	1	8,000	5	180-210	-	20.6
	2	8,000	5	180-210	-	23.2
	3	8,000	5	180-210	-	25,8

Table 2: Occurrence Probability of Wave Patterns

METEOROLOGICAL SEASON	PROBABILITY OF OCCURRENCE (%)					
	PATTERN					
	I	II	III	IV	V	VI
Spring	5.2	11	5.7	0.5	0	8.0
Summer	0.3	6.7	1.7	0.1	2.7	10.0
Fall	8.5	6.3	2.5	1.0	1.5	5.8
Winter	18.5	7.8	5.0	3.9	0	0.9

Table 3: Directional occurrence Probability of Northwest or West Storm Swell

	METEOROLOGICAL SEASON															
	SPRING				SUMMER				FALL				WINTER			
	PERCENTAGE OF OCCURRENCE															
Direction	Category				Category				Category				Category			
(degs.)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
180																
185																6.7
190																
195																
200																1.3
205																
210																2.7
215																
220				20								7.1				
225												7.1				4
230																1.3
235																1.3
240															0.8	
245																
250															2.3	4
255												7.1			2.3	8
260												7.1		1.5	3.1	5.3
265			4.5						2.5		4		0.83	3.1	4.7	9.3
270			13.6	20							4	14.3	1.7	11.4	13.3	13.3
275		11.5	9.1	20	5	5	5	5	2.5	2	7.8	21.3	9.2	13.7	17.2	13.3
280		3.8	18.2		10	10	10	10	10	5.9	7.8	7.1	23.3	24.4	14.0	8
285	9.1	19.2	22.7		15	15	15	15	17.5	19.6	13.7		25	16.8	14.0	5.3
290	36.4	26.9	9.1		25	25	25	25	25	31.4	25.5	7.1	21.7	13	12.5	5.3
295	45.5	26.9	9.1		20	20	20	20	30	21.6	13.7		12.5	9.2	8.6	2.7
300	9.0	11.5	9.1		15	15	15	15	7.5	13.7	11.8	21.4	2.5	5.3	4.7	2.7
305			4.5	40	10	10	10	10	5	6	11.9		3.3	1.5	2.4	5.2

Table 4: Directional Occurrence Probability of Tropical Storm Swell

DIRECTION (deg.)	PERCENTAGE OF OCCURRENCE		
	Category 1	Category 2	Category 3
165	70	78	87
175	20	15	10
190	10	7	3

Note: Probability distribution applies to all seasons.

Table 5: Directional Occurrence Probability of Southerly Swell

DIRECTION (deg.)	PERCENTAGE OF OCCURRENCE		
	Category 1	Category 2	Category 3
185	50	50	50
195	35	35	35
210	15	15	15

Note: Probability distribution applies to all seasons.

Table 6: Coupling Probability Distribution by Category for Northwest or West Storm Swell

CATEGORY	PERCENTAGE OF COUPLING PROBABILITY DISTRIBUTION			
	1	2	3	4
1	30	40	20	10
2	18	36	28	18
3	15	30	30	25
4	25	25	25	25

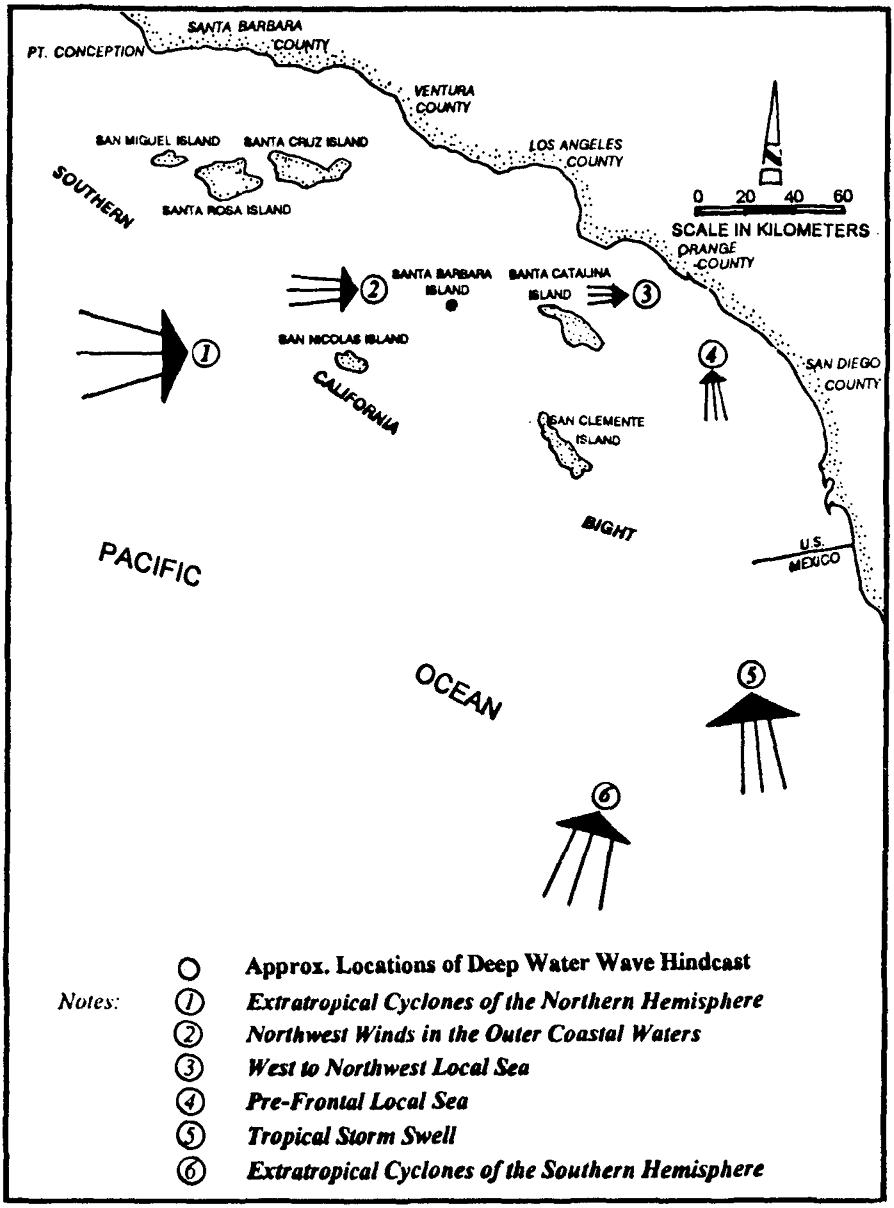

Figure 1: Study Area

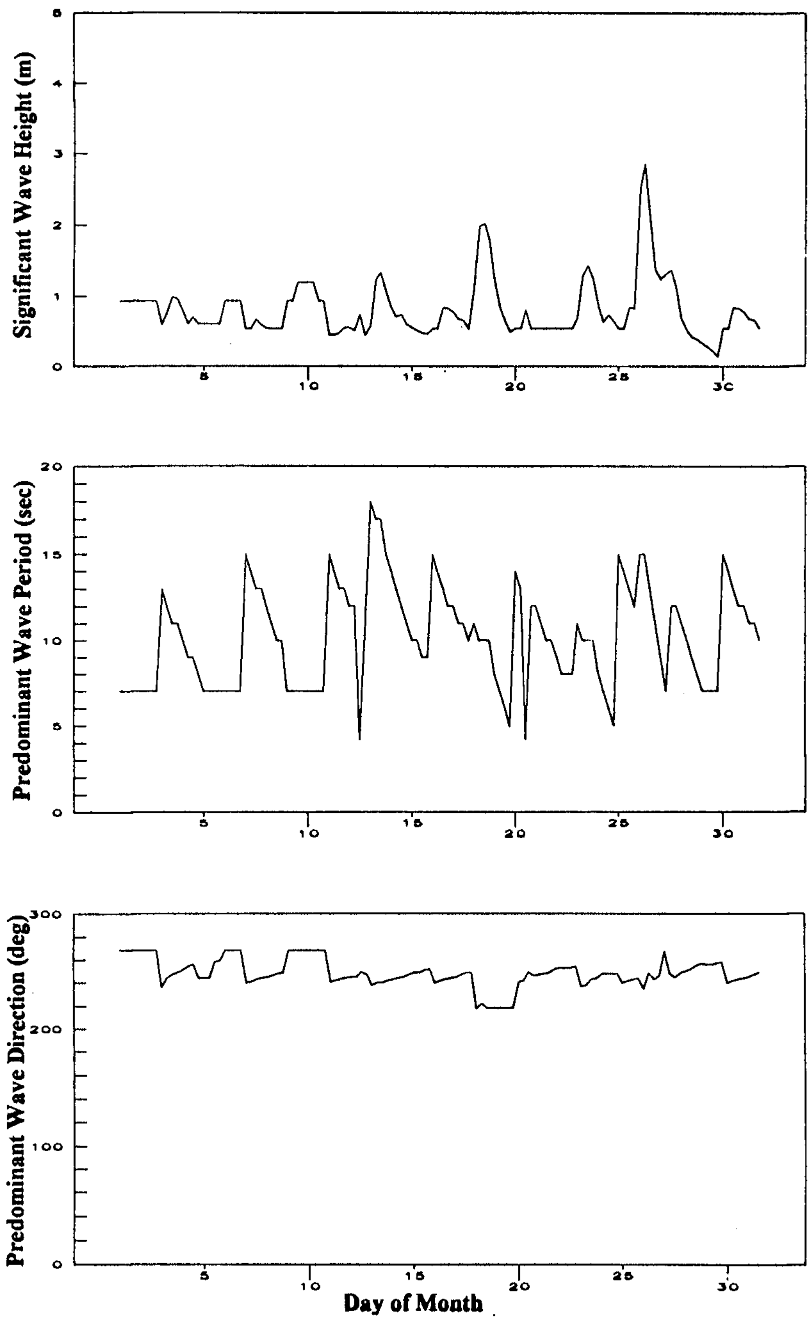

Figure 2: Simulated Daily Wave Climate for Winter Month

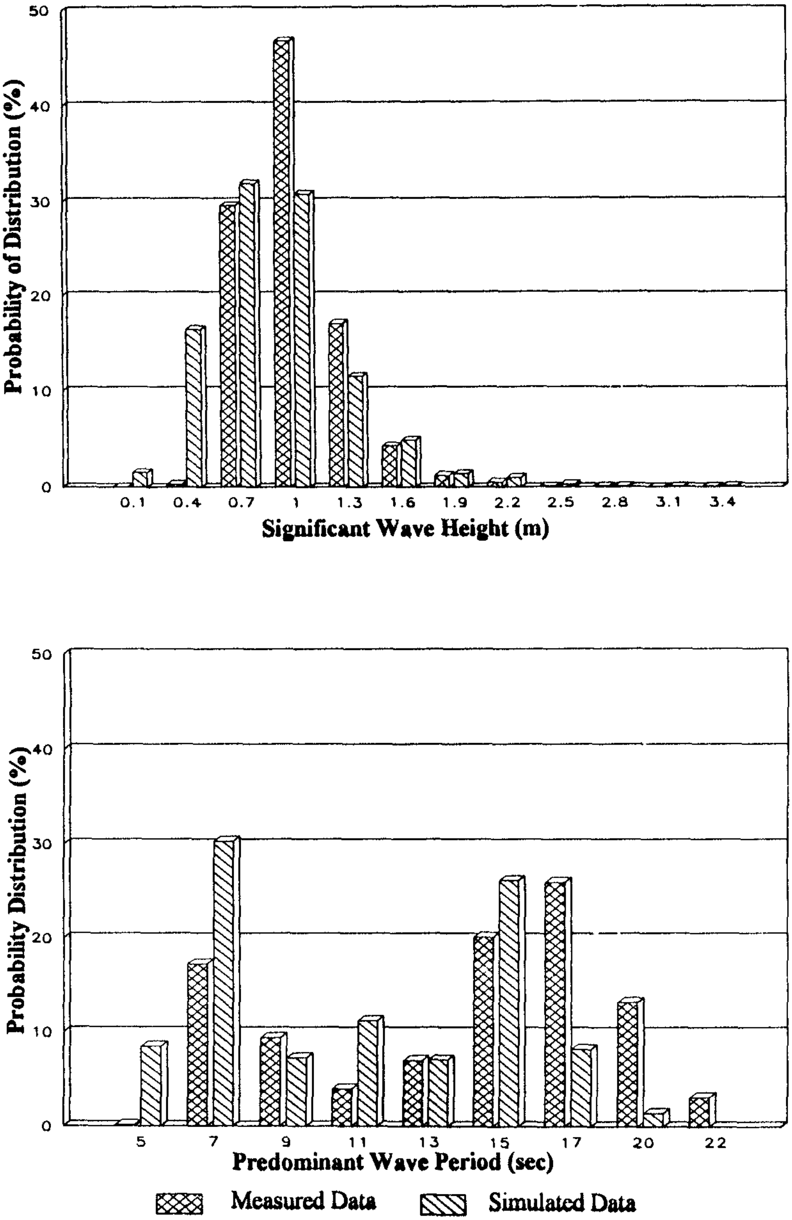

Figure 3: Comparison of Annual Wave Statistics at San Clemente Gage Station