Shore & Beach

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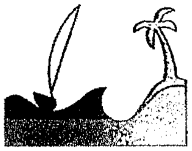

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COVER: *Top: Ocean Front Walk on South Mission Beach, San Diego, California flooded by waves and tide, 18 January 1988. San Diego Union, Dana Fisher photo.*
Bottom: Wave overtopping north breakwater, and boat awash, King Harbor, Redondo Beach, California, 18 January 1988. Photo by Bill Brown, Redondo Beach, California.

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ORGANIZED 1926 — SIXTY-THIRD YEAR

SHORE & BEACH is published four times per year by the American Shore and Beach Preservation Association, 412 O'Brien Hall, University of California, Berkeley, CA 94720. The views expressed and the data presented by the contributors are not to be construed as having the endorsement of the Association, unless so specifically stated.

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Editorial

THE GREAT STORM OF JANUARY 1988

STRONG WINDS AND EXTREMELY large waves resulting from a largely unforecast "southeaster" struck the Pacific coast from Baja California to San Francisco on Sunday and Monday, 17 and 18 January, 1988. The sight of surf zones extending almost to the horizon was one that local coastal engineers will not soon forget. The measured wave heights exceeded anything every recorded or hindcast for this coastline. It was clear from the beginning that this was an exceptional storm. The Naval Ocean Systems Center tower, long part of the seascape offshore of Mission Bay in San Diego, went down - perhaps a victim of the thousands of tons of kelp wrack that eventually littered the area beaches. Redondo Beach was pummelled by huge waves that found an unimpeded path between the offshore islands. Flooding and overwash of seawater, cobbles, sand and kelp was common in low-lying areas.

A few months later I read the harrowing account of a two-man fishing boat crew, caught by the storm because of the inability of present technology to provide warning of such a tight and intense storm, as they fought their way back to port in Los Angeles. The descriptions of the storm evolution, the backing of the wind and the building of the waves, were remarkably similar to Richard Henry Dana's observations in *Two Years Before the Mast* of the dangerous southeasters off this same coast during the 1830s. The problems of the modern boat with breaking glass on the bridge and flooded electrical panels raised interesting questions about how much new marine technology has contributed to the safety of vessels in a severe storm.

During the following months, a number of researchers with interests in coastal engineering, sea level extremes, wave height distributions and weather forecasting continued to study this event. It became even more obvious to them that the January '88 storm did not fit the usual population of winter storms in this part of the Pacific. As coastal engineers and oceanographers fortunately do, they got together informally at some point to discuss their findings. Some one suggested that it would be a good idea to record all this for posterity and the idea of a workshop was generated. It seemed appropriate to me to hold it on the first anniversary of the storm. Dr. Reinhard Flick, staff oceanographer of the California Department of Boating and Waterways (DBAW) agreed to host the event, which was held at Scripps Institution of Oceanography (SIO) on 18 January, 1989. Dan Cayan, of SIO and I provided some assistance with planning the program and recruiting speakers.

The workshop, which consisted of eleven papers and a very spirited discussion period, was co-sponsored by SIO and DBAW. A total of 34 people attended from industry, government and academe. The quality of the papers and the interest generated by them suggested that we should attempt some broader venue than a typical workshop proceedings volume. Probably because a majority of the attendees were members of ASBPA, a special issue of Shore & Beach was suggested. I volunteered to contact the editor for permission and to try to assemble the papers into a single issue devoted to this remarkable storm. Bob Wiegel had been greatly impressed already with the significance of this storm and it was not difficult to convince him to set aside for us the October '89 issue.

Bill S. Satow, the Deputy Director of DBAW, and George Armstrong who heads the Beach Erosion unit in that department, provided valuable and appreciated support for my task of assembling the drafts, obtaining the reviews and putting together this issue. DBAW has supported the CDIP wave data gathering network, which supplied much of the wave data on this storm, for the twelve years of its existence and has also been an important sponsor of research in sediment transport, beach erosion processes, sea level extremes and other topics of interest to Shore & Beach readers. In times of shrinking federal budget, this support by a state agency assumes even greater importance. The community of coastal engineers in California recognizes and appreciates the foresight and the perseverance of Bill Satow and George Armstrong in furthering the objectives of our profession and our organization.

I enjoyed my stint as guest editor of this special issue and I would recommend to others that this focussed effort can be a very effective means for bringing international attention to any number of important events, geographical areas, technologies or projects. The efforts of the reviewers and the authors in meeting the deadlines are greatly appreciated. I hope the readers will find the Great Storm of '88 as interesting and exceptional as we did.

RICHARD J. SEYMOUR
Scripps Institution of Oceanography
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Meteorological Development of the Unusually Severe Coastal Storm During January 16-18, 1988

By R.R. Strange[1], N.E. Graham[1,2], and D.R. Cayan[2]

INTRODUCTION

TO A METEOROLOGIST, the storm that hit the southern and central California coast on January 16-18 1988 stands out as an exceptional event, because it is extremely rare for such a powerful storm to develop so suddenly in a region of the eastern North Pacific, a region where extratropical cyclones are usually decaying rather than growing. This regionally developing storm and two similar ones that occurred earlier are in sharp contrast to much larger scale weather systems which originate far to the west and are carried into the California coast such as in the winter of 1983. Although available observations in this storm's spawning region are very sparse, a handful of ship reports, NOAA coastal buoy observations, and assorted coastal meteorological observations along the California coast permit a reconstruction of the storm's development. Winds and pressure falls observed in this storm were extremely high, leading to the unusually large waves, high sea levels, and accompanying coastal damage which is detailed elsewhere (see Cayan et al.[1]) and other articles in this issue). The inability of the operational numerical forecasts to properly capture the observed deepening of the storm, as well as the sparseness of observations over the Eastern North Pacific, underscores the difficulty faced by marine weatherforecasters in attempting to predict the severity of such an event.

DESCRIPTION

This storm was a particularly intense example of the final phase of a rather commonly occurring weather pattern that develops over a period of approximately 6 days (see Elliott[5]). As this pattern emerges, a series of disturbances in the upper level flowon the atmospheric polar front ripple eastward across the North Pacific into the Pacific Northwest and northern California, each successively farther south. The pattern's finale, which is the analog to the January 1988 storm, occurs when the upper-level westerlies buckle over the eastern Pacific as high pressure builds in the Gulf of Alaska, and the last of the series of frontal systems sweeps southward through California. The January storm represents the end phase of this pattern. An interesting though probably coincidental postscript to this episode is that it marked an abrupt demise of a rather active early winter storm season in California. This change threw the state into a prolonged high pressure pattern leaving it with extensive water shortages due to a remarkable absence of storm precipitation in the central and northern part of the state.

As noted above, the features that distinguish the January 1988 event from others of this type were its intense and unusually far south track. As a result of these features, three aspects of the storm combined to produce extreme wave conditions at many southern California locations: (1) An east-southeast storm track with strengthening westerly winds aimed directly at the area; (2) Maximum intensification occurred as the storm moved inland just north of Pt. Conception; (3) Record low pressure associated with an extremely-intense, though relatively small, cyclonic circulation. In comparison, the storms which produced the extensive wave damage during the 1982-83 winter were considerably larger in spatial extent but were typically located much further away with wave decay distances frequently on the order of 1600 *km* or more.

The rapid evolution of the violent marine weather is outlined by a sequence of surface weather charts reproduced (from Pacific Weather Analysis analyses) in Fig. 1(a-d). Figure 1a shows the offshore storm intensifying during the night of January 16, accompanied by significant pressure falls along the California coast. The pattern shows a moderately strong developing frontal wave located about 1000 *km* west of San Francisco with strong high pressure further west and southwest of the low. Prior to this time the frontal system and trough aloft appeared to be rather weak, but the front could be clearly identified passing the NOAA buoy located at 40.8° N, 137.6° W between 10:00 AM and 1:00 PM PST on the 16th.

As can be seen in the Fig. 1a, there was little ship data on which to base the analysis, emphasizing the critical need for a more extensive meteorological buoy network off California such as those off Oregon, Washington and Alaska. The only ship between southern California and the deepening low to the west was apparently in error in its reported pressure or location. The following map, Fig. 1b, for 10:00 PM on Jan. 16, shows the center of the low racing southeast at approximately 35 *kts* accompanied by increasing pressure falls along the west coast. Though ship data is sparse for this map as well, a strong northwest fetch is apparent to the west of the low, where reported winds reach 40 *kts* with a 30 *ft* swell.

By 10:00 AM on the 17th, the storm continued its track to the southeast at about 35 *kts*, as central pressure dropped from 1002 millibar (*mb*) to 986 *mb*, a fall of 16 *mb* in 12

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[2] Scripps Institution of Oceanography, La Jolla, CA 92093

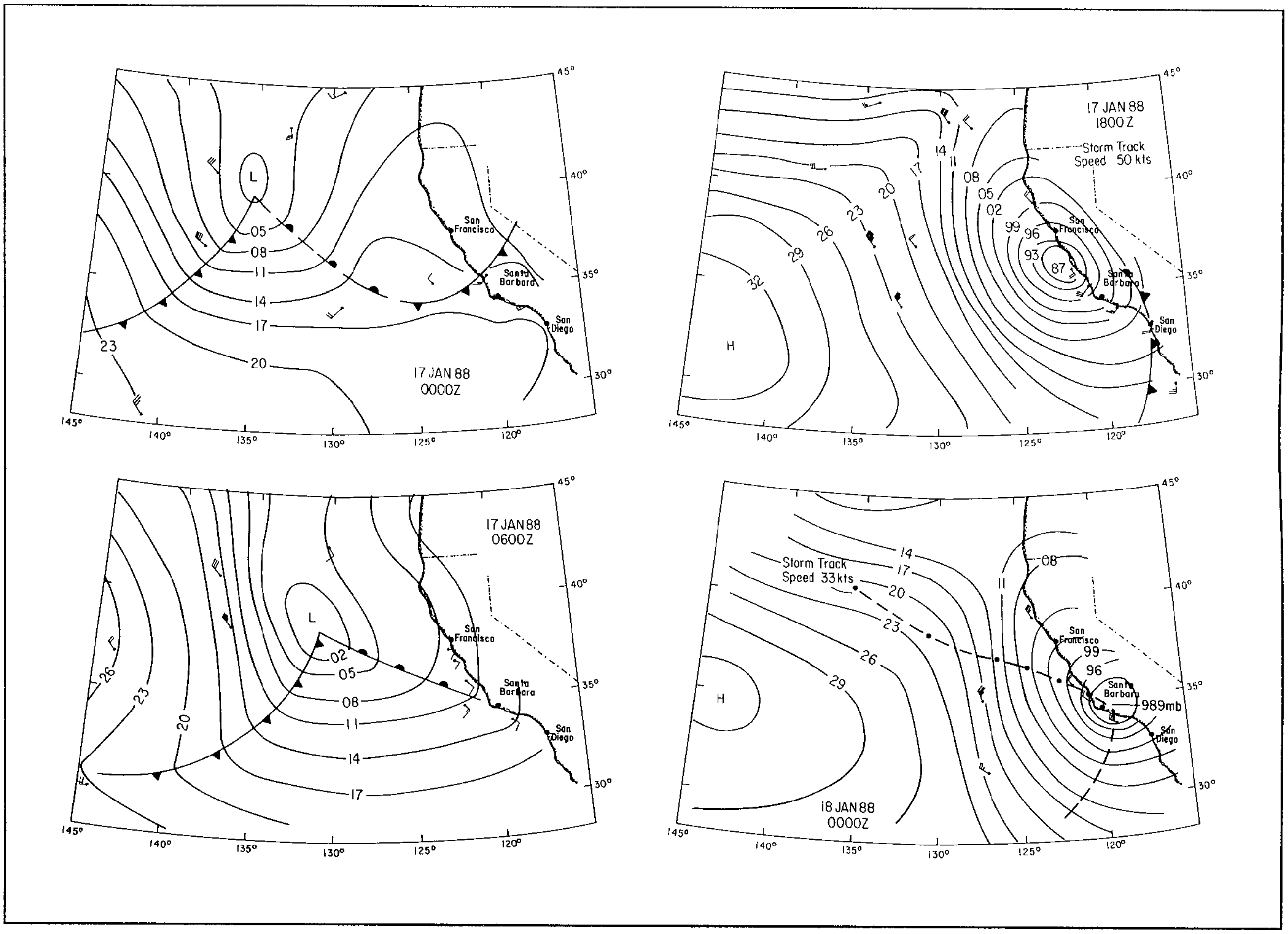

Figure 1. Surface pressure analyses during the period of the Jan. 16-18 storm (from Pacific Weather Analysis). Contours are in millibars (less 1000), contour interval is 3 *mb*. Small barbs on wind reports represent 5 *kts*, large barbs represent 10 *kts*, and flags represent 50 *kts*. Storm track is shown with times indicating location of low pressure center every 6 hours.

hours, (as seen by comparing Fig. 1c with Fig. 1b). The rapid deepening (surface pressure fall) of this storm is large enough to classify it as a "bomb", a name coined by meteorologists for extratropical storms whose central pressure falls by an average of at least 0.7 *mb* per hour over a 24 hour period at the latitude of central California (see Sanders and Gyakum[10]). Although such explosively deepening winter storms are comparatively common off the east coasts of Asia and North America where there are large gradients of moisture and temperature, it is quite unusual for them to occur this far south in the eastern Pacific (for example, see Klein[8]). By this time the intense storm was centered just off Big Sur, California and the front, moving ahead of the system, was inland through most of California and just coming on shore in San Diego. Southerly winds ahead of this front gusted to 60 *kts* at oil drilling platforms Harvest and Hondo located off Point Concepcion and in the Santa Barbara Channel, respectively. Following frontal passage, the winds turned southwest, then northwest gusting to 50 *kts* at Platform Harvest. Also evident in Fig. 1c is the powerful west-northwesterly wind fetch located southwest of the storm center. It is this region of high winds that generated the unusually large and damaging waves which began reaching California about six hours later.

By 1:00 PM on the 17th, the low pressure center, now beginning to slowly fill, made landfall near Avila Beach in central California with surface pressures as low as 989 *mb* Three hours later, at 4:00 PM (Fig. 1d), the low pressure center had moved east-southeast about 80 nautical miles to a location about 20 nautical miles northeast of Santa Barbara. At about this time all-time record low pressures were recorded at many southern California weather stations [see the hourly sea level pressure history at Catalina Ridge (just off Los Angeles) NOAA Buoy in Fig. 2]. Behind the front, strong northwesterly winds now extended along the entire coast of central California and through the southern part of the state. Platform Harvest observed gusts to 79 *kts* with an average wind of 70 *kts* at this time, and at more protected Platform Hondo, sustained winds of 40 *kts* were recorded.

By 10:00 PM on the 17th, the low pressure center had moved inland into the Mojave Desert and was filling rapidly. However, west-to-northwest winds remained high, with 35 to 40 *kts* reported at coastal stations and buoys from San

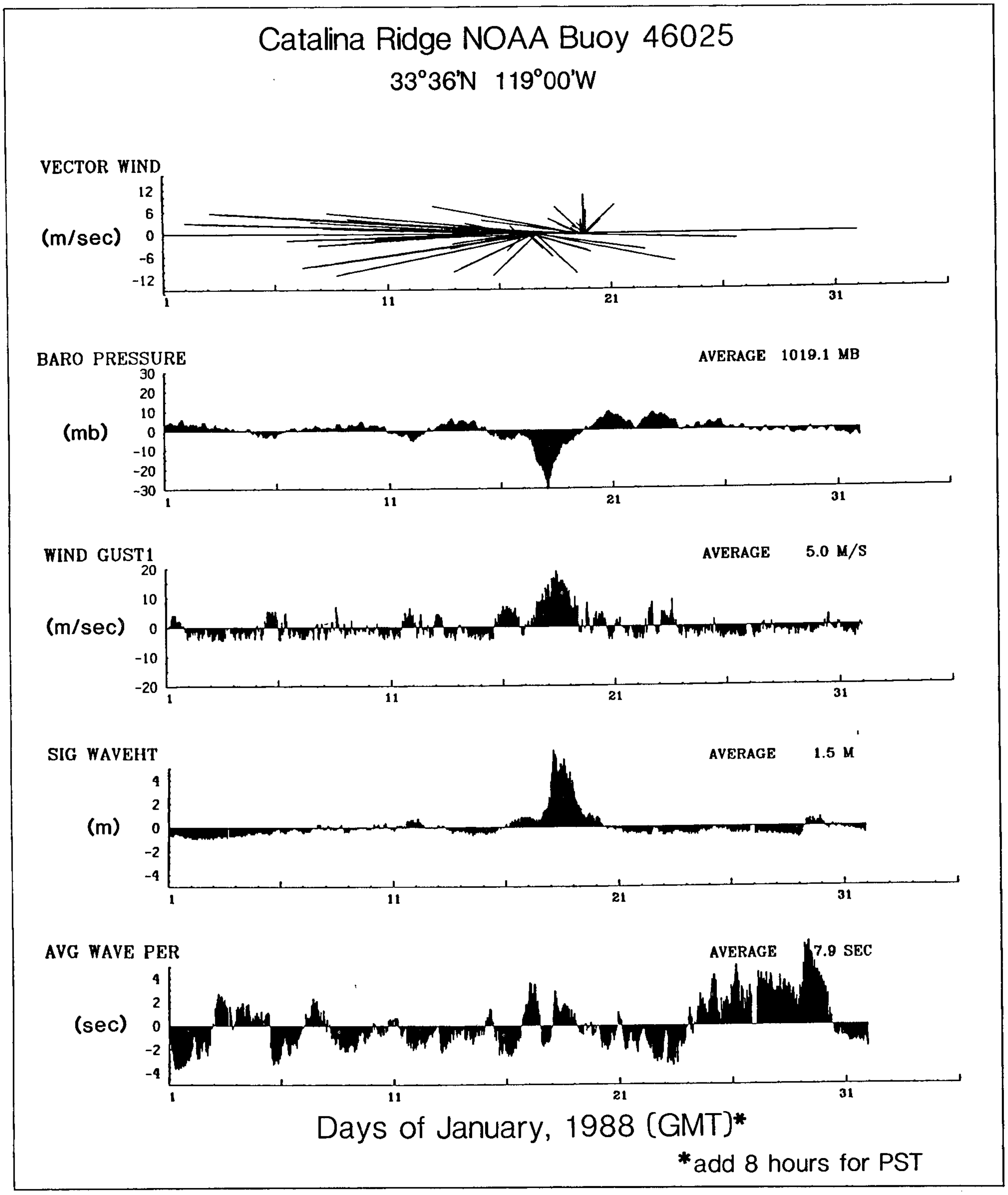

Figure 2. Hourly surface observations during January, 1988 at the NOAA Buoy 46025 off the southern California coast near Los Angeles. For clarity, wind vectors (upper graph) are only provided for Jan. 15-19. Wind direction such that wind points toward time axis, with a stick from below axis indicating wind from south, a stick from left indicating from west, etc. Wave periods (lower graph) are average zero crossing periods, typically much shorter than the peak energy period.

Diego to central California. Along the central California coast, these northwesterly winds provided a second source of high waves, and locations in regions as far south as Platform Harvest experienced their largest waves from the entire storm episode on the 18th, in association with this second fetch. Along southern California, which is shielded from northwesterly swell by Point Concepcion and the Channel Islands, maximum wave heights were observed on the 17th, although close inspection of wave data clearly shows contribution from the post-frontal northwesterly winds on the 18th.

The hourly time history of meteorological and wave observations along the southern California coast can be seen in Fig. 2 extracted from the Catalina Ridge NOAA Buoy, just northwest of Catalina Island. As mentioned above, near-record low barometric pressure readings were recorded along coastal southern California, accompanied by unusually large pressure falls exceeding 25 *mb* over the period of about one day. Several minute average wind "gusts" at the Catalina Ridge Buoy were measured above 20 *meters/second* (40 *kts*)during the peak of the storm on the afternoon on January 17. During this period the strong winds followed the typical storm pattern of veering from the southwest to the northwest as the front moved onshore.

High sea levels in the storm (see Flick and Badan-Dangon[6]) apparently resulted for the most part from the unusually low barometric pressure, and possibly by the strong southwesterly winds ahead of the front[7].

This storm's potency is indicated by the fact that these anomalies are about as large as the extreme sea level anomalies observed along the southern California coast in Winter 1982-83, as shown in Cayan and Flick[2]. However, it is interesting that the 1982-83 anomalies were assisted by a background increase in sea level of about 0.3 feet due to warming associated with El Niño while background sea level during January, 1988 was closer to its climatological normal elevation.

FORECASTING PROBLEMS

An aspect that is crucial to meteorologists is how well storms such as this one can be foreseen in the standard numerical forecast models. Overall, the numerical models performed very poorly on this storm, giving very inconsistent guidance during the critical period from 72 hours to 24 hours before landfall. The longer range (3 to 5 day) outlooks were quite good, but as the day of landfall approached the error increased. Figure 3 shows the observed (more correctly, analyzed) 500 millibar heights for 1600 PST on January 17th, the numerical forecast for that time issued 36 hours earlier, and the forecast error (i.e. 36 hour forecast observed) at that time. It can be seen that although both the forecast and observed maps show a well-defined trough along the southern California coast, the forecast heights were more than 200 meters too high in that region. In addition, the presence of a deep cut-off low over Pt. Conception and very

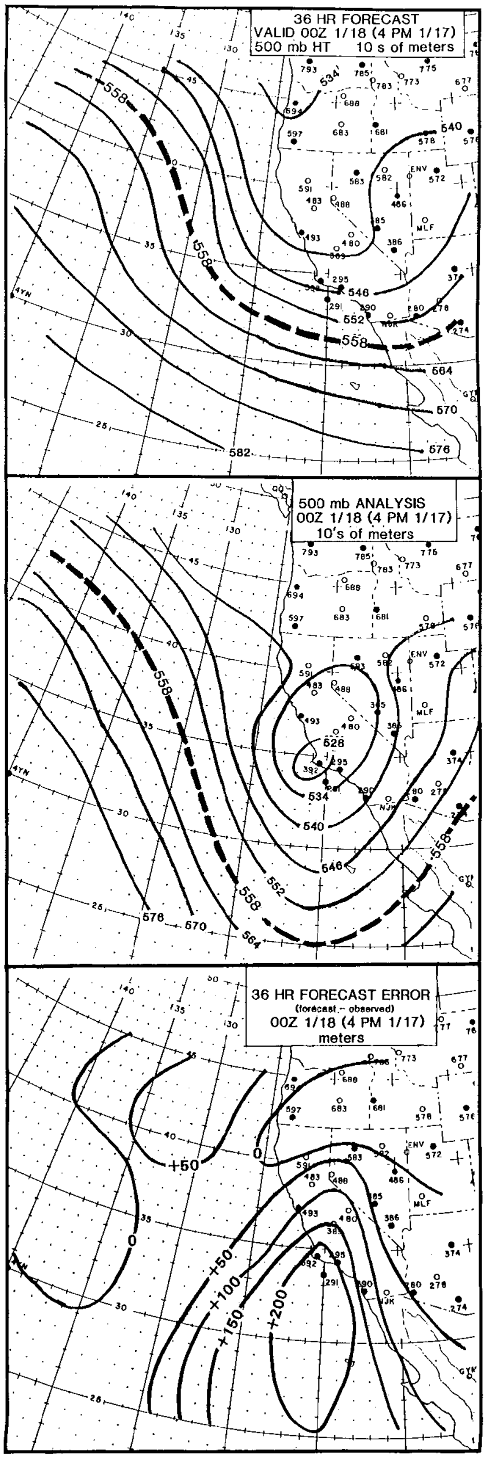

Figure 3. NOAA 500 millibar height 36 hour forecast valid for 1600 PST Jan. 17 (top), 500 millibar height analysis for that time (middle) and difference between the two (forecast-observed).Contours of two upper maps in 10's of meters, bottom map in meters.

sharp trough in the observations contrasts with an open, broader trough in the forecast. The combination of the very large errors in 500 *mb* height and differences in the spatial patterns could have led marine forecasters to assume the impending storm would be much weaker, track farther north into the Pacific Northwest and develop more slowly than actually occurred. To have made a good (or even reasonably correct) forecast of very high waves and near-hurricane force winds along the southern California coast, a forecaster would have had to accepted only the numerical guidance that indicated the most severe conditions, and would have had to do it on the basis of very little ship data in the key area of the ocean west of California.

The development of exceptionally high waves along southern and central California during the storm, detailed by Seymour[11], is an indication of the unusually strong winds and their time evolution during this storm. Although the major problems in predicting waves from this storm are: a) forecasting the storm track and intensity, and; b) properly delineating the wind field—it still remains for the wave model to accurately define the directional wave spectra in deep water off southern California. In this regard there are several points of interest. First the storm speed was much greater than the wave group speed for the 24 hour period preceding the sudden intensification of the storm on the morning of Jan. 17. This means that the westerly swell which caused such extensive damage from Santa Barbara south had at most 9 hours in which to be generated. Records from NOAA Buoys off Pt. Sal and Santa Monica showed this swell peaked at 1900 PST Jan. 17 with maximum energy at 14 to 17 seconds and considerable energy in the 18 to 22 second period band. Starting with a flat ocean and using sustained winds of 50 *kts* (well above average wind speeds reported by the buoys) wave models commonly in use will put the peak energy at about 10 to 12 seconds after 9 hours with very little energy at 18 to 22 seconds. There was, however, a west-northwest swell, generated by an earlier, more distant storm, already present off southern California as the intensifying storm neared the California coast. The presence of this swell probably allowed more rapid generation of large, long period, swell than would otherwise have been possible. It also seems possible that the storm peaked somewhat earlier than suggested by the surface pressure analyses.

Figure 4 shows a plot of the percent of wave energy per frequency band (for periods of 10 seconds and above) at the NOAA Buoys 46011 (Pt. Sal) and 46025 (Santa Monica Basin) for (a) 1000 PST Jan. 17, just prior to the arrival of the storm waves; (b) 1900 PST Jan. 17 at the peak of the storm waves. The Pt. Sal data show wave energy to be distributed almost identically at the two times. In contrast, although the Santa Monica Basin Buoy initially has a similar peak near 14-17 seconds, no energy is present in the 18-22 second band (plotted as 20 seconds). This is probably due to the fact that the earliest long period waves were arriving from the west-northwest and were selectively removed from the spectrum in rounding the western end of the Channel Islands. Later, at 1900 PST, there is a very impressive amount of energy in the 18-22 second band. The authenticity and statistical significance of this low frequency energy is indicated by its evolution over several hours of observations and its appearance several wave gauges, as shown in the Coastal Data Information Program Monthly Summary Report[3]. These waves must have approached from a more westerly direction and, given the geometry of the coast and the wind field, would have had to have been generated in a very short time.

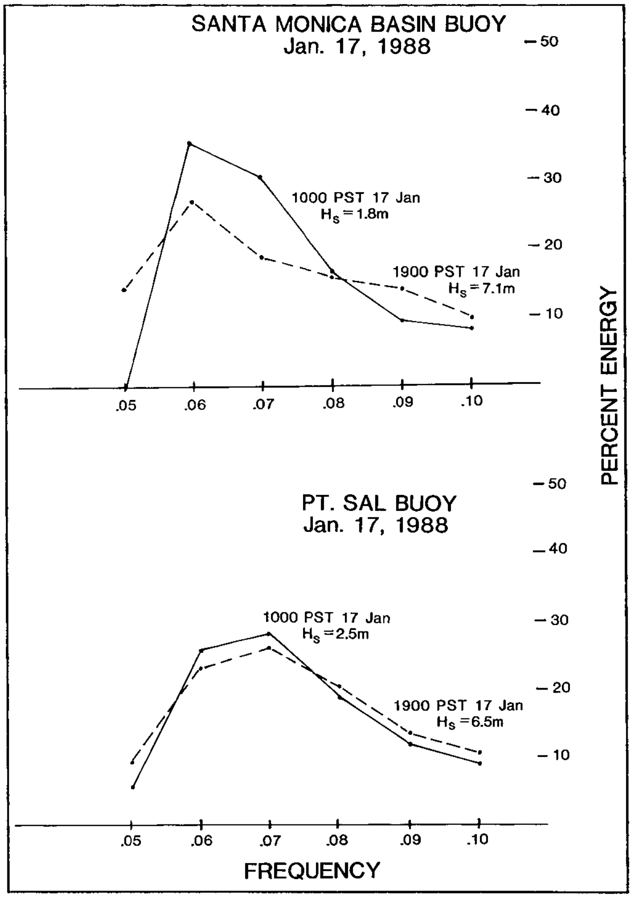

Figure 4. Normalized wave energy by frequency band recorded at NOAA buoys 46025 (top; Catalina Ridge, off Los Angeles) and 46011 (bottom; Pt. Sal, just north of Pt. Concepcion). Spectra are shown for 1000 PST Jan. 17 (solid) and 1900 PST Jan. 17 (dashed). Significant wave height (H_s) is also indicated.

SIMILAR PREVIOUS STORMS

Two cases which come closest to matching the meteorological conditions of Jan. 17, 1988 are discussed briefly below. Neither storm however had both the perfect track and timing of maximum intensity to produce extreme westerly swell conditions in southern California.

(1) November 19-20, 1961

This storm originated as a typhoon in the western Pacific, but weakened gradually on becoming extratropical as it moved through the mid-Pacific. A point that comes to mind here is that the ship data available 2–3 decades ago in the eastern North Pacific is as good or better as that today. The storm was steered by the jet stream into a broad trough along the west coast the storm intensified rapidly beginning late on Nov. 18 and by the night of the 19th was centered 1000 *km* west of San Francisco (Fig. 5). On an east-southeast track, very similar to that of the storm of January, 1988, the low moved directly toward Santa Maria (near the Pacific coast at approximately 35° N), but perhaps still retaining some of its tropical characteristics began to weaken upon reaching the cold water off California and the cyclonic circulation virtually disappeared as the storm moved inland. In this case, the track was very favorable for producing wave damage in southern California, but intensification occurred about 12 to 24 hours too soon so that the heaviest wind and waves did not reach the coast. It is interesting to note that five days later a cutoff low formed off Pt. Conception and with southeast winds of 65 *kts* and 20 to 25 foot seas sank an offshore drilling rig in the Santa Barbara Channel.

(2) December 15-16, 1987

Bearing the greatest resemblance to the January, 1988 storm is a storm which occurred just one month earlier. This proximity in time should not be considered coincidental as it is not at all uncommon for distinctive weather patterns to repeat two or more times in a given winter. The December, 1987 storm developed further off the coast than its January counterpart. By the night of Dec. 14 a 1005 *mb* low was centered 1000 *km* west of San Francisco and by the following afternoon it had deepened to 975 *mb*, centered just 400 *km* west of San Francisco (Fig. 6). The low turned southeastward on the 16th, passing slightly over 160 *km* west of Pt. Conception and Los Angeles, though filling slightly to 989 *mb*. At offshore oil platforms southeast winds gusting to105 *kts* were recorded, and there was considerable damage to Santa Barbara's waterfront from the wind and southeast seas. Because of the trajectory of the storm, however, westerly swell was only moderate, reaching heights of 12 to 14 feet for about 3 hours. This was an exceptionally intense storm, and had it maintained its intensity for another 12 hours and moved inland near Pt. Conception, the damage from westerly swell in southern California would very likely have exceeded that of its near twin a month later.

FINAL REMARKS

The evolution of January 1988 storm was considerably different from the storms that struck the California coast earlier in the 1980's such as in February 1980, shown by Dickson[4], and the winter months of 1982-83, as presented by Quiroz[9]. In contrast to the regionally-confined development of the January 1988 storm, these earlier storms were considerably larger in spatial extent and tracked across most of the North Pacific basin, and occurred in families that resulted in a progression of disturbances. The difference in the large-scale meteorological conditions associated with these two storm types is brought home by monthly mean maps the anomalies of sea level pressure (SLP) for March, 1983 and January 1988 in Fig. 7, lower panel. March 1983 coincided with a strong El Niño, and displayed a tremendously deepened Aleutian-Gulf of Alaska Low which characterized the entire that year. In Fig. 7 it is seen that the anomalous low nearly filled the entire North Pacific basin. As shown by the storm tracks in Mariners Weather Log[13], depicted by the dotted arrow on Fig. 7, the deep monthly mean low represents a swarm of vigorous, southerly displaced storms which tracked eastward along 35° N–40° N.

The long fetch of the westerly wind embedded in these cyclones generated high, long period swell which combined with anomalously high sea levels (see Cayan and Flick[2]) to batter the California coast several times during this winter, reported by Seymour et al.[12] In comparison, most storm activity during January 1988 was confined well to the north and the west of California; the singular exception was the January16–18 storm, (see storm track on Fig. 1, lower panel.), whose unusual development began only 15–20° to the west.

Because of their proximity, storms of this type are potentially the most severe storms to impact the southern California coast. Indeed, projecting the track of the December, 1987 storm so that the center passes over Pt. Conception at the time of maximum intensity (and raising the winds by 10%), and assuming the largest waves arrive during an unusually high tide, probably represents a realistic near worst-case scenario for southern California wave damage. Compounding the danger of the rapid development just a short distance offshore is the scarcity of ship reports and the

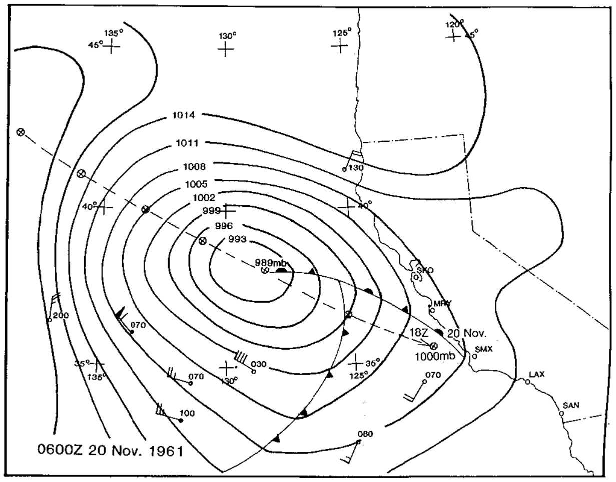

Figure 5. Surface analysis for 2200 PST, Nov. 19, 1961. Contours are in millibars, contour interval is 3 *mb*. Surface wind reports are as in Fig. 1; dashed line indicates storm track with ⊗ indicating position of low pressure center at 6 hour intervals.

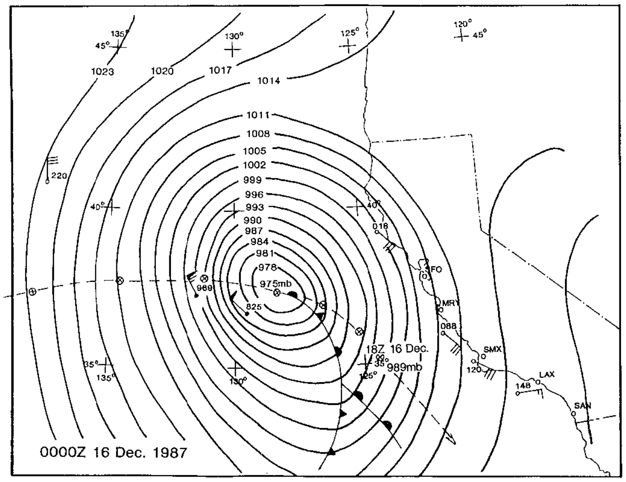

Figure 6. As in Fig. 5, but for 1600 PST, Dec. 15, 1987.

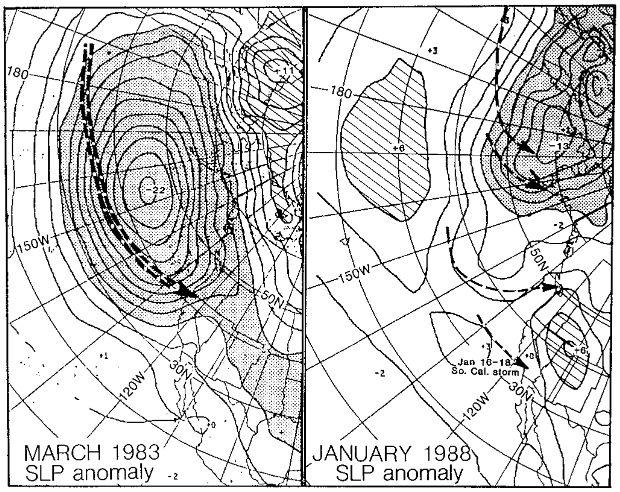

Figure 7. Monthly mean SLP anomalies for January 1988 (above), and March 1983 (below). Storm tracks for these two months, from *Mariner's Weather Log* are indicated by dashed lines. Contour interval is 2 millibars; stippling (hatching) indicates anomalies less than -4 *mb* (more than 4 *mb*).

region. Further, because few meteorologists are willing to gamble on predicting gale to hurricane force winds on the basis of a few meteorological indicators when the storm is not already present, without accurate numerical forecasts few such unusually severe events are likely to be adequately predicted even 12 hours in advance. Although improved forecast models may help in this direction, the addition of one or two meteorological buoys (perhaps using the one currently located near Pt. Sal) placed several hundred nautical miles offshore (for example, near 37° N, 127° W and 34° N, 125° W, respectively) would assist both numerical models and human forecasters alike.

ACKNOWLEDGEMENTS

NEG and DRC acknowledge the support from NOAA grant NA86AA-DCP104 for the Experimental Climate Forecast Center at the Scripps Institution of Oceanography, and DRC would like to thank the State of California Department of Boating and Waterways for support. The comments of two anonymous reviewers were most helpful in improving this manuscript.

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Wave Observations in the Storm of 17-18 January, 1988

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INTRODUCTION

SOUTHERN CALIFORNIA, BECAUSE of the complexity of its maritime borderlands, its relative susceptibility to wave attack from major storms anywhere in the Pacific Basin, the economic significance of its developed shoreline and offshore petroleum production facilities, and the wisdom and foresight of a few government sponsors, is blessed with perhaps the greatest concentration of wave measurement devices of any comparable area in the world. Therefore, although the Great Storm of January '88 was small in area, it was still possible to observe some of the structure in its wave fields as it developed and moved ashore. This paper will report on the observations and will consider some aspects of their characteristics.

WAVE MEASUREMENT STATIONS

In all, 21 stations between San Francisco and the border with Mexico reported the storm. Five of these were buoys operated by NOAA as part of their data gathering in support of weather forecasts and other services. The remaining 16 are operated by Scripps as part of the Coastal Data Information Program (CDIP) and sponsored jointly by the Coastal Engineering Research Center of the U.S. Army Engineers and by the California Department of Boating and Waterways[6]. Although the CDIP data gathering network was unaffected by the storm, the Pacific Telephone lines on which it depends went out close to the peak of the storm, resulting in a data gap of several hours. A utility power outage at Imperial Beach kept that station down throughout the storm. The locations of the 21 active measurement sites are shown in Figure 1.

Of the CDIP stations, eight of these (Mission Bay entrance, Scripps Pier, Del Mar, Oceanside, San Clemente, Sunset Beach, Marina and Santa Cruz) are nearshore stations (average depth about 30 ft) and are sheltered in various degrees by the offshore islands or headlands. The Mission Bay Buoy, although in deeper water, is similarly sheltered. This limits the usefulness of these stations for this study. The remaining 7 stations, either in deep water or on open coastlines, have been selected for their generality in characterizing the storm (although the Santa Cruz Canyon buoy, in deep water, is sheltered by the Channel islands). The deep water NOAA buoys (Catalina Ridge is partially sheltered), plus the 7 selected CDIP stations provide the most general data on the storm.

WAVE DATA

Figure 2 shows the growth and decay of the significant wave height measured at the three stations in the vicinity of the Channel Islands. The gap in the CDIP data caused by the loss of telephone service is clearly evident. The highest measurement at Begg Rock (33.4 ft) was the maximum measured by any of the stations during the storm and the energy at this point was peaked at a period of about 15 s. Because of the similarity in the rise and decay between the Begg Rock buoy (essentially open ocean exposure) and the nearby and partially shadowed NOAA Catalina Ridge site, the peaking of NOAA buoy an hour or so after the start of the data gap, and the rapid rise rate of the Begg Rock significant height all suggest that the actual peak weight may have been significantly higher than recorded here - perhaps as great as 36-38 ft, with the peak period near 17 s. If so, this would imply a one-in-one-thousand wave height of about 75 ft! This assumption is based upon a theoretical distribution of wave heights for a storm in which conditions change very slowly. It would not necessarily be the best model for this rapidly changing event.

Figure 3 shows the build up and decay of wave heights near Point Conception. The maximum significant height

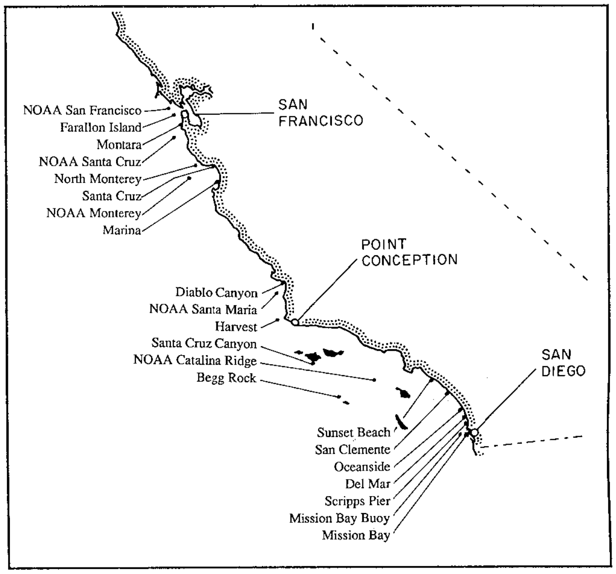

Figure 1. Wave measurement stations that reported during the storm of 17-18 January, 1988.

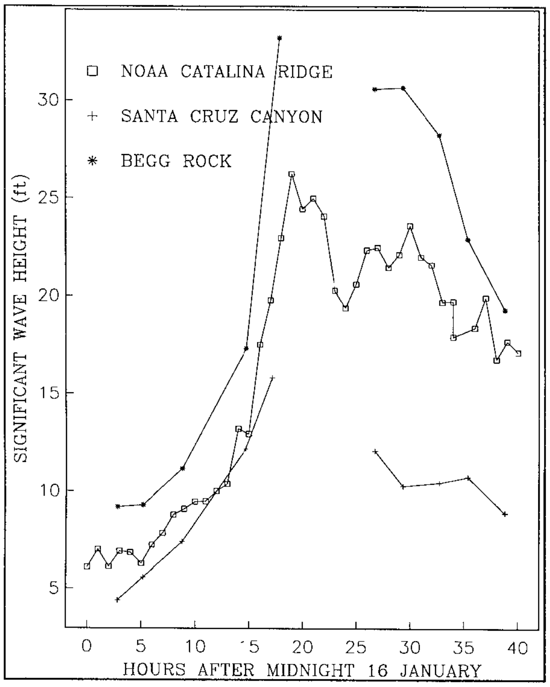

Figure 2. Wave heights near the Channel Islands during the storm.

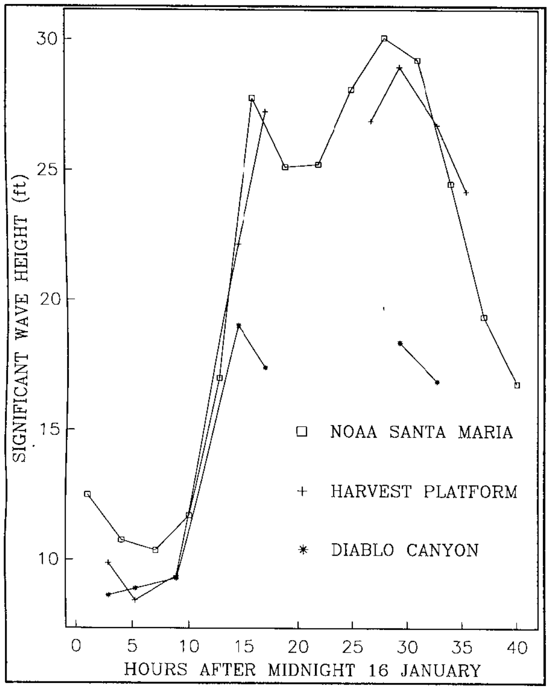

Figure 3. Wave heights in the vicinity of Point Conception during the storm.

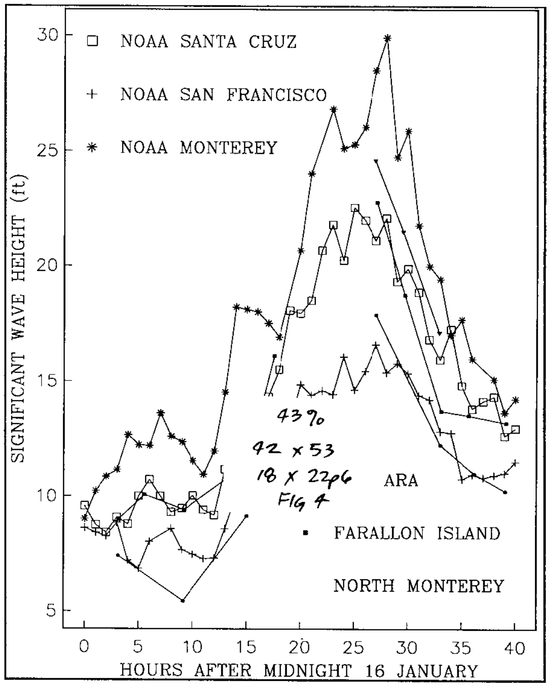

Figure 4. Wave heights in Central California, between Monterey Bay and San Francisco, during the storm.

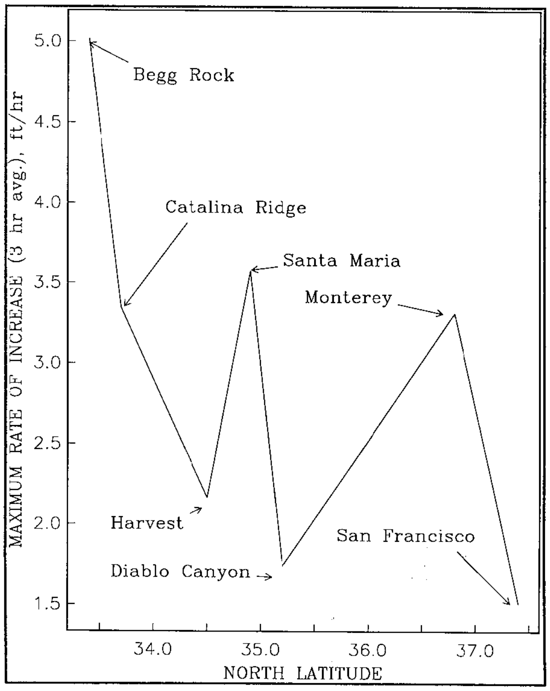

Figure 5. Maximum growth rates of significant wave height, averaged over 3 hour periods, from a number of open coast sites.

measured in this region was 30.4 ft at a peak period of about 17 s. In Figure 4, the heights from the 6 reporting stations in the Monterey/San Francisco area are shown. The maximum height here was the same — 30.4 ft — but was peaked at only 15 s.The intensity of the winds and, very probably, the existence before the storm of long period swell (about 17 s) of considerable height (about 10 ft), caused a very rapid increase in the significant wave height. Figure 5 shows the maximum rise rates (3 hour averages) for several open coast sites with Begg Rock measuring about 5 ft/hr. This compares with a maximum growth rate of about 1 ft/hr at this same site during the 27 January, 1983 storm when the significant height reached 24 ft[1]. It should be noted that the peak wave generation zone was far removed in space and time from the Begg Rock measurement site in 1983, but was probably very close in 1988. A better comparison can be made with rise rates for the 1 March storm, the largest in 1983. Earle *et al*[3] shows, in the generation area about 1500 miles offshore, an average rise rate of 4.6 ft/hr in the 3 hours prior to the peak significant height of 39 feet. The growth of the '88 storm as a function of latitude is shown schematically in Figure 6.

STORM RANK

It is of interest to try to rank this storm in the long term wave climate of southern California. The record of storm wave observations along this coast is less than 100 years in length, so that very little can be said about return periods. However, it is possible to make some conjectures based upon what is known. Seymour *et al*[5] reported on the major storms in the period 1900–1983 in this region. Figure 7 shows a distribution of extreme significant wave heights taken from that study, as reported in Walker *et al*[8]. Moffatt & Nichol[4] calculated another return period estimate for various wave heights applicable to the southern California area and this has been plotted in Figure 8. The January, 1988 storm has been shown on both distribution lines. The return period implied by each of these distributions is much greater than 200 years, perhaps as much as 400–500 years. Because projections beyond about 200 years would be totally unwarranted, based upon the length of the data record, a recurrence interval of not less than 100–200 years for a storm of this magnitude appears reasonable.

Two recent studies of the January '88 storm further illustrate the intensity of this event. Seymour *et al*[7] describes the extreme damage to the Point Loma kelp forests, much greater than the combined effects of the six major storms of 1983 (the largest previous recorded). Dayton *et al*[2] deals with damage to geological structures at great depths (up to 100 ft) offshore of San Diego that also greatly exceeded that in the 1983 season. Table 1, taken from the latter study, suggests the likely reason for this increased destructiveness. It shows that, at a nominal depth of about 60 feet near the entrance to Mission Bay, both the maximum velocity-squared (proportional to the drag force) and the maximum acceleration (proportional to the inertial force) were about twice as great in the '88 storm as the worst observed during the '82–'83 season.

Table 1

Winter Season	Maximum Velocity Squared (ft^2/s^2)	Maximum Acceleration (ft/s^2)
82-83	58.2	3.5
87-88	110.1	6.3

CONCLUSIONS

It is clear from these wave observations that this was an exceptional event, far exceeding any ocean storm in recorded history in this area. As pointed out by Strange *et al* in this issue, the presence of pre-existing swell resulted in wave periods of much greater length and much larger significant heights than can be predicted by any wave generation model that starts, as the present models all do, from an assumption of a flat ocean. This may be the most important single observation about the Storm of '88 if it leads to successful research on wave generation with pre-existing swell.

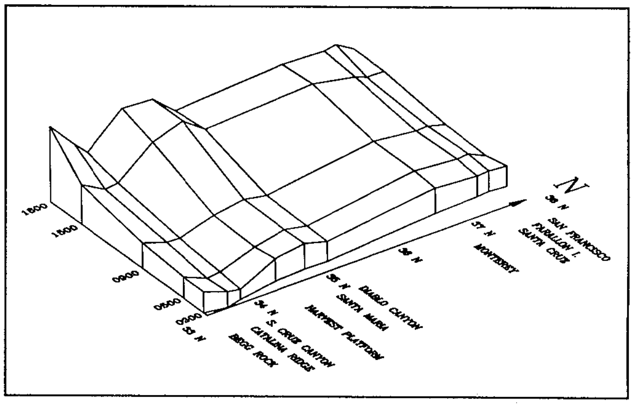

Figure 6. The growth of the storm along the coast. The vertical dimension is relative significant wave height, plotted against Pacific Standard Time on 17 January, 1988, and north latitude.

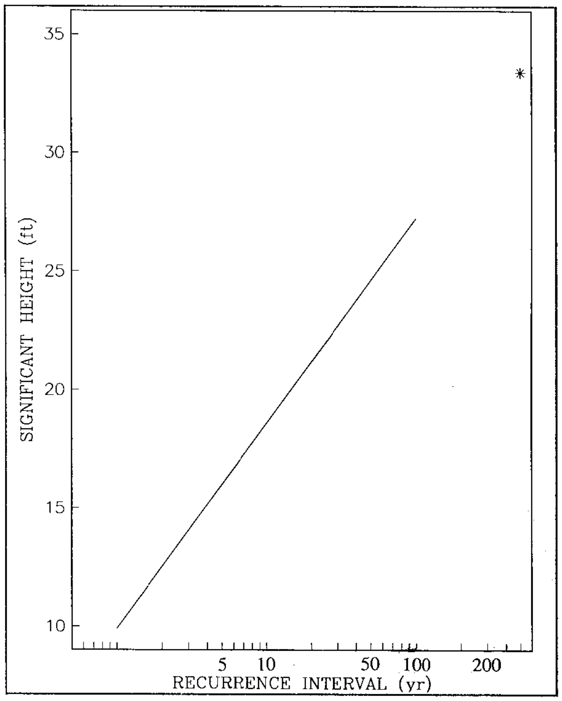

Figure 7. Return period estimation function for major storms of various significant wave heights from Walker *et al.*, 1984 The January 1988 storm is indicated with an asterisk.

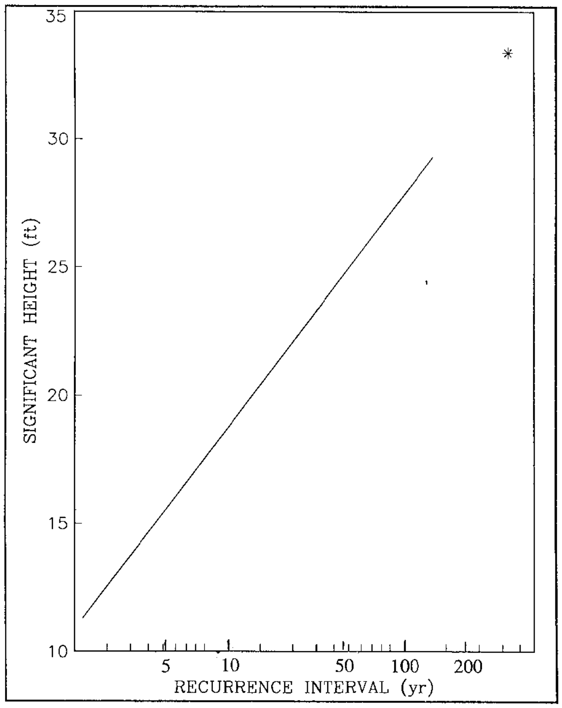

Figure 8. Return interval estimates, similar to Figure 7, from Moffatt & Nichol, 1988.

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Southern California Beach Changes in Response to Extraordinary Storm

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INTRODUCTION

DURING THE PERIOD 16–18 January 1988, a rapidly moving storm of major intensity passed through the southern California bight producing record heights offshore and causing extensive coastal damage. The storm-induced damage was particularly severe at King Harbor (Redondo Beach) where waves breached the breakwater and partially destroyed several buildings, parking lots, and a pier. By sheer coincidence, on 15 January, a shallow-water beach profiling survey was carried out about 5 miles north of King Harbor along Dockweiler State Beach and beaches fronting the city of El Segundo (Figure 1). In order to study the effects of the extraordinary storm event on the beach profiles, the profile survey was repeated on 23 January, and continued periodically through August 1988. Subsequent refraction analyses using deep-water wave records (from NOAA Date Buoy 46025 located roughly 35 nm southwest of the study site) revealed that, off Dockweiler/El Segundo, this storm produced significant wave heights of 25–29 ft in 30 ft of water and breaking waves further offshore[7].

This paper discusses the beach changes associated with the mid-January 1988 storm with emphasis on both storm-induced erosion and post-storm accretion. Beach changes observed at Dockweiler/El Segundo are also compared with those from several other southern California locations. For details regarding the meteorologic and oceanographic elements of this storm, the reader is referred to Cayan et al.[2] and companion papers in this issue of *Shore and Beach.*

STUDY AREA

The Dockweiler/El Segundo beach area is located along the central portion of Santa Monica Bay, facing roughly west-southwest (Figure 1). The regional configuration of the shoreline and the presence of several offshore islands and shoals are such that the study site is directly exposed to deep -water waves through a window that spans roughly west to west-southwest.

The shoreline in the study area is intersected by one long and several shore groins (Figure 1). The long groin, referred to as the Chevron groin, extends roughly 900 ft offshore from its landward terminus. This rubblemound structure, together with the bulk of the sand impounded on its northern flank, was constructed in 1983–84, following the the severe winter storms of 1982–83, to provide protection for oil pipelines crossing the shoreline. South of this groin, the beach is narrower, and is backed by a steep rubblemound revetment that protects the coastal frontage of the Southern California Edison station.

The beaches in the study area are in large part the product of a series of beach nourishment operations involving a total of over 20 million cy of sand between 1938 and 1984. Sediment samples collected in 1987 from several locations between the back beach and –6 ft (MLLW) indicated mean-grain sizes in the range of 0.15 to 0.36 mm. Shortly after the mid-January storm, a nourishment operation between February and August 1988 added another 705,000 cy to these beaches, with about 22% of this material being placed along the southern segment of Dockweiler State Beach and the remaining 78% in the area south of the Chevron groin.

The pre- and post-storm profiles of the Dockweiler/El Segundo beaches were surveyed at nine locations (numbered lines in Figure 1). The profiles extended from a control point on the beachfront bike-path seaward to a depth of –2 to –5 ft below Mean Lower Low Water (MLLW).

To provide information on the regional distribution of storm-induced beach volume changes, data from surveys sponsored by the U.S. Army Corps of Engineers were utilized. The Corps-sponsored surveys, which spanned the southern California shoreline between Dana Point and the U.S./ Mexican border, extended from a back-beach monument to –40 ft (MLLW). Virtually coincident surveys along the southern California region by the Corps and at Dockweiler/ El Segundo were performed in September–October 1987 and just after the storm in January 1988.

RESULTS

Dockweiler/El Segundo Beach Erosion

When evaluating storm-induced profile changes, the timing of the post-storm survey relative to the storm cycle must not be overlooked. Investigators of post-storm beach recovery processes, such as Sonu[6] and Chiu[3], have noted the rapidity with which the rebuilding of a storm-eroded beach occurs. Observations by Sonu[6] of post-hurricane recovery along Gulf coast beaches indicated that landward movement of material and beach face deposition was initiated within hours of the passage of the peak storm waves. Since the post-storm survey at Dockweiler/El Sugundo was performed roughly four days after the peak storm waves reached the coast, it is likely that recovery of the beaches was well underway, and that the profiles measured at that time did not reflect the maximum recession produced by the storm.

For the beaches north of the Chevron groin (Figure 2,

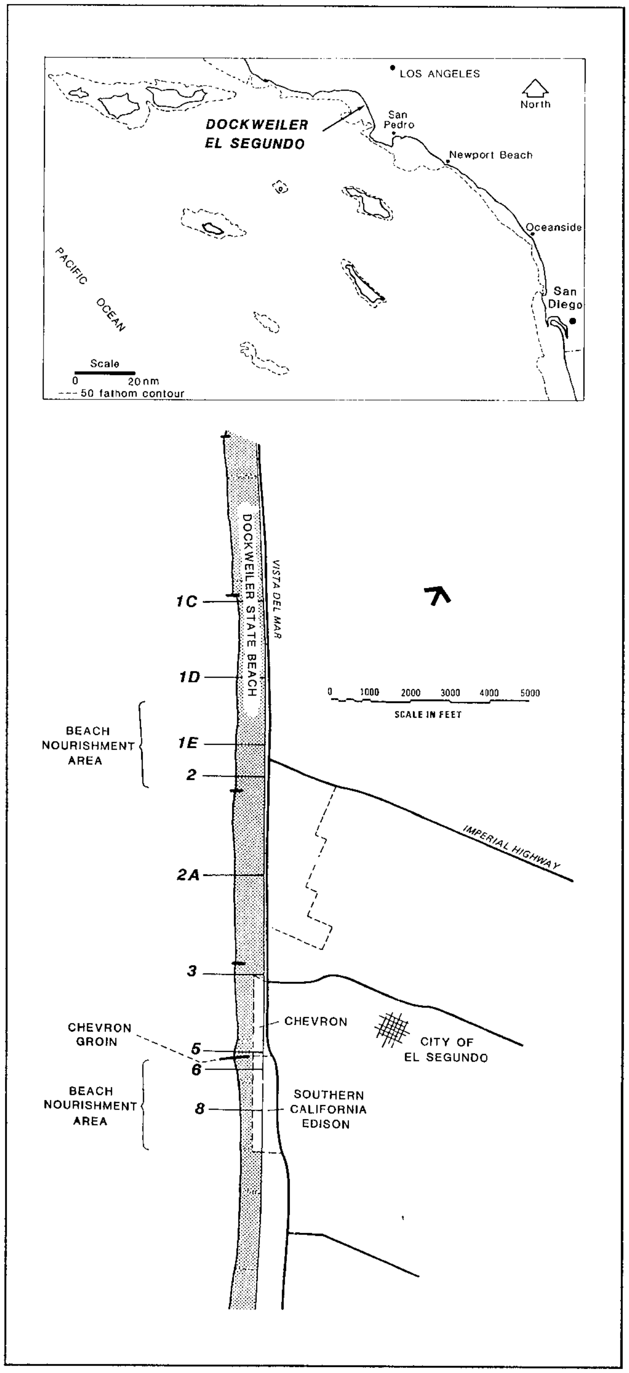

Figure 1. Location and Vicinity map.

Lines 1C - 5), the pre-storm storm profiles generally displayed a convex shape with the beach berm at about +11 to +13 ft (MLLW), and a fairly uniform beach face slope of about 1V:10H. With the exception of Line 5, the storm removed the berm, creating a nearly flat beach face with a slope of 1V:20H. At line 5, the erosion of the profile extended deeper than at the other profiles, but produced only minor flattening of the beach face to a slope of about 1V:13H. South of the Chevron groin (Figure 2, Lines 6 and 8), there was substantially less change in the profiles compared with those to the north. The beaches in this area are backed by a high rubblemound revetment that limited the landward extent of the profile changes (the revetment showed no evidence of damage following the storm).

North of the Chevron groin, the erosion volume above –2 ft (MLLW) ranged progressively from minimum of 20 cy/ft at Line 1C (located about 11,200 ft north of the groin) to a maximum of 63 cy/ft at Line 5 (nearest the groin). South of the groin, the net erosion volume was much smaller, 4 and 10 cy/ft at Lines 6 and 8, respectively.

Dockweiler/El Segundo Beach Recovery

Some information on the significant wave heights that prevailed during the post-storm monitoring period can be derived from hindcast/refraction analyses that were carried out for the two-week period preceeding each survey. These data showed that, with the exception of a minor storm in early May that generated local seas of up about 2 ft and swell of about 4 ft.[7] Wave data collected and reported by CDIP[4] may also be referred to for further information.

Since beach nourishment at the northernmost end of the study area and south of the Chevron groin obscured the progression of natural post-storm beach recovery in these areas, attention was focused on Lines 2A, 3 and 5 (Figure 3). Recovery of the beach (given as a percentage of the volume eroded by the storm above –2 ft, MLLW) showed two distinct phases over the 9-month post-storm monitoring period. The first phase, covering the initial 3 weeks, was characterized by a very rapid recovery with the beach at all three lines regaining between 45% and 65% of the volume eroded by the storm. The second phase was marked by a significantly lower recovery rate that was roughly constant through to the end of the montoring period. Except for a period of minor storm-induced erosion at Lines 2A and 3 in early May, the beach volume increased to between 90% and 132% by 263 days after the storm. The excessive recovery at Line 5 (132%) was undoubtedly caused by material transported south from the nourished Dockweiler State Beach and impounded by the Chevron groin.

The recovery rates observed at Dockweiler/El Segundo fall within the range observed by other investigators, although these rates range widely, Birkemeir[1], in a study of the New Jersey coast following a December 1977 storm, found that over half of the eroded volume returned within two days. At the other end of the scale, Dean and O'Brien[5] found that roughly seven years elapsed before a segment of New York's Long Island south shore reached 90% recovery following a particularly long, severe storm in March 1962.

Southern California Regional Beach Changes

Regional beach profile volume changes were determined using coincident Corps and Dockweiler/El Segundo survey data obtained in September-October 1987 (pre-storm) and January 1988 (post-storm) (Figure 4). Between Dana Point

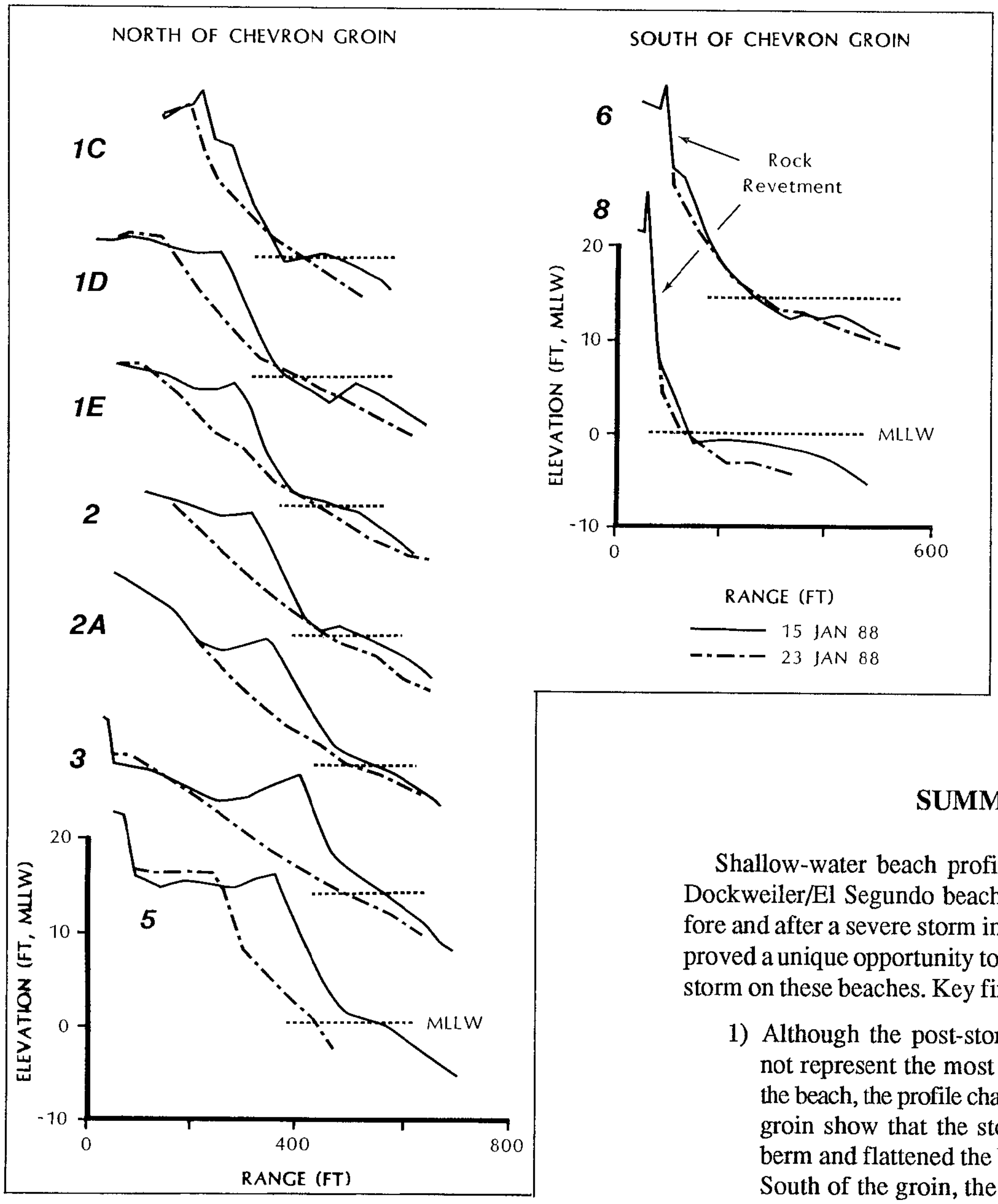

Figure 2. Comparison of Pre- and Post-Storm Beach Profiles at Dockweiler/El Segundo.

and Imperial Beach, the erosion magnitude varied from place to place, although values tended to be higher to the south in conjunction with the island sheltering effects that generally diminish in that direction. None of these southern stations experienced the maximum erosion of 76 cy/ft which occurred at Dockweiler/El Segundo (note that the Dockweiler/El Segundo erosion values given here and in Figure 4 differ from those in the above discussions due the use of survey data coincident with the available Corps data).

SUMMARY

Shallow-water beach profiles were acquired along the Dockweiler/El Segundo beaches of Santa Monica Bay before and after a severe storm in mid-January 1988. The data proved a unique opportunity to study the impacts of this rare storm on these beaches. Key findings from this analysis are:

1) Although the post-storm profiles probably do not represent the most severely eroded state of the beach, the profile changes north of the Chevron groin show that the storm waves removed the berm and flattened the beach face significantly. South of the groin, the beach experienced only minimal profile changes.
2) At the seven profiles surveyed north of the Chevron groin, the storm-induced beach erosion volume (above -2 ft, MLLW, per unit shoreline length) ranged from 20 cy/ft at the northernmost profile (about 2.1 mi away) to a maximum of 63 cy/ft at the groin (based on surveys from the day before and four days after the storm.)
3) The profiles not directly affected by the local beach nourishment operations, showed two distinct phases of post-storm beach recovery: an initial period of rapid accretion in which the

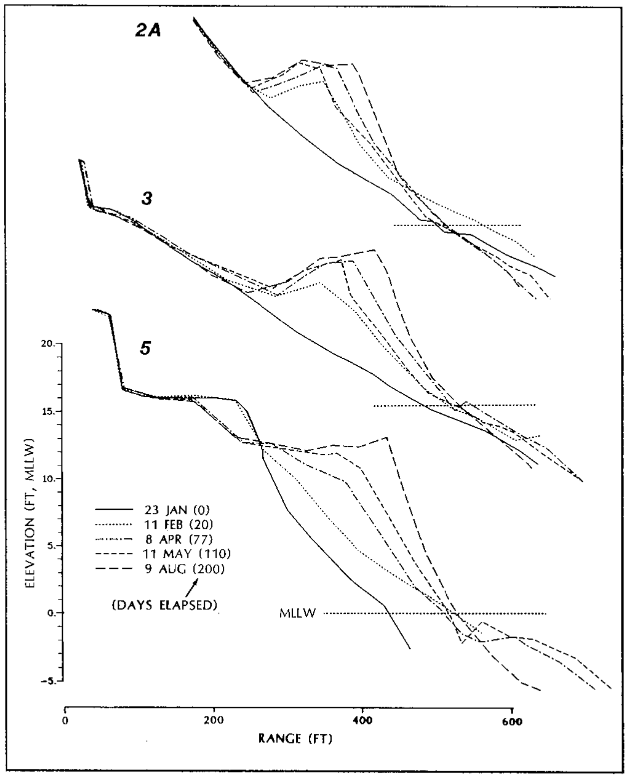

Figure 3. Comparison of Post-Storm Beach Profiles at Dockweiler/El Segundo.

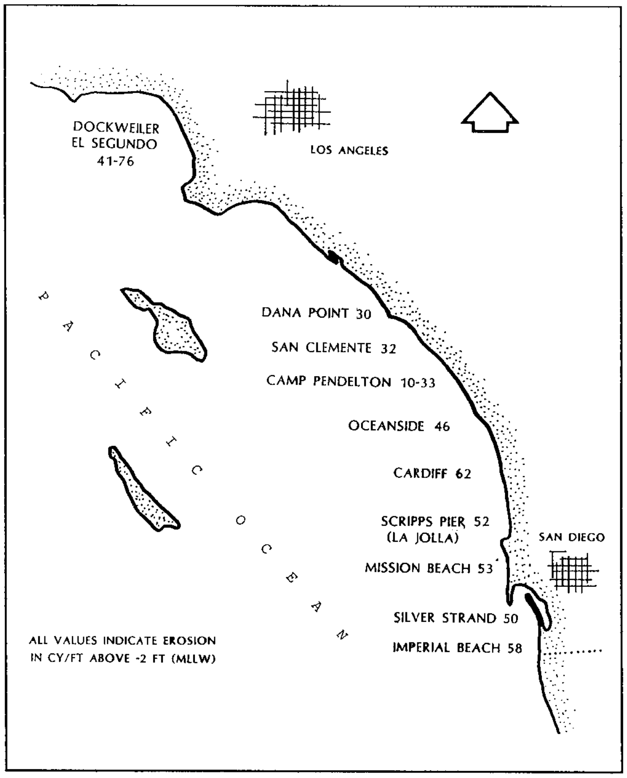

Figure 4. Beach Volume Changes along Southern California Shoreline between September-October 1987 and January 1988.

beach regained roughly 50% of the volume eroded by the storm within about 20 days, and subsequent period of slower accretion in which the beach reached essentially full recovery after about 200 days.

4) On a regional scale, the erosion at Dockweiler/El Segundo was slightly greater than that measured at a number of stations spanning the coastline between Dana Point and the U.S.-Mexican border (based on pre- and post-storm surveys from the period September 1987 - January 1988).

ACKOWLDEGEMENTS

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Storm Damage Assessment for the January 1988 Storm Along the Southern California Shoreline

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INTRODUCTION

DEVELOPMENTS ALONG THE HEAVILY populated coastal segments of southern California and northern Baja California sustained serious structural and flooding damage during the high intensity storm of January 1988. The magnitude and extent of damage was directly related to the size, distribution and duration of the storm waves attacking each segment of coastline, as well as the relative timing of the waves, tides and storm surge. These factors, as well as the meteorology of this fast developing storm event, are discussed in the accompanying papers of this volume.

The purpose of this paper is to catalog the types and extent of damage to coastal structures, including dollar amounts where these are available. The primary source of information for this chronicle is a reconnaissance and photo documentation of the coastline between Malibu and San Diego, conducted by the authors on 19 to 21 January 1988. This survey did not include inspection of offshore facilities, such as drilling rigs or the offshore islands. Survey information was heavily supplemented with published newspaper accounts of the damage. Figure 1 shows a map of the southern California and northern Baja coastline, indicating place names referred to in the text.

The one day duration of the storm of 1988 was relatively short for its' intensity[2]. The resulting damages were therefore relatively minor compared with the El-Niño winter of 1982-83. Except for a few areas, notably Redondo Beach, Huntington Beach and Ensenada, structural damage to coastal property was minor. Widespread cosmetic damage and debris deposition did occur, however.

Our conclusion is that the southern California shoreline is everywhere vulnerable to at least minor flooding damage from high waves associated with coastal storms[3]. The location of areas vulnerable to severe damage change and depend on the timing and duration of storm wave attack, and particularly on the precise deep water wave approach angle.

STORM DAMAGE COST ESTIMATES

Newspaper reports from various coastal areas were reviewed during the weeks following the January 1988 storm, and these were the primary sources for the cost estimates quoted below. Table 1 summarizes the dollar damage as a function of location. We estimate total property damage from the storm at over $28 million.

Table 1.
January 1988 Storm Damage and Cleanup Cost Estimates

Locations	$ Damage
Ventura	$ 300,000
Malibu	
Zuma Beach	2,000
Manhattan Beach	1,500
Hermosa Beach	13,000
Redondo Beach	16,000,000
LA-Long Beach	
Seal Beach	25,000
Huntington Beach	4,500,000
Pacific Coast Highway	250,000
Laguna Beach	1,150,000
San Diego	6,700,000

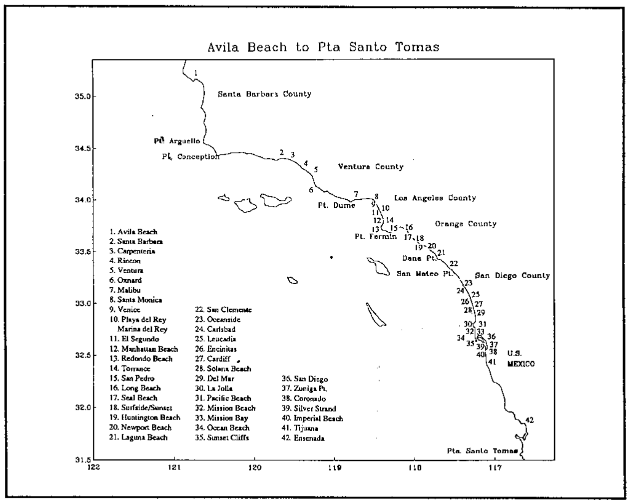

Figure 1. Map of southern California and northern Baja showing place names referred to in the test.

The major effects of the storm were highly localized. The largest concentration of property damage occurred at Redondo Beach where the breakwater was breached and overtopped. A hotel, restaurants, piers and harbor boating facilities were destroyed or severely damaged (Figure 2). A detailed account of these damages is presented by Domurat and Shak[1].

The next largest dollar damage was inflicted at San Diego, where a number of restaurants were flooded and some boats on San Diego Bay were damaged or sunk. In addition, major costs were incurred to clean up kelp and other debris that covered all low lying roads between Oceanside and Imperial Beach.

Huntington Beach suffered costly damage when the seaward 250 feet of the city pier was lost, along with the recently constructed "End Cafe". The breakwater at Ensenada in Baja California was overtopped and damaged. Fishing boats moored in the harbor were washed ashore and some were sunk. No dollar damage estimates were available. No estimates could be made of the dollar value of sand loss to the southern California beaches. The magnitude of beach retreat (and subsequent recovery) is discussed by Domurat and Shak[2].

STORM DAMAGE BY LOCATION

Santa Barbara and Ventura Counties

As shown in the accompanying papers by Strange et. al and Flick and Badan Dangon (this issue), the storm made landfall at Avila Beach (Figure 1) with record setting low barometric pressure and very strong, gusty winds. The storm moved south-east and inland, exposing the shore south of Point Conception to intense rainfall as well as high storm surge.

Figure 2. Photo showing collapsed roof section of Portofino Inn, located on Mole B, inside King Harbor, Redondo Beach. Hotel guests were rescued off the roof of the damaged structure by a news helicopter on Sunday evening, 17 January 1988.

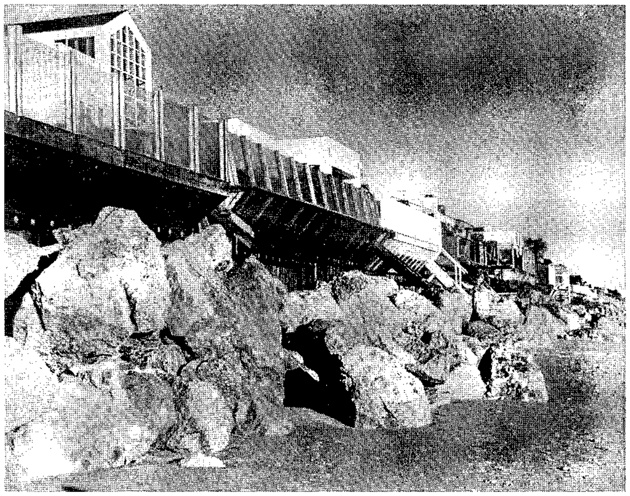

Figure 3. Photo of Malibu Beach showing sand loss and widespread damages to beach access stairs, windscreens and patios. Rock rip-rap protection was placed after 1982-83 winter storm damage.

Minor damage occurred at Santa Barbara Harbor and Sterns Wharf, but little if any erosion was observed at Leadbetter Beach. Damage to boats in the harbor and at the yacht club was largely avoided by moving the boats. Waves broke over the harbor breakwater causing large harbor surge and mooring line tugging, but little damage.

Homes along the shoreline in Carpinteria were damaged when the seasonally maintained, artificial dune was breached. High breakers washed through the gap and inundated the entire back beach, starting the evening of 17 January. Eleven beach front homes along Sandyland Road were flooded, and some sustained foundation damage. Truckloads of sand were transported in to plug the break in the dike, and sandbagging operations were carried out.

Highway 101 in the Rincon area, from Punta Gorda south to Emma Wood State Beach, was overtopped and covered with sand, cobbles and debris during the storm. The entire reach was closed to traffic from late 17 January through 18 January and campers along the shoreline were evacuated.

Ventura area parking lots, promenade and beach access points were flooded and covered with sand, cobbles and debris. Extreme beach erosion and flooding occurred between Groin # 1 and Groin # 2 upcoast of Greenock Lane, flooding upland homes and destroying the cul-de-sac beach access point. Damage to the groin and the rock rip-rap revetment along the shore of Marina Park was minor. No major structural damage was sustained by the Ventura pier during the storm.

Oxnard Shores beach was overtopped and Mandolay Beach Road was flooded and covered with sand and debris between Fifth Street and Breakwater Way. Wave overtopping and flooding also occurred landward of Capri and Neptune Way.

Los Angeles County

The Malibu area sustained no major damage, in contrast to the damages inflicted during the severe 1982 - 83 winter. However, there was frequent cosmetic damage to beach access stairs, windscreens, beach level decks and other private facilities at the very expensive beach front homes (Figure 3). Breakfast diners fled when a huge wave crashed through the door of Malibu Sand Castle restaurant, flooding the dining room with sand and surf on 18 January. The beach along the west end of Malibu Colony was lowered about 5 - 6 feet and narrowed by 80–100 feet. This is a common occurrence for the south facing Malibu beaches during storms approaching from a southerly direction.

Parking lots and bicycle paths in Santa Monica, Venice, Playa del Rey and Manhattan Beach were overwashed and covered with sand and debris. The Venice Beach Safety Headquarters was flooded. About 90 homeless persons living in tents along Venice Beach were evacuated when wind and surf tore away their shelters. Venice Pier withstood the storm even though waves broke over the end.

Playa del Rey and Dockweiler State Beach were eroded severely enough to expose the root of the Marina del Rey south jetty and groin, as well as about 200 feet of storm drain outfall. The beach area upcoast from the Chevron Groin in El Segundo and the adjacent refinery was cut back 100–150 feet at the upcoast end of the sand fill, with less erosion near the groin. Estimates of sand loss within the groin pocket range from 40–50 percent (Los Angeles County Department of Beaches and Harbors). The beach downcoast of the groin was eroded back to the bicycle path and the rip-rap revetment along the ocean side of the path was damaged at numerous locations. The path was closed for several weeks until debris was removed and the path repaired.

There appeared to be no major damage to the numerous storm drains crossing the beach in the reach south of Redondo Beach to Torrance State Beach, although the beach width was substantially diminished. The walking and bike path between Torrance Beach and Malaga Cove was overtopped and littered with debris, and protective rock was displaced along the seaward side of the path. Royal Palms State Beach and White Point County Recreation Area parking lots were covered with debris and long strands of uprooted kelp. Pavement at the downcoast end of the Whites Point parking lot was peeled back and washed away.

Cabrillo County Beach, located downcoast from Point Fermin retreated 100–150 feet and lowered 4–5 feet within the cove area. The ocean view parking lot, located near the end of San Pedro Breakwater, and just upcoast of the rock-rubble groin anchoring Cabrillo Beach, was totally destroyed (Figure 4). The parking lot pavement was scoured away and the entire area was littered with rocks and cobble displaced and carried on shore from the rock-rubble revetment.

Figure 4. Photo showing overwashed and destroyed parking lot at Cabrillo Beach located at the western root of the San Pedro Breakwater.

Figure 5. Abrupt end of Huntington Beach Pier photographed 20 January 1988. The seaward 250 feet of pier and "The End" Cafe were washed away Sunday evening 17 January 1988.

The San Pedro Breakwater was breached at two locations. The major breach was 285 feet long, located halfway between the root and the easterly end adjacent to the ship channel.

Orange County

The beach north of the Seal Beach pier and groin eroded to the parking lot. The 8th Street parking lot was overwashed, covered with debris and had pavement unraveled. The restrooms landward of the parking lot were flooded. Several concrete sheet-piles on the groin were displaced but did not fail. Two pier piles were sheared off and 8–10 cross-members were damaged.

The seasonally constructed artificial dune on the downcoast beach was overtopped and eroded by the high waves, but was not breached. No major flooding occurred between the pier

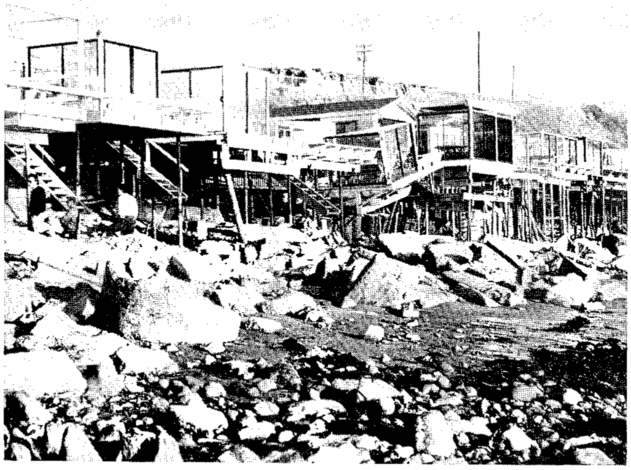

Figure 6. The trailer park at El Morro Beach suffered extensive damage to pipe pilings that support the trailer platforms. The entire cove area was stripped of sand.

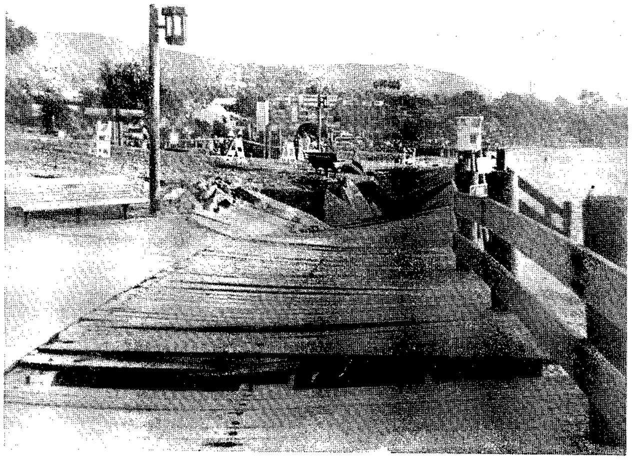

Figure 7. Sections of the main boardwalk at Laguna Beach collapsed after heavy wave surge eroded the sand and undermined piling foundations.

and the West Anaheim Jetty. The Surfside/Sunset Beach area did not have any structural damage to beach front homes, although the outer sand dike, constructed each winter to reduce wave overwash, was breached at numerous locations and was entirely obliterated toward the southern end of Sunset Beach, near Warner Avenue.

Bolsa Chica State Beach was overwashed along its entire length. Restrooms were inundated and floors covered with sand. Pacific Coast Highway from Warner Avenue to the bluff area was closed due to flooding and debris coverage from 17 to 19 January. This particular section of roadway, at the foot of the Huntington Beach bluff area near Golden West Street, has been closed during each recent major storm, due to overwash and flooding. The cost of cleanup in this area was $250,000.

The most severe damage along the Orange County shoreline occurred at Huntington Beach where the outer 250 feet of the municipal pier were lost (Figure 5). This section had been re-constructed after it had been damaged during the 1982-83 winter. The end section of pier was built 6 or 7 feet lower than the original 1430 feet to conform to construction that had taken place in the re-building of 1940. The current replacement cost is estimated at $4.5 million. The pier section, along with "The End" cafe, collapsed and was washed away when waves exceeding 18 feet broke over it on Sunday, 17 January. Additional damage was inflicted the next day.

The beach at Newport between the Santa Ana River and the Newport Pier was overwashed. No residences were flooded, but parking lots were covered with sand and debris and the parking area south of the Safety Headquarters was washed away. The Newport Pier sustained only minor damage, while the Balboa Pier had none.

El Morro State Beach mobile home park, located in the cove upcoast of Abalone Point, sustained serious damage during the storm (Figure 6). Numerous units mounted on pipe piling platforms were washed off their mountings. Several of the beachfront decks attached to the mobile homes were uplifted by breaking waves, while the entire cove was stripped of sand.

In downtown Laguna Beach, about 100 feet of the Main Beach boardwalk collapsed after high wave runup scoured the beach below the ends of the supporting piles (Figure 7). Aliso County Beach was eroded back to the parking lot sidewalks and base of the bluff. The concrete walkway and boardwalk were undermined and damaged. The Aliso Fishing Pier, damaged in the 1982-83 storms, received additional damage and was closed during the storm. Wave overwash and debris covered the entire parking area to the Pacific Coast Highway. Scouring occurred at all of the small and medium sized pocket beaches along this stretch of the Laguna coastline to Mussel Cove. Damage to the pier and boardwalk was about $150,000.

In South Laguna Beach twenty-four beachfront homes were damaged by debris and cobbles carried by the high waves. The majority of the damage consisted of broken windows, flooding and exterior structural damage. Several ocean view homes on Lagunita Drive came close to falling from their bluff-top perches as the high wind driven waves breached the protective seawall along the base of the bluff and began eroding it away. The covered glassed-in patio of one home was ripped away from the main structure and fell halfway down the face of the bluff. More than 20 units in the adjacent Blue Lagoon condominiums were flooded by the ocean waves. Damage to homes and condominiums in this area was around $1 million.

The Dana Point Harbor jetty was overtopped by huge waves, but all transmitted energy was dissipated in the main entrance channel. No damage was reported to the jetty. In the southern basin several boats were reported damaged from storm surge.

Capistrano Bay County Beach parking lot and restroom area were flooded during the storm. Sand and debris covered the area shoreward of the entrance to the Capistrano Bay Colony. The beach was lowered several feet along the oceanside. The curbing of the parking lot was undermined, although no structural damage to county park facilities was observed. The Capistrano Shores mobile home park took waves over the timber seawall, flooding several homes.

San Clemente City Beach retreated of 75-100 feet at the upcoast end of the beach along Estagion Avenue. The storm berm was only a few feet seaward of the restrooms and concession building (which were destroyed during the 1982-83 storms). Debris and sand were carried beyond the Santa Fe Railroad tracks and partially covered the adjacent parking lot. The beach was eroded to within 50 feet of the tracks. During the peak of the storm waves broke at the end of the San Clemente City Pier, flooding Fisherman's Gallery. The railroad pedestrian underpass at the pier was filled with sand and debris and closed for several days.San Clemente State Beach was overwashed and eroded to the railroad, where sand and debris littered the tracks and street shoreward to the base of the cliffs.

San Diego County

Structural damage was reported in the county in both beachfront and inland areas. The San Diego Port Authority sustained almost $2 million in damage, split evenly between public and private property. Waterfront homes and businesses had windows shattered in Oceanside and there was flooding in seaside communities south to Imperial Beach. In La Jolla Cove the beaches were void of sand, eroded down to the underlying cobble beach.

In Oceanside, the North Pacific Drive ford over the San Luis Rey River was overwashed and closed through the five day storm period. Numerous shorefront homes, condominiums and motel properties were flooded and damaged by overwash and flying cobbles. Along the central Oceanside shoreline at least three people were injured by flying glass when waves burst through the windows of their homes. The newly reconstructed Oceanside Pier took breaking waves exceeding 20 feet over its' end but was not damaged.

In Carlsbad, the newly renourished beach sand (dredged from Agua Hedionda Lagoon and placed seaward of the Carlsbad Avenue seawall) was carried away during the first high waves on 17 January. The pavement on Carlsbad Avenue at the Agua Hedionda spit was partially stripped off by the wave overwash, and was closed from 17 to 19 January waiting for debris to be removed. The parking area pavement seaward of the main roadway was completely destroyed.

Highway 101 over the Batiquitas Lagoon spit was overtopped, flooded and closed during the storm. The narrow sandy beach along the base of the high cliffs in Leucadia and Encinitas was stripped of sand. Moonlight State Beach in Encinitas was also stripped of sand and the restrooms and concession stand were flooded and closed during the storm period. The beach access stairs at Swami's Park were damaged by waves which carried away the lower landing.

In Cardiff, wave overwash and flooding closed the Pacific Coast Highway across San Elijo Lagoon spit. The Charthouse, Charlies Grill and the Triton restaurants were flooded (Figure 8). The Fish House West, Pastels and Krake Grill and other restaurants and shops were closed for several days after the storm due to flood damage and subsequent cleanup. The beach fronting the highway was eroded 5-6 feet vertically, uncovering cobbles, concrete and timber piles and other remnants from earlier structures (Figure 9).

At the north end of Solana Beach a house, located on Circle Drive, clings to the edge of a retreating cliff just above Cardiff State Beach. This home has been endangered for

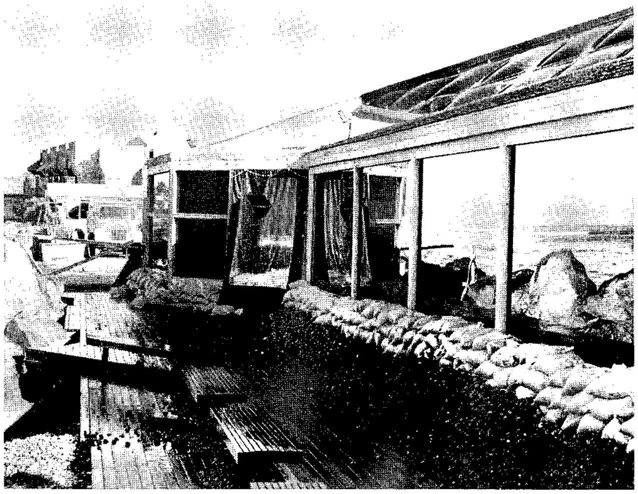

Figure 8. Wave overwash flooded the Chart House and other restaurants in Cardiff and along the shoreline in North San Diego County. Note cobbles thrown shoreward against the building.

Figure 9. North San Diego County shoreline at Cardiff showing bared cobble and bedrock beach stripped of sand. Old pilings and foundations of previous structures are rarely exposed.

several years but the storm of January 1988 increased the probability that the property will be undermined soon.

The high cliff fronting Del Mar Beach and Tennis Club at 825 Sierra Avenue in Solana Beach has continued to erode to within 10 feet of some units.

Along the Del Mar shoreline numerous beach front homes and the Poseidon restaurant were flooded. Jakes Restaurant and the Del Mar Motel survived without severe damage, but numerous businesses were closed during the storm, largely because of extensive flooding along the Coast Highway.

The beach at La Jolla Shores was littered with debris and clumps of kelp that washed up and over the wall along the seaside walk. The beach narrowed along the entire reach from the Scripps Pier to the La Jolla Beach and Tennis Club. The small pocket beaches along Point La Jolla were stripped of sand and received huge deposits of kelp uprooted from the beds immediately offshore. Continued cliff erosion and minor slides, caused by the high waves and rainfall, endangered homes in the Bird Rock area.

The entire Pacific Beach and Mission Beach oceanfront was littered with thick mats of kelp and debris, that required weeks of cleanup effort. Along the reach from Crystal Pier to Mission Bay channel entrance, wave surge and ocean spray, propelled by high sustained winds, overtopped Ocean Front Walk, flooding adjacent homes. The wind shattered large plate glass windows in homes facing the beach. Debris, sand and kelp were carried along the numerous streets and alleys inland to Mission Boulevard.

Off Mission Bay, extremely large waves sheared off the Mission Bay Tower, a local offshore landmark, that was used many years for naval oceanographic research. At the inside of the entrance channel, breaking waves dislodged smaller rocks along the jetty and partially destroyed the revetment on the curved channel section. The waves overtopped the rock revetment, flooding the parking lot and restrooms about 200 feet inland. Reflected waves battered the revetment near Mission Point, overtopping the parking lot and park area, and fracturing piles on the timber baffle across the Quivera Basin entrance. Surge beached some boats in Mariners Basin and damaged moored smallcraft from Ventura Point to Santa Clara Point.

Debris deposition and beach face erosion was noted within Ventura Basin, Santa Barbara Cove and on the Bahia Point spit into San Juan Cove. Debris and kelp were strewn along the entire northern portion of Sail Bay. Debris and some dislodged rocks were noted along the western portion of Vacation Island. Additional damage was inflicted to piers, pile guides, boarding floats and moorings along the shore, including Dana Basin, from Sunset Point, up Mission Channel, to Stony Point and the Vacation Island bridge.

Storm damages at Ocean Beach were similar to those in Pacific and Mission Beach. The seawall fronting the parking lot upcoast of the Ocean Beach Pier, off Newport Avenue, and along Abbot Street was overtopped by breaking waves flooding the streets and depositing debris and kelp.

At Coronado, the south facing stretch of beach from Zuniga Point to the Hotel Del Coronado was overwashed and minor flooding occurred inland to the bathhouses and restrooms. Wave overtopping and minor flooding occurred along the seawall walkway at the Coronado Towers complex. At Silver Strand State Beach, the parking lot and restrooms were flooded and covered with sand and debris, as were large portions of Silver Strand Boulevard.

The entire shoreline of the City of Imperial Beach was inundated by high waves. Waves overtopped the beachfront boardwalk and parking lot at the foot of the Imperial Beach fishing pier. Wave overwash flooded the Surfside Motel and parts of Ocean Lane. The central city beach receded back to the rock reveted, timber seawall. Wave damage and flooding occurred at numerous apartments and homes.

In San Diego Bay, historic ships moored at the Maritime Museum along the Embarcadero were battered by high winds and storm surge during Sunday night, 17 January, as winds reached 65 mph with gusts greater than 80 mph. Many private boats anchored in the live-aboard area from Laurel Street along the Embarcadero near Lindbergh Field were torn from their mooring's and battered against rock-rip bank protection at the promenade. Other boats sank at their anchorages along the shoreline off Harbor Island and Shelter Island.

ACKNOWLEDGMENTS

The authors are grateful to the Department of Boating and Waterways, and in particular to Assistant Director Bill S. Satow, for supporting ongoing activity to document and reduce shoreline erosion in California. We thank the anonymous reviewer who made substantial editorial improvements in the manuscript.

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The Storm of 1988 — Damage to Coastal Structures

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INTRODUCTION

ON 16–18 JANUARY 1988, a severe extratropical storm developed off the California coast coupling high waves, winds and water levels to cause losses in excess of $28 million dollars to coastal structures in southern California. Particularly hard hit was the Redondo-King Harbor area which sustained considerable damages to the breakwater structures and harbor facilities. The storm event was unusual in its rapidity of development, southerly track, localized intensity and ability to defy early detection by meteorologists. The reader is referred to the accompanying papers in this issue for detailed discussions of the meteorology, sea level and wave processes related to this storm event.

STORM WAVES HIT REDONDO BEACH–KING HARBOR

Deepwater storm waves approaching the Redondo–King Harbor area can undergo significant modifications in height as a direct result of interaction with the complex local bathymetry associated with the Redondo Submarine Canyon (Figure 1). Using a linear wave propagation model, RCPWAVE, to predict the wave refraction/shoaling coefficients for this area, Figures 2 and 3 show the sensitivity of these coefficients to various deepwater wave directions, periods and location along the breakwater structure. These data indicate that deepwater waves from a westerly direction (270 degrees) with wave periods of 14-16 seconds are substantially amplified and focused onto the 32+00 to 44+00 portion of the North Breakwater. This correlates well with both visual estimates of large waves overtopping and damaging the structures at the harbor (Figure 4) and statistical descriptions of the predominant wave direction and peak period for this storm event (see accompanying papers in this issue).

DAMAGES TO HARBOR STRUCTURES AT REDONDO BEACH

At Redondo Beach–King Harbor, City officials reported wave heights in excess of 20 feet beginning to overtop the fourteen foot high section of the North Breakwater (stations 36+00 to 52+00) between 6:00 and 7:00 pm on Sunday, 17 January. By 10:00 pm wave energy within the harbor was severe enough to destroy the front of the Portofino Hotel located on Mole C. Fifty-four patrons of the hotel had to be evacuated by helicopter as waves caused a barge to impact the bottom floors of the hotel. Figure 5 shows that the entire south end of the building eventually collapsed as high waves overrode the elevated water levels (over +7 feet MLLW). Wave overwash also damaged vehicles in parking areas, washed a pick-up truck into a berthing area, damaged many of the moored vessels and sunk six small craft within the harbor (primarily in Basin 2). Other structures severely damaged or destroyed include the yacht club, Ruben's Restaurant, the Blue Moon Saloon (see Figure 6) and many of the small shops and restaurants located on the Horseshoe Pier. Major structural damages to the pier consisted of broken windows, collapsed decking and broken pilings. A diner at Reuben's restaurant related to the press that Sunday night everyone was cheering as the waves got higher but panic set in when waves crashed through the windows and people were thrown to the floor.

By 5:00 am Monday morning, 18 January, the City Manager for Redondo Beach declared a State of Emergency. Several city officials and a member of the Corps of Engineers were swept by waves into the Harbor during an emergency inspection of damages on Mole B, attesting to the dangerous conditions, still in effect. With the collapse of the revetment around Mole C, waves threatened to breach into Basin 2. This was averted only through the emergency placement of 3000 tons of stone by the U.S.Army Corps of Engineers.

Assessment of damages to the North Breakwater on 18 January showed two breached areas approximately 50 and 70 feet in length and slumping of 760 feet of 10 to 20 ton armor stone between breakwater stations 14+00 and 23+00. Major losses to armor protection also occurred along most of the North Breakwater between stations 32+00 and 48+00 (see Figures 7 and 8). Repairs required over 52,000 tons of stone at a cost of approximately $2 million.

DAMAGES TO OTHER FEDERAL STRUCTURES

Major damages to other Federal structures attributable to this storm event included: a 285-foot breach in the San Pedro Breakwater of the Los Angeles - Long Beach Harbor complex and a loss of breakwater cap stone at many other locations (Figures 9 and 10); loss of armor materials at the head and trunk of the west jetty at Anaheim Bay Harbor; and

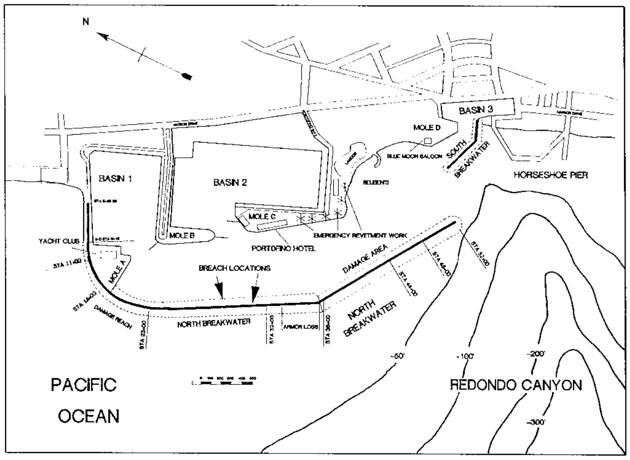

Figure 1. Redondo Beach (King Harbor) - Damage Area.

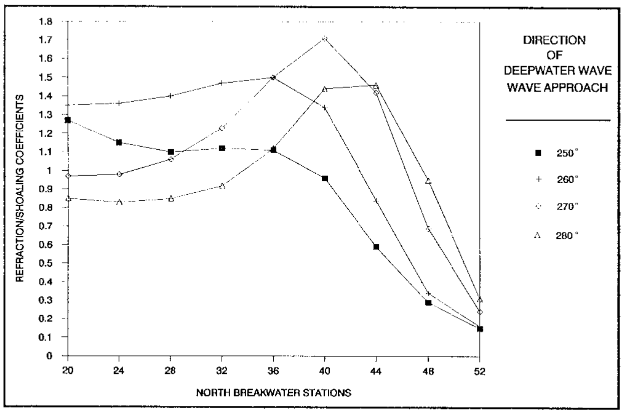

Figure 2. Refraction/shoaling coefficients for four principle wave directions (Wave Period = 14 seconds).

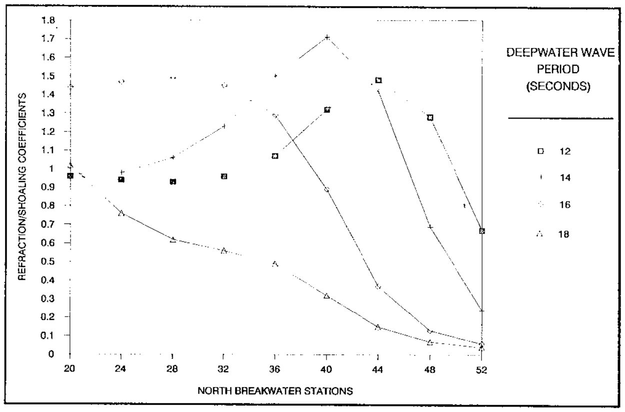

Figure 3. Refraction/shoaling coefficeints for four deepwater wave periods (principle direction = 270 degrees).

loss of armor stone at the head of the north jetty at Mission Bay in San Diego along with a 220-foot breach of a revetment inside Mission Bay (Figures 11 and 12). Minor loss of breakwater armor stone was also observed at Ventura Harbor but did not warrant emergency repairs.

Repair costs at the San Pedro Breakwater and the Mission Bay Jetty exceeded $1 million and $435,000 dollars respectively. Jetty repairs at Anaheim Bay are now underway with an estimated construction cost of $340,000 dollars.

STORM EFFECTS ON BEACHES

The shoreline from Santa Barbara to San Diego also responded rapidly to the increase in wave energy and storm surge. Losses in beach widths from 75 to 150 feet were observed during the two day duration of this storm. Figure 13 shows beach width measurements made by the U.S. Army Corps of Engineers, Los Angeles District at several beaches in Orange County where shoreline recessions averaged 30 to 150 feet. Equally interesting was the rapidity of beach recovery. Data collected on 8 February 1988 show that for most locations, recovery to pre-storm beach widths occurred within three weeks of the event. It is probable that due to the short duration of the storm, sand material removed from the beach remained close to shore allowing for rapid post-storm beach reconstruction.

CONCLUSIONS

Severe storm waves of 16-18 January, coupled with high winds and sea levels in excess of predicted values, caused flooding and damages to breakwaters and other coastal structures along the entire southern California coastline. Damages at Redondo Beach-King Harbor alone exceeded $16 million dollars.

Other structures and beaches in southern California also responded to the increased wave energy. However, catastrophic damages and sand losses did not occur because of the short duration of this extreme event and non-coincidence of maximum wave heights with high tides predicted for this time period.

As shown through numerical modeling of wave propagation, to minimize the types of damages experienced at Redondo, coastal engineers must pay close attention to the entire directional wave energy spectrum as it affects their structural design, especially in areas of complex bathymetry. To date, data of this type have been minimally available and of questionable resolution to be applicable in solving coastal engineering problems.

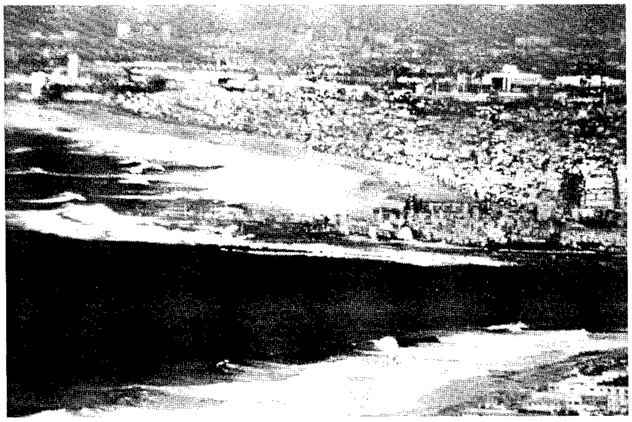

Figure 4. Waves overtopping the North breakwater at Redondo-King Harbor. Aerial Photo.

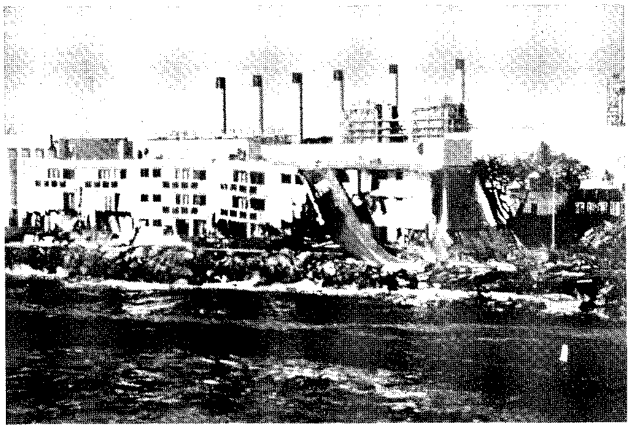

Figure 5. Damage to the Portofino Inn at Redondo-King Harbor.

Figure 6. Loss of the Blue Moon Saloon.

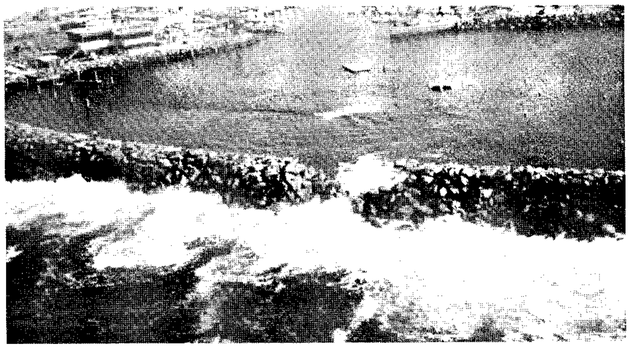

Figure 7. Breach in the north breakwater, Redondo-King Harbor.

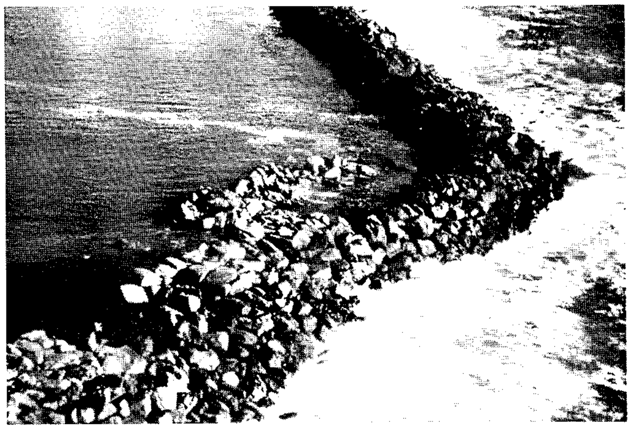

Figure 8. Armor stone stripped from structure at Redondo-King Harbor.

Figure 9. Damage of San Pedro breakwater.

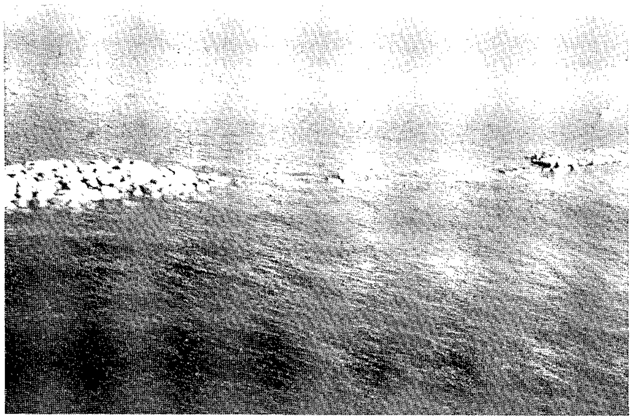

Figure 10. Breach in San Pedro Breakwater, Los Angeles - Long Beach Harbor.

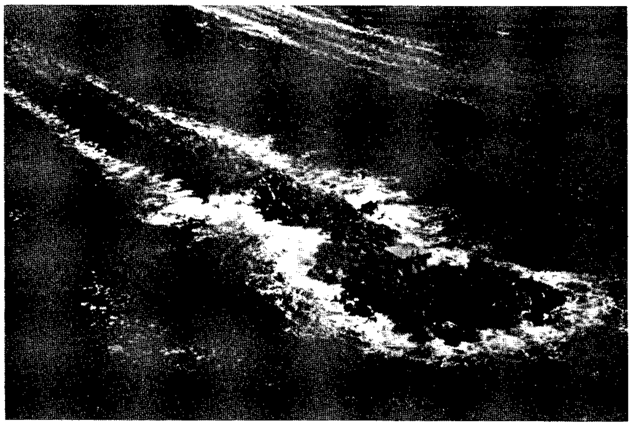

Figure 11. Damage to the head of the north jetty at Mission Bay, San Diego.

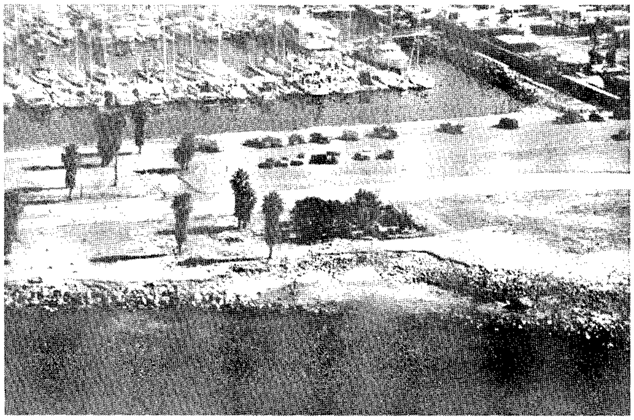

Figure 12. Loss of revetment at Mission Bay.

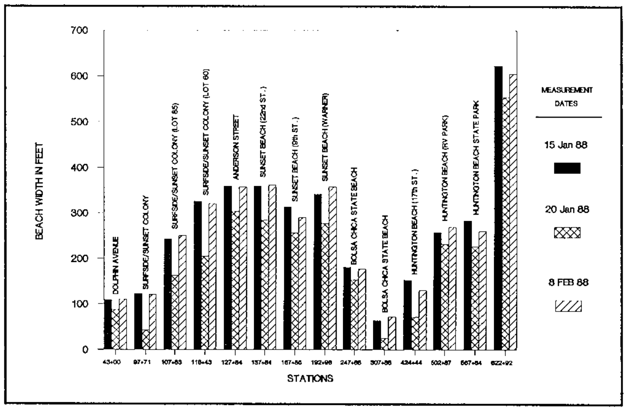

Figure 13. Beach width measurements.

Coastal Sea Levels During the January 1988 Storm off the Californias

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INTRODUCTION

COASTAL SEA LEVELS play a key role in determining the magnitude and extent of coastal damage during storms. On open coasts such as those of the Californias, ocean waves provide the destructive power as well as much of the set-up that erodes beaches and overtops and floods coastal structures. However, the elevation of mean sea level, the tide and storm surge largely determine the degree of damage that waves can inflict on the shoreline. This was dramatically demonstrated during the highly destructive El Niño winter of 1982-83 when over $100 million of coastal damage occurred.[5]

On 16 to 18 January 1988, a remarkable winter storm approached and collided with the coasts of California and Baja California (Figure 1). Cayan et al.[1], as well as the other papers in the present volume, discuss the meteorology of this event as well as the pattern of damage on the California coast. We will show that were it not for some fortuitous conditions, the damage could have been much worse. The purpose of this paper is to examine the details of the coastal sea level related to this storm, and to describe how the different contributing factors varied along the coast and in time. Hourly data from 7 coastal tide gauges from San Francisco to San Quentin (Figure 1) have been analyzed for this study. We conclude from this and other work that we should be able to enhance the possibility of short-term warnings of coastal damage, using readily available information.

LARGE-SCALE CONDITIONS

Large-scale conditions in and over the Pacific Ocean are highly relevant to sea level along the west coast of North and South America. In southern California the annual sea level cycle is dominated by ocean surface temperature, with a small effect due to mean atmospheric pressure.[8] At La Jolla, this steric cycle is about 15 cm in amplitude, and is lowest in April (coldest water) and highest is September (warmest water). Steric heights in summer and winter are close to long-term mean sea level.[4]

High sea levels are a common manifestation of El Niño-Southern Oscillation episodes.[2,4] These long-term events are related to the relaxation of the westward blowing trade winds, as well as to a decrease in atmospheric pressure over the eastern tropical Pacific, as compared with the western Pacific. El Niño conditions tend to recur every four to seven years, with four or five strong events per century. These large-scale conditions, including the shifts in mean sea levels, were in a state of transition during January 1988. A moderate El Niño, present during 1986 and 1987, was breaking down and atmospheric pressure and wind pattern anomalies were reversing. The commonly cited *Southern Oscillation Index*, whose negative values are indicators of El Niño conditions, is formed with the normalized differences of sea level pressure anomalies at Tahiti and at Darwin, which are shown in Figure 2. The months of December 1986, 1987, and 1988 are indicated on the figure as A, B, and C. The index shows the El Niño of 1986-87 was forming at A, weakening at B, and reversing at C.

Large-scale sea level maps of the Pacific Ocean corresponding to those times display the effects of the El Niño cycle on sea level distribution (Figure 3). During an El Niño, sea level is high to the east and low toward the west, with typical sea level differences about 30 cm across the Pacific. During an anti-El Niño episode (Figure 3C), the exact reverse is true; positive anomalies are found in the extreme western Pacific, and negative anomalies are closer to the west coast of North America, as a result of the reversal of the atmospheric pressure deviations and of the strengthening of the trade winds. This translates into differences for the California coast between El Niño episodes and their counterparts, of about 10 to 20 cm in the position of mean sea level.

Figure 3B represents the conditions obtaining in late 1987 and early 1988. Although pockets of negative sea level deviations persisted in the western equatorial Pacific, conditions over most of the ocean were close to average. Specifically, sea levels along the west coast of the Americas were close to long-term mean values, and falling. The monthly average sea level at La Jolla during January 1988 was 83 cm above mean-lower-low water and nearly equal to the 1960-78 tidal epoch mean value.

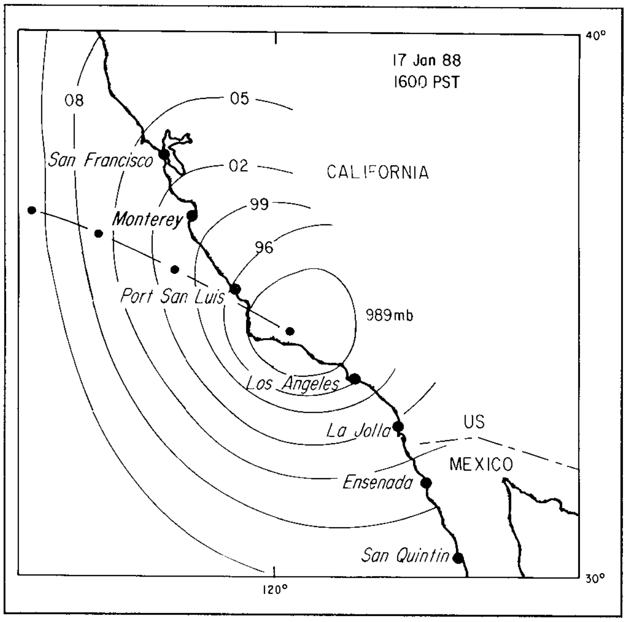

Figure 1. Map of the coast of the Californias showing location of the sea level stations and the storm approach path. Isobars show pressure pattern about the time storm made landfall at Avila Beach near Port San Luis.

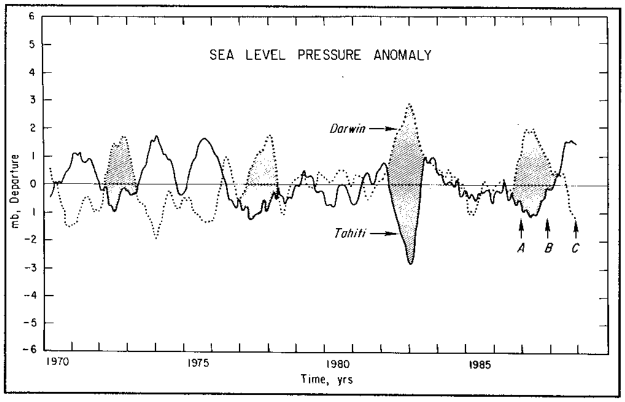

Figure 2. The *Southern Oscillation Index*, shown by five-month running means of sea level pressure anomalies at Darwin (dashed) and at Tahiti (solid). El Niño episodes are shaded (from Climate Diagnostics Bulletin, 1989).[3]

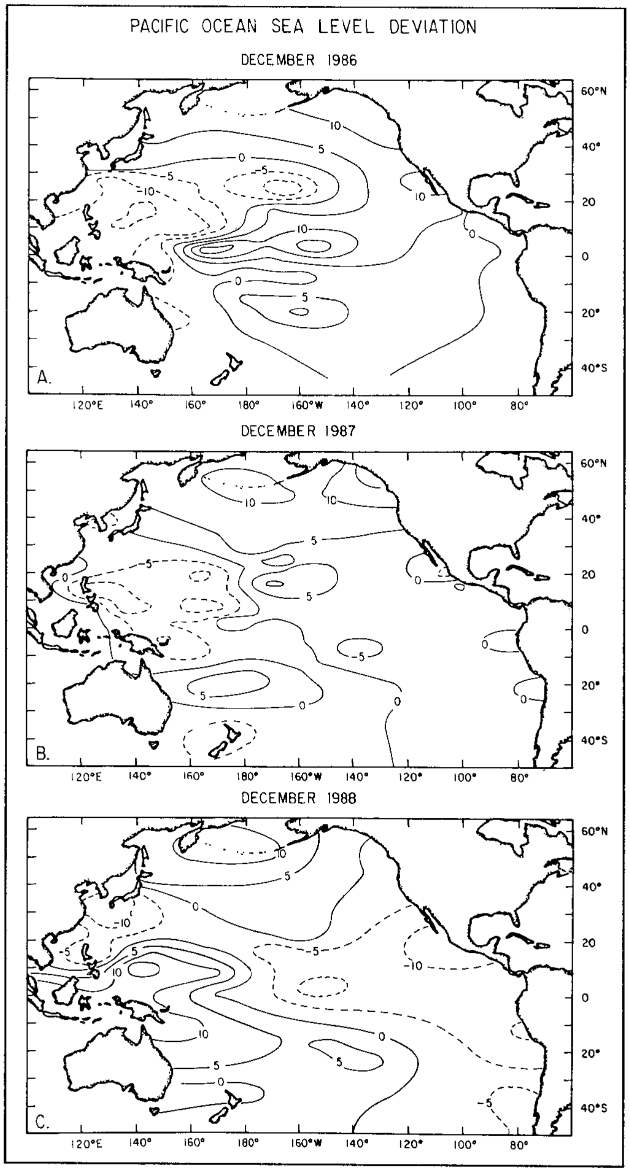

Figure 3. Monthly mean sea level distribution during December 1986 (A), December 1987 (B) and December 1988 (C) corresponding respectively to El Niño conditions, breakdown of the El Niño and reversal. Figures redrawn from Climate Diagnostics Bulletin; data supplied by Dr. Klaus Wyrtki.

THE TIDE

On the California and Baja California coasts, extreme tide ranges approach 3 m and exhibit a number of features relevant to the likelihood of coastal flooding. California's monthly predicted tidal extremes have only recently been tabulated and described.[9,10] The tide dominates sea level fluctuations on the west coast of North America. In this mixed tide region, a lunar day consists of two high and two low tides, each of different magnitudes. The lower-low typically follows the higher-high after about 7 or 8 hours. Partly because of this steep decrease, the tide remains near the maximum level, within 15 cm, for example, for about two hours. The rise from lower-low to the next higher-high requires the remainder of the tidal day, or about 18 hours. This aspect would have significance in limiting damage in southern California on 17 January 1988. During winter, higher-high water always occurs during the morning hours, often very early. In case of storm warnings, this timing can hinder preparations since these must be carried out at night.

Tidal variability during the lunar month is dominated by the spring-neap tidal cycle, with two periods each of relatively high ranges (springs) and low ranges (neaps). Spring tides coincide closely with the new and full moons, while neaps occur with waning and waxing half-moons. One spring tide each month is generally higher than the other, a consequence of monthly changes in lunar distance and declination. The declination cycle also influences the diurnal inequality.

Annual tide peaks occur in winter and summer, with as much as 60 cm higher monthly peaks compared with spring and autumn. The winter extreme is usually slightly higher than the summer due to the earth's closest approach to the sun, which occurs during the northern winter. The modulation itself is due to the declination of the sun, which is maximum in winter and summer and is another characteristic of the mixed-tide regime. The fact that the highest tides usually occur in the winter tends to enhance the effects of storm related sea level extremes. It also obscures the relatively small 15 cm annual cycle of steric mean sea level change, which is conventionally included in the predicted tide.

There is a substantial 4.4 year modulation of extreme tides resulting from progression of the lunar perigee past the equinoxes. This raises high tides roughly 15 cm. The cycle peaked in 1982-83, and contributed to the extreme flooding of that El Niño winter. The cycle also peaked in 1986–87, and will crest again in 1990–91. The winter of 1987–88 occurred near the mid-point of this modulation, with peak tides 6-9 cm below the highest extremes.

SEA LEVEL ON 16 TO 18 JANUARY 1988

The week of 15 to 22 January 1988 was scheduled to include the highest tides at all stations of the Californias, both of that month and of that year, with peaks on either 18 or 19 January.[9] Figure 4 shows the predicted tide (thin line) and the storm surge (thick line) over the 2-week period from 11–24 January at 7 locations from San Francisco to San Quintin (Figure 1). Tide predictions were prepared using standard harmonic constituents and subtracted from the respective sea level measurements to obtain the storm surge residual. The result was screened for errors and filtered[7] to obtain the smooth representation shown in Figure 4. It is clear that the overall timing of the mid-January storm surge event coincided closely with the peak tides. It is important to note that storm surge calculated from tide gauge records do not include the set-up due to breaking waves, since the gauges are frequently in water depths outside the surf zone, or in sheltered locations.

The peak surge amplitudes were large, but not record-setting.[6] The maximum value (plotted relative to long-term mean sea level at each location) occurred at Monterey around midday, 17 January and reached 30 cm. This is consistent with available weather charts that suggest record low barometric pressures around this time.[1] Peak values decrease both to the north and south, with relatively little surge (8 cm) at San Quintin. However, it is the timing and duration of the surge that is of primary interest. Peak tides and peak storm surge coincided only at San Francisco and Port San Luis and nearly coincided at Monterey (Figure 4). This occurred on the morning of 17 January when, for example, the high tide at Port San Luis exceeded the predicted value by 25 cm.

Flood damage on the central California coast from San Francisco south to Port San Luis was limited largely because coastal wave amplitudes were modest.[1] Significant wave heights along this reach were below 4 m until after about noon on 17 January when they began to increase sharply, reaching 9 or 10 m after midnight.[1] By that time, the tide was at the lower-high water stage, only about 30 cm above mean sea level at all stations, and about 90 cm below the higher-high of the morning. In addition, the storm surge dropped rapidly during the afternoon of 17 January. Residual sea levels eventually reached 15-20 cm below normal within a day or two at all stations, largely because of a strong high pressure system behind the storm system.[1]

Wave heights increased earlier from Pt. Conception south, reaching near peak values by early afternoon on 17 January.[1] The tides, however, at stations south of Pt. Conception were dropping sharply (Figure 4) at this time. The storm surge peaked during the evening while tides were either low or rising to the lower-high. By the time of the higher-high tide on the morning of 18 January, the storm surge had subsided to zero, or actually turned negative, while the wave heights were decreasing rapidly.

The major storm damage was concentrated at Redondo Beach where waves broke over the harbor breakwater on Sunday night, 17 January. The structural damage along the southern California coast would undoubtedly have been much more extensive had the storm passed over 12 hours earlier, or (especially) 12 hours later. The maximum storm surge amplitude at Los Angeles of around 25 cm would then have been added to the 120 cm tide.

Figure 4 shows that the timing of the storm surge maximum becomes progressively later to the south because of the storm approach path and coastline orientation. The tide peak, on the other hand becomes progressively later to the north due to the local tide regime. This propagation accounts for the increasing spread in time toward the south between the two peaks. The maximum storm surge at San Quintin was only about 8 cm, but occurred earlier than peaks farther to the north. This may be accounted for if the surge at San Quintin was mostly driven by frontal winds. This idea is consistent with available weather charts[1] which show frontal passage through the area around noon on 17 January.

Besides the timing of the storm, a second reason for the relatively limited extent of coastal damage was the short duration of this event. The average duration (over a 35-year record) for positive storm surge residuals at La Jolla is about 6 days.[6] This surge event only lasted 1 to 3 days, depending on location, and deteriorated rapidly as previously noted.

CONCLUSIONS

Storm surge during 16-18 January 1988 reached 25-30 cm along the coast of the Californias, ranking it in about the upper 10% of all tide residuals.[6] The duration of the storm surge and large ocean waves was relatively short compared with other severe storm episodes of comparable magnitude, notably 1982-83. The coast was spared much more widespread and severe damage largely because of the fortunate relative timing of peak high tides, storm surge, and wave attack, and the existence of average, background, mean sea level conditions.

The storm hit San Francisco about half a day before it hit Ensenada, and as the storm progressed, it should have been possible to provide sufficient warnings along the coast in time to alert the fleets in the various ports. Local weather reports on the west coast do not routinely include average sea level or expected storm surge conditions. The times and heights of high and low tides and the wave period and breaker heights, on the other hand, are often printed and broadcast, especially during storm periods. As Figure 4 illustrates, this may not be adequate, as the continuous tide curve is much more useful in estimating the potential coincidence and severity of a high tide and a storm surge (and large waves).

The essential elements for calculating useful, near real-time, west coast sea level heights and forecasts exist. Large-scale background monthly sea level heights are routinely circulated.[3] Storm surge models exist that use atmospheric pressure and wind predictions (measurements) to produce water level forecasts (hindcasts).[4,7] Real-time access to NOAA tide gauge data is now possible at six west coast stations, incuding La Jolla and San Francisco. Simple tide prediction computer routines are readily available and these could be used to compute surge in real-time. Combining these resources to produce near real-time, total sea level heights and forecasts seems relatively straightforward. Together with existing weather service wave forecasts, dissemination of these products could perhaps significantly reduce the level of damage during future storms along the coast of the Californias.

ACKNOWLEDGMENTS

Sea level data for U.S. stations were supplied by Steve Gill at the National Ocean Service, NOAA. Sea level data for Ensenada and San Quintín were provided by Ing. Francisco Grivel at UNAM, and by Ignacio Gonzalez at CICESE. This research was supported by the California Department of Boating and Waterways (REF) and by the Secretaría de Programación y Presupuesto of Mexico (AB-D). Early support for research on the extreme sea levels off southern California was provided by the California Sea Grant Program (REF) and is gratefully acknowledged. We thank Steve Gill and an annonymous reviewer who kindly provided suggestions for improving the paper.

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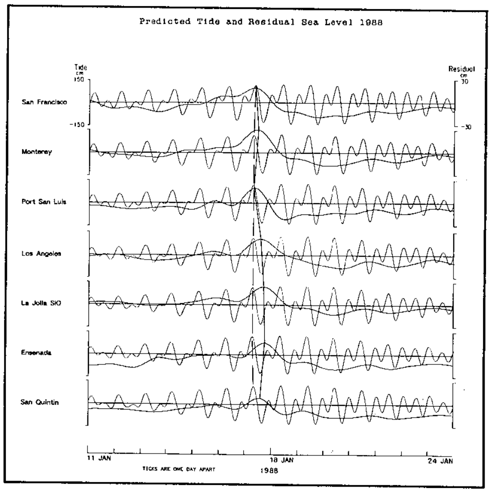

Figure 4. Predicted and residual sea level signals from selected tide stations along the coast of the Californias. Note that tidal phases propagate northward (dashed line), while storm surge peak generally progresses southward (solid line), following storm track.

Modelling the Storm Waves of January 17–18, 1988

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INTRODUCTION

THE STORM OF January 17–18, 1988 produced the largest waves ever measured in the Southern California Bight. The wave event was significant not only in terms of its magnitude, but also with respect to the amount of wave data that was collected both inside and outside the Channel Islands. In this sense, the storm had a silver lining, because it has become a sounding board from which to address questions concerning our ability to forecast and hindcast wave conditions along the southern California coastline.

This storm will undoubtedly become one of the more important wave events to be considered by coastal engineers and planners when estimating extreme wave conditions at sites along the California coast. Modern engineering practices often turn to numerical wave models in order to apply regional offshore wave data to a specific study site. Unfortunately, the Southern California Bight has proven to be a particularly challenging region for wave modelling due to the complex array of islands and shoals offshore.

Wave modelling methods will be used here to examine the effects of both island sheltering and nearshore bathymetry on wave conditions inside the Bight during the storm. The Redondo Beach area was particularly hard hit by large waves and will be the focus of the discussion on modelling waves in the nearshore region.

The purpose of this paper is not to attempt to define rigorously the wave climate during the storm nor to estimate design wave heights at the coast, but rather to describe how one might apply well documented wave modelling techniques to gain insight into what was observed.

WAVE CONDITIONS OUTSIDE THE ISLANDS

A logical starting point for a wave model would be in the deep ocean outside the Channel Islands. Wave data from Harvest Platform and the Begg Rock Buoy (see Seymour, this issue, Figure 1) provided estimates of the wave energy spectra during the storm, but they did not measure directional information. Therefore, wave hindcasts were used to define the directional properties of the deep ocean spectrum. However, the resolution of these hindcasts depends greatly on how well the wind field in the wave generation area can be defined. Wind data offshore from the California coast is generally sparse and this case was no exception.

Obtaining estimates of deep ocean directional wave spectra outside the islands is a major stumbling block when estimating wave conditions along the southern California coastline. The sheltering effects of the islands and shoals result in a very complicated relationship between the deep ocean and nearshore wave conditions. Deployments of much- needed directional wave gauges outside the islands are presently in the planning stages. However, it is unlikely that the limited directional information obtained from these instruments (typically pitch and roll buoys) can be used as the sole source of input to wave models.

A deep ocean frequency-directional spectrum was created by combining wave measurements and hindcasts, provided by Dr. N. Graham (Scripps Institution of Oceanography), in an attempt to make a reasonable directional representation of the largest wave conditions observed during the storm (Figure 1). The peak direction of the spectrum was 280 degrees (270 being directly from the west and 360 from the north), with a peak period of 17 seconds. Note that, due to the close proximity of the generation area to southern California, the directional spectrum was quite broad in comparison to a swell from a distant storm.

TRANSFORMING A WAVE SPECTRUM THROUGH THE ISLANDS

Once a deep ocean frequency directional wave spectrum was chosen, wave spectra were estimated inside the islands. A technique well-suited for such a task, spectral transformations by refraction, was derived by Longuet-Higgens[3] and

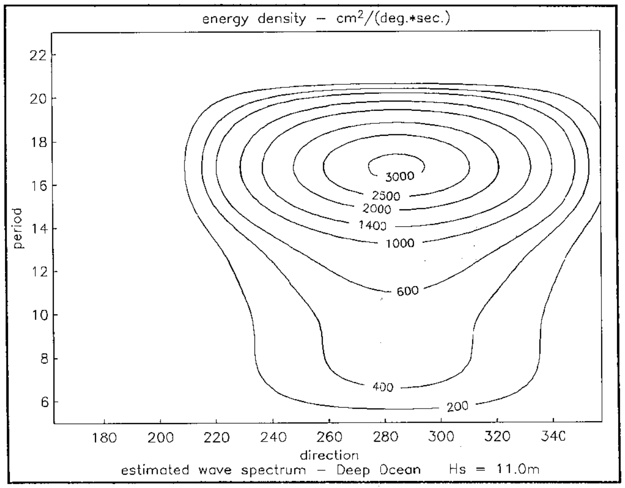


Figure 1.

discussed more recently by LeMehaute and Wang[2].

Spectral transformations begin by back-refracting wave rays from a sheltered site of interest to the deep ocean. Back-refracting consists of using some type of ray tracing method (e.g. Runge-Kutta integration) to calculate ray paths over a grid of bathymetry data. Wave rays are calculated over the range of all possible frequencies and directions. The relationships between the rays' starting directions in sheltered water and their eventual deep ocean directions are used to transform deep ocean spectra to sheltered locations. Island sheltering is incorporated when rays strike an island and do not continue into the deep ocean. The starting angles associated with these rays cannot receive energy from outside the islands.

This method uses only wave refraction theory and is of limited use in areas close to shoals or near island edges, where diffraction effects can be important. However, it is a valid method for transforming spectra into local deep water, which is defined as an area that is several hundred meters deep, offshore from the coast, but still well within the islands. Local deep water is in the far-field of (i.e. many wavelengths away from) any sources of wave diffraction and can only receive a small fraction of the wave energy which has passed through these diffraction regions. Therefore, if a significant portion of the deep ocean energy reaches a local deep water site, then it can be assumed that the wave field at that site is dominated by refracted waves. Through spectral transformations, estimates of wave spectra directly offshore from a study site can be made, thereby simplifying the problem of estimating wave conditions in nearshore areas.

Back-refraction was performed for a number of local deep water sites in southern California where measurements were taken during the storm (NOAA buoy 46025, Mission Bay buoy, Santa Cruz Island buoy; see Seymour, this issue, Figure 1). The deep ocean spectrum shown in Figure 1 was transformed to the location of the Mission Bay buoy (Figure 2). Note that the directional spectrum became bi-modal due to the sheltering effects of the islands. The main peak was at 17 seconds from 260 degrees, and represented waves which passed south of San Clemente Island. The second peak at 290 degrees was associated with the gap north of San Clemente Island and south of San Miguel and Santa Rosa Islands.

Table 1. Estimated and Measured Significant Wave Heights

Location	Significant Wave Height# Estimated	Highest Measured
Deep Ocean	11.0	10.1 ; 8.8 **
Mission Bay Buoy*	7.2	6.6
Santa Cruz Canyon Buoy*	5.5	4.8
NOAA Buoy 46025	7.1	8.0

* no data for the peak of the storm wave heights due to power outage at the Scripps' data collection facility.

** data are for Begg Rock buoy* and Harvest Platform*, both of which are partially sheltered for some deep ocean wave periods and directions.

\# Heights in meters

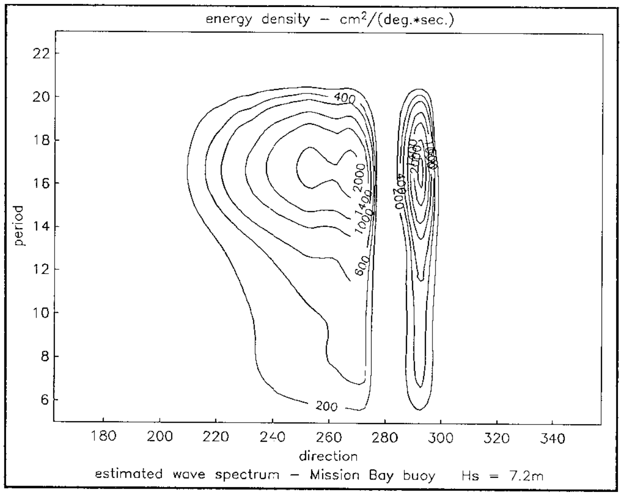


Figure 2.

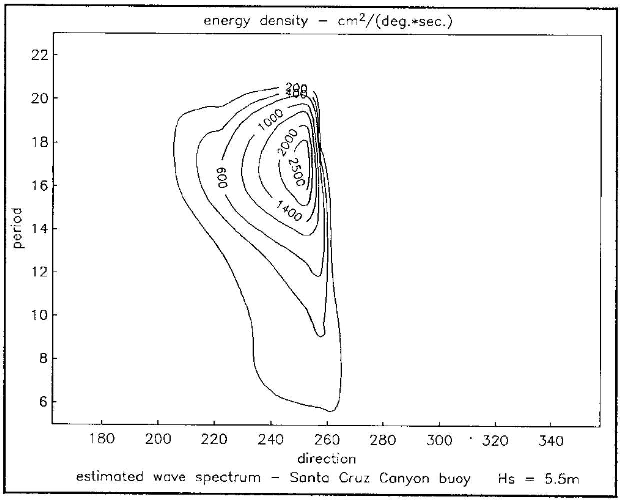
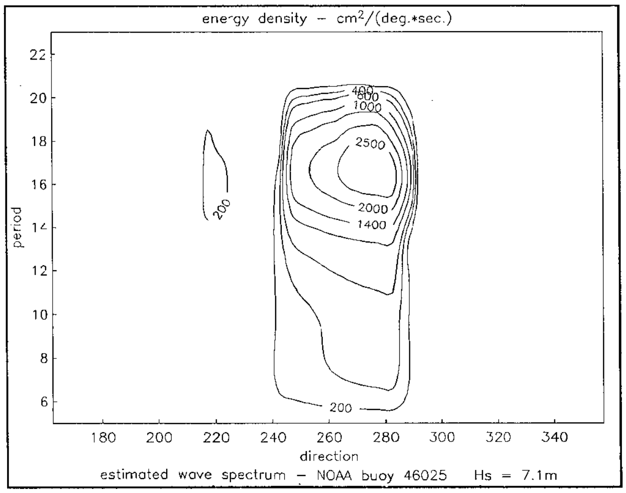
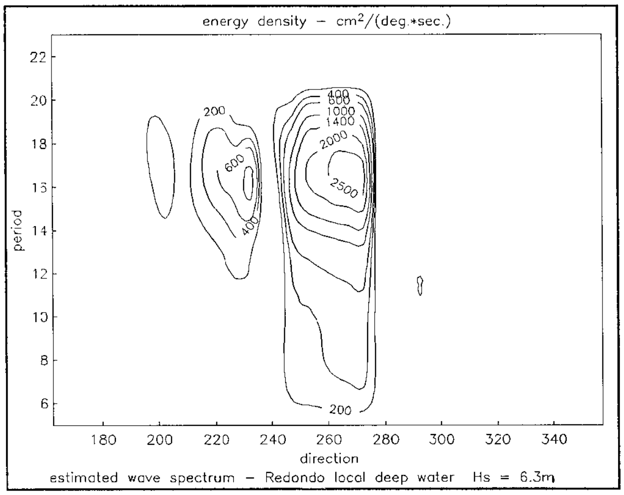


Figure 3.

The deep ocean spectrum was also transformed to the sites of the Santa Cruz Island Buoy and NOAA buoy 46025 northeast of Santa Barbara Island (Figures 3 and 4). In each case the strong sheltering effects of the islands can be seen. The Santa Cruz Island buoy only received wave energy from the west-southwest, and the NOAA buoy from more westerly directions. The significant wave heights for all three estimated spectra were consistent with the largest actual measurements (Table 1.), giving some support to the claim that the idealized deep ocean spectrum was not grossly incorrect. This does not imply, however, that sufficient deep ocean wave information exists to calculate, for example, the alongshore transport of sediment. In order to confidently model the wave conditions in detail, and over the entire time period of the storm, a great deal more directional information would be required.

It is important to mention that no allowance for locally generated winds was made in the model discussed above. The portion of the wave spectrum which would grow under such conditions (periods less than roughly 8 seconds) typi-





cally contained less than 20% of the total energy during the period of peak wave heights. However, there were periods of very high local winds which did make significant contributions to the wave spectra inside the islands. A complete model, especially for the case in which a storm passed directly through the study region, should include local wave generation.

THE WRONG PLACE AT THE WRONG TIME, REDONDO BEACH

The Redondo Beach area, particularly the breakwater at King Harbor, sustained an inordinate amount of damage compared to most of the southern California coastline. Thus, it is of interest to transform the deep ocean wave spectrum to a local deep water site offshore from the Redondo Submarine Canyon, and to use a recent finite-difference refraction method[1] to look for regions of wave energy concentration in the nearshore.

The estimated local deep water spectrum is shown in Figure 5. In this case the spectrum has become tri-modal, with the majority of the wave energy arriving from the west. The peak direction for this portion of the spectrum was roughly 265 degrees with secondary peaks at 230 and 200 degrees. Note the fact that the significant wave height calculated from the spectrum was actually a little smaller than that for the Mission Bay buoy. This implies that the Redondo Beach area was sheltered by the islands to the same degree as other, less damaged, sections of the southern California coastline.

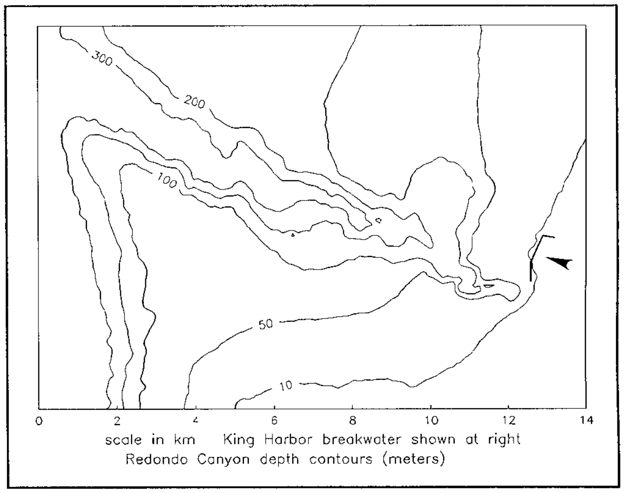


Figure 6.

King Harbor is located at the end of a very deep, long, and narrow underwater canyon (Figure 6). The use of a wave refraction model over such an area may seem somewhat futile at first, and if, in fact, one's goal were to make accurate extreme wave height estimates in shallow water, it wouldn't be of much help. However, refraction, even over complex topography, does lend itself to the task of mapping out regions of wave energy convergence and divergence with a minimum amount of computational effort. Munk and Traylor[4] provided an early demonstration of this for the case of the north and south branches of the La Jolla Submarine Canyon.

A contour map of wave heights from the refraction program, for an incident 15 second deep water wave and a direction of 265 degrees, is shown in Figure 7. Figure 8 is for waves which arrived from 230 degrees, after passing through the gap between Santa Catalina and Santa Barbara islands. Refraction provides a linear relationship between the incident and shallow water wave heights when wave breaking is neglected. In this case, the wave heights shown are relative to the incident deep water height. The energy in the local deep water spectrum associated with the peak at 265 degrees translates to a deep water significant wave height of approximately 5.5 meters. The secondary peak at 230 degrees contained about 20% of the total energy and had a significant wave height of roughly 2.5 meters. A comparison of the two refraction diagrams reveals that wave energy, coming through the islands from the west, was primarily concentrated south of the canyon, with a few isolated zones of extreme wave heights near the breakwater. Interestingly, the waves from the southwest, although presumably smaller than those from the west, showed a strong convergence pattern at the head of the canyon and may have made a significant contribution to the large wave heights at King Harbor.

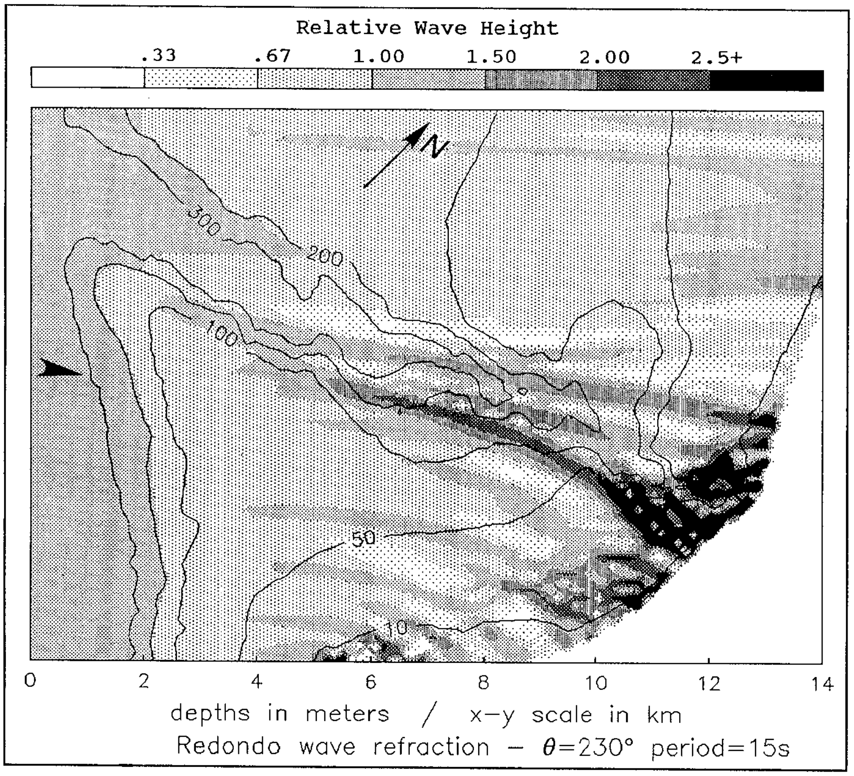


Figure 8.

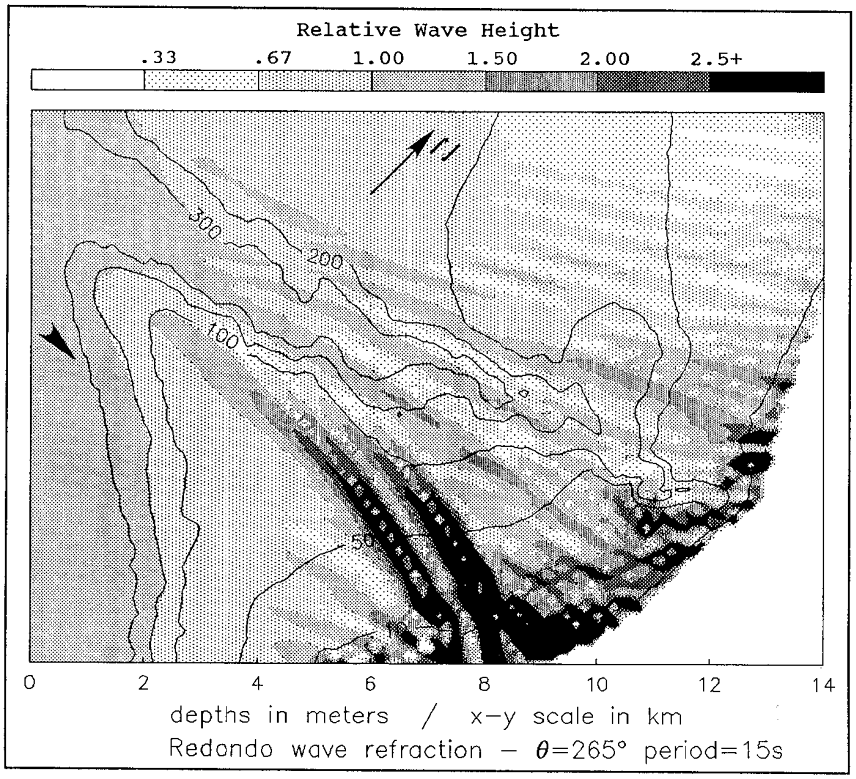


Figure 7.

CONCLUSIONS

A somewhat heuristic look has been taken at modelling the extreme wave conditions of January 17–18, 1988. A significant shortcoming was due to the limited amount of deep ocean directional wave data. The geographic complexity of the Southern California Bight, makes the need for accurate deep ocean directional wave information even more acute than for sections of open coastline.

Spectral transformation by refraction is a useful means for transforming deep ocean spectra into sheltered spectra over large and relatively complex coastal regions. The method is most reliable in local deep water, where the penalty for neglecting diffraction is minimized.

Based on what can be gleaned from hindcasts and wave energy measurements, it appears that the unusually large wave heights at Redondo Beach were due to the concentration of wave energy by the Redondo Canyon, and not due to a lack island sheltering compared to the rest of the Bight. The majority of the local deep water wave energy was estimated to be from the west and zones of high wave heights in the vicinity of the breakwater were calculated for this incident wave direction. Waves from the southwest also converged strongly near the breakwater and potentially played a significant role as well.

ACKNOWLEDGEMENTS

The wave spectrum transformation model for southern California was developed as a part of an ongoing wave data applications study, funded by the California Department of Boating and Waterways. Thanks to R.A. Dalrymple for providing the source code for the refraction program, and R. T. Guza, R.E. Flick, and R. Simon for their helpful comments.

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Morphologic Response of an Inlet-Barrier Beach System to a Major Storm

By Christoper K. Webb, Douglas A. Stow and Kurtis S. Baron

INTRODUCTION

THE COASTAL ZONE in the vicinity of the Tijuana River Estuary is a morphologically dynamic inlet-barrier beach system in a relatively natural state. This coastal system supports delicate dune and wetland ecosystems, the latter depending upon the existence of clean, brackish water conditions maintained by tidal conveyance of water between the estuary and sea[9]. The quality of these ecosystems is a function of the direct passage of tidal flows into the slough arms within the estuary. River flows are very low most of the year, except during winter storms, when very high discharges can occur (as in December 1987 and January 1988). The configuration of the Tijuana River Estuary is significant in that the slough arms extend laterally from the inlet and run parallel to, and behind the backshore of the barrier beach. With such a configuration, the slough arms are susceptible to barrier overwash and sedimentation during extreme wave conditions.

Requirements for continued flushing of the estuary are:

1) protection of the barrier beach from extensive overwash;
2) preservation of the potential tidal prism within the estuary, and
3) maintenance of an open inlet.

Wave, storm runoff and tidal processes can affect the above factors.

The inlet-slough channel system experienced occasional instability following major storms related to the El Niño of 1982-83. Dune overwash and tidal inlet closure and have occurred three times (1983, 1984 and 1986) since those storms[8]. The storm of January 17-18, 1988 was as potentially damaging to the stability of this system as storms that have caused instability in the past.

METHODS

Topographic data and aerial photography of the Tijuana River inlet-barrier beach had been acquired during a Sea Grant study of entrance channels in southern California[2]. Direct visual and photographic observations were made on the morning of January 18, 1988. Most of the energy of the storm had already been expended by that time, but storm waves were still very large at the time of observation.

A baseline survey representing conditions prior to the storm was obtained on December 20, 1987, and post-storm conditions were recorded on January 22, 1988. Topographic elevations were surveyed with two persons using a plane table, aledaide and survey staff. Inlet cross-sectional measurements were made along the same transects (ie. cross-sections) for both dates. Point elevation measurements were also made on the barrier beach and flood delta. All elevations were referenced to Mean Lower Low Water using a survey benchmark.

Aerial photography was acquired from a small plane using a 35 mm camera on December 21, 1987, and after the storm on January 27, 1988. The timing of photographic acquisitions coincided approximately with low tide for each day.

INLET CONSTRICTION

During the early morning of January 18, 1988, wave erosion along the foreshore in the vicinity of the inlet, coupled with flood tidal currents to produce sediment transport directly into the inlet and estuary. Barrier beach washover processes that occurred during the storm are addressed by Fink (this issue). The flow velocities of flood tidal currents diminished as waters entered the lagoon, causing sedimentation around the flood-tidal delta. As compared to the clear channel shown in Figure 1, photographed in December 1987, a sediment plug resulting from this deposition in January 1988 is visible within the slough channel in Figure 2. Point elevation measurements obtained on January 22, 1988 showed that approximately one meter of sediment was deposited in the vicinity of the flood-tidal delta.

Figure 1. Oblique aerial photograph of the Tijuana River inlet at low tide on December 21, 1987. The inlet has a wide, deep channel following high storm runoff and spring tidal conditions. Note the unrestricted slough channels and deltaic deposits on either side of the mouth.

Figure 2. Oblique aerial photograph of the Tijuana River inlet and south barrier beach at low tide on January 27, 1988 after the storm of January 17-18, 1988. The inlet is constricted and slough channel sedimentation is visible. Note the wide, eroded foreshore zone and the absence of a delta at the inlet mouth.

Some of the sedimentation within the inlet channel likely occurred during peak tidal elevation or slack water[6]. Under these conditions wave swash appeared to have eroded the banks of the inlet, depositing sediment within the channel.

The inlet constricted initially due to sedimentation by wave-generated currents and flood tidal flows, and later by reduced tidal scouring. Figures 3 and 4 show the topographic surveys of December 20, 1987 and January 22, 1988. The inlet is much narrower in width and shallower at the thalweg after the storm. Later, further constriction occurred because of the ineffective scouring of ebb tidal flow, which was limited due to the reduced tidal prism resultant from slough channel sedimentation[5]. The depositional sill created by the presence of the sediment plug at the confluence of the sloughs acted as a partial barrier to tidal filling of the estuary, effectively reducing the estuary's potential tidal prism. This reduction of the tidal prism decreased the effectiveness of tidal flows to scour the inlet, allowing further sedimentation by wave-generated currents within the inlet[3].

The fact that the inlet even remained open at all was attributed to the superposition of storm runoff from the Tijuana River. The storm runoff, augmented by the hydraulic head between lagoon and sea during spring tide, resulted in flow velocities that were high enough to scour some of the newly deposited sediment from within the inlet. As the streamflow subsided, it is likely that further sedimentation took place in the inlet from the high waves that persisted several days after the storm. Thus, much of the channel aggradation recorded in the surveys of January 22 and channel constriction observed on the aerial photograph of January 27, probably took place after the storm runoff had subsided.

NEARSHORE PROCESSES

Many of the processes and morphologic changes in the nearshore zone that occured during the storm of January '88 could be inferred from field obervations made on the morning of January 18 and by visually interpreting larger-scale aerial photographs. Processes that could be descriptively inferred included erosion of an existing delta and beach sediment on the foreshore, as well as the alteration of submarine topography, leading to changes in the pattern of wave refraction, wave breaking and sediment transport.

The mouth, as well as the rest of the inlet, constricted as the scouring capacity was reduced by the decreasing tidal prism. The mouth appeared to have deflected further north, becoming oriented with the major source of tidal prism and storm runoff supplied by the main river channel.

On December 21, 1987, synchronized storm and ebb tidal currents flowed through deltaic deposits, with remnant bifurcating channels on either side of the main channel. While there is often a small, bifurcating ebb tide delta seaward of the mouth, this relatively large feature was created by sediment that was transported to the sea during large storm runoff associated with an earlier storm in December of 1987. By January 27, 1988 this delta had been eroded away by waves associated with the January '88 storm.

More subtle features interpreted on the aerial photographs were wave-related patterns that differed greatly between the two dates. On December 21 wave refraction patterns offshore from the mouth were characteristic of those associated with a submerged delta. The wave breakpoint was displaced seaward and wave-current interactions were evident even farther seaward from the breakpoint. The only influence on the inlet by waves was the interaction of run-up with tidal currents that generated standing waves at the mouth.

By January 27 the subaerial delta had been removed and there were no signs of wave refraction that would suggest the existence of a submarine delta. Wave refraction patterns had changed substantially in and around the inlet channel, with higher wave velocities in the deeper parts of the channel.

The changes in the foreshore morphology and wave refraction patterns due to storms such as the one that occured on January 17-18, 1988 may substantially alter the nature of

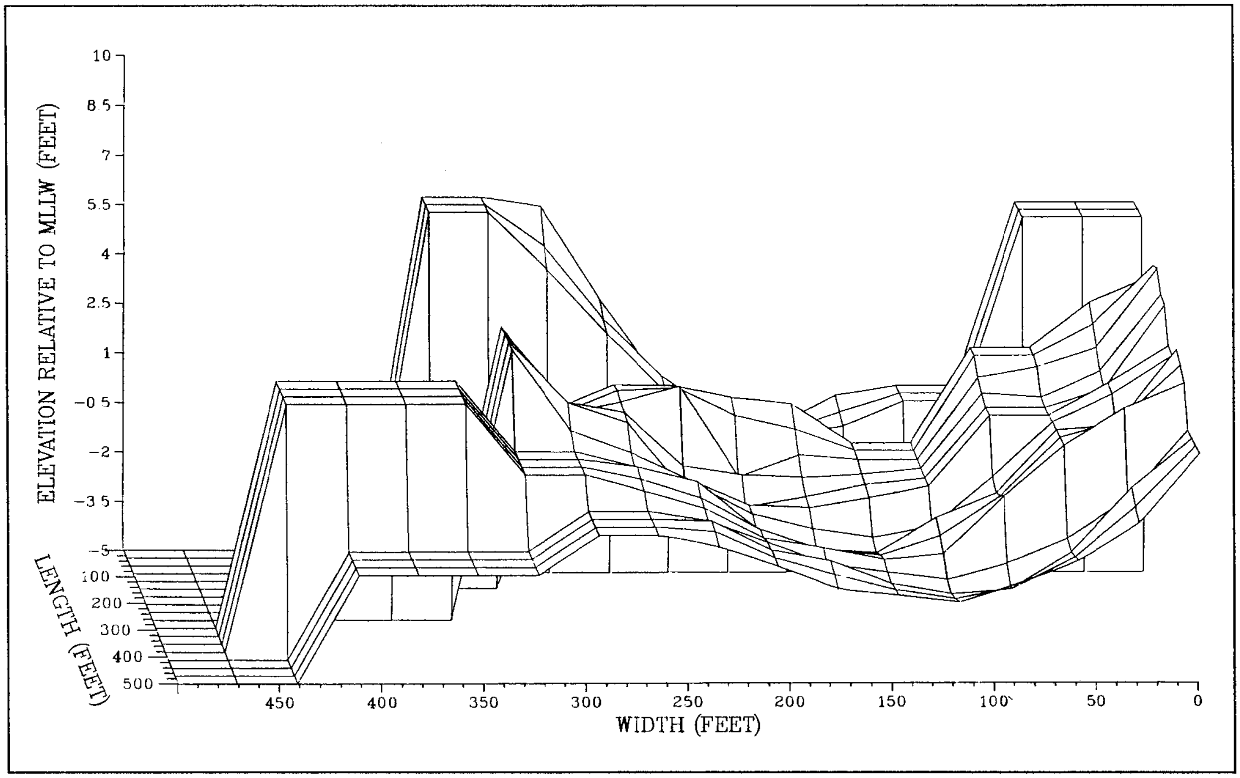

Figure 3. Three-dimensional depiction of the Tijuana River inlet on December 20, 1987, 28 days before the storm. Data are from topographic surveys conducted during low tide. View is looking upstream from the sea toward the lagoon. Inlet cross-sections were surveyed from right to left across the diagram. Areas of no data are to the far left side of the inlet and represent the termination of cross-sectional surveys.

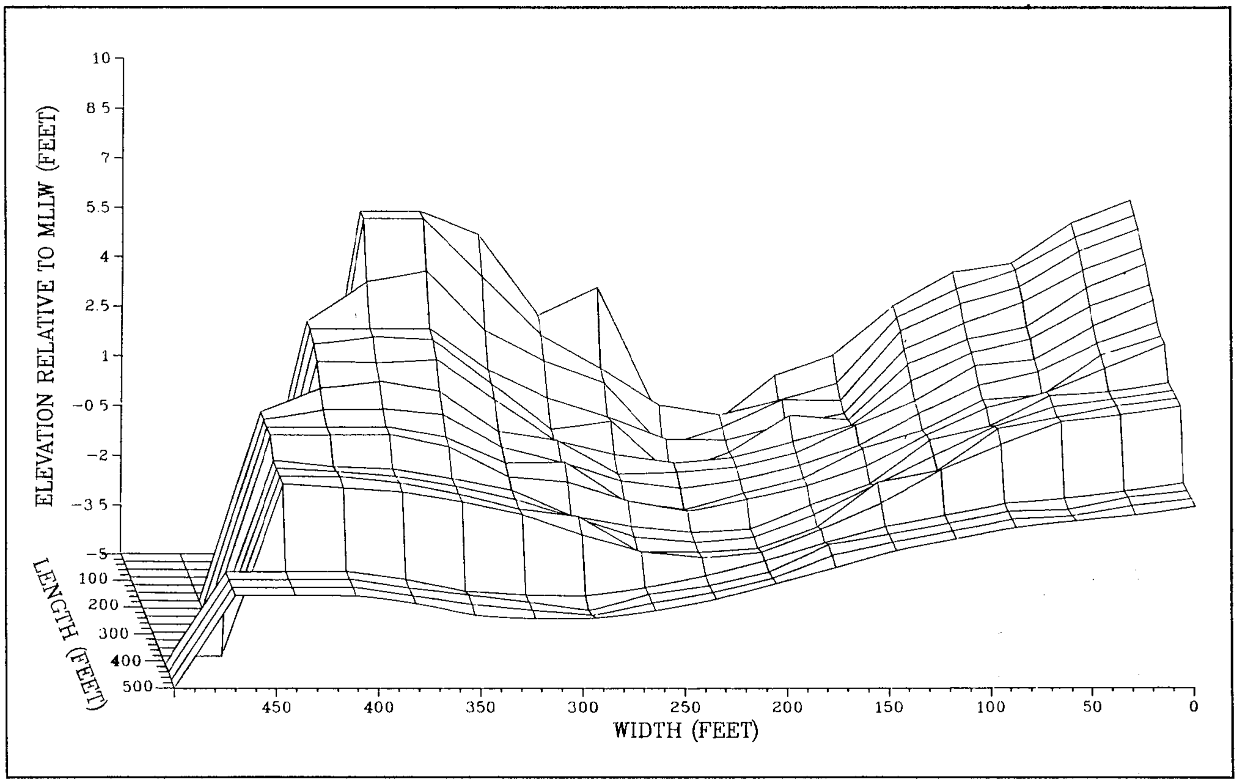

Figure 4. Three-dimensional depiction of the Tijuana River inlet on January 22, 1988, four days after the storm. View is looking

wave-related sediment transport, and subsequently the stability of the inlet. The probability that sediment transported by wave-related processes will reach the inlet increases once the foreshore and surf zone is flattened in the vicinity of the mouth[7]. When waves refract and break further offshore due to the presence of a delta, wave-related transport to the inlet is inhibited[1]. As influenced by refraction, locally divergent longshore drifting will tend to transport sediment away from the mouth[4]. When the wave break point moves further offshore, the probability that sediment will be transported cross-shore into the mouth is reduced. Once the delta is removed, longshore drifting is more likely to become locally unidirectional or convergent at the mouth, the latter case causing sediment to be delivered to the inlet. Following removal of the delta the breaker zone moves closer to shore and waves are more likely to propogate up the deeper waters of the inlet channel.

CONCLUSIONS

The storm that hit the coast of southern California on January 17 and 18, 1988 provided an excellent opportunity for studying the effects of storms on an inlet-barrier beach system. Field observations, topographic surveys and aerial photographic acquisitions made before and after the storm at the Tijuana River Estuary provided much insight into how storm-related processes affect the stability of such a system.

Several conclusions can be drawn concerning the morphological response of the inlet-barrier beach system at the Tijuana River Estuary to the January '88 storm. First, inlet constriction occurred as large storm waves were synchronized with high water levels (associated with spring tide and storm surge conditions), causing sedimentation to occur within the slough arms near the inlet. This lead to sill formation and effectively reduced the potential tidal prism. The inlet narrowed and became shallower, initially due to direct deposition of wave-transported sediment, and later because of limited flushing when the tidal prism was reduced.

Inlet constriction was followed by sedimentation from processes associated with storm waves. These processes acting within the nearshore zone caused erosion of an existing submerged delta, that altered nearshore morphology in a manner that enhanced wave and longshore transport of sediment into the inlet.

Had the largest waves been more closely synchronized with the highest spring tides, much more sedimentation would likely have occurred in the slough arms, seriously decreasing the long term stability of the inlet. The fact that the inlet remained unstable for only a short time was apparently due to the ability of stormflow from the main river channel to scour and maintain a functioning inlet.

The findings from this study illustrate the complexity of processes that interact to influence the stability of coastal inlets, and underscores the need to take a systems approach when trying to manage them. The logistical and practical difficulties in trying to obtain field measurements of process variables for these short-lived and infrequent storms, points to the need to develop numerical models incorporated with available field data to predict their effects on inlets.

ACKNOWLEDGEMENTS

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Effects of Dune Overwash During the January 18, 1988 Storm at the Tijuana Estuary, San Diego, California

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ABSTRACT

AT THE TIJUANA ESTUARY, storm overwash of the coastal dune and adjacent saltmarsh has been common in recent years. This process has caused a gradual decline in the estuary's tidal prism, loss of saltmarsh habitat and local mortality of dune and estuarine organisms. In addition, the coastal dune has been reverted to a less mature state of development characterized by low species diversity and plant cover. Positive aspects of this overwash include a small gain of coastal dune habitat, exclusion of glycophytic weedy plant species, and nourishment of the dune and estuarine habitats through deposition of wrack and seawater ions. The effects of the January 1988 storm, although not as severe as the El Niño storms of 1982-83, had significant impacts on the Tijuana Estuary dune and saltmarsh ecosystems.

TIJUANA RIVER ESTUARY

The Tijuana River Estuary, a 1500 acre system[8], is located immediately north of the United States-Mexican border. Here, extensive saltmarsh is bordered on the west by a coastal dune that extends the entire 3.5 kilometers of the river valley. Two of the largest estuary channels are situated parallel to the coast, immediately inland of the dune (Figure 1). The north arm empties approximately 50% of the estuary[7], while the south channel contributes about 20% to the tidal prism. This juxtaposition of the estuary channels to the mouth and the dune (both highly dynamic during storms), has led to repeated sedimentation of those channels with sand eroded from the dune during wave overwash.

Since these two channels comprise the majority of the tidal prism of the estuary, dredging is necessary after sedimentation to retain the tidal prism, presently one-fifth of its former size[7]. Mouth closure occurs when the tidal prism reaches a critical minimum and scouring decreases at the mouth during ebb flow. When the mouth is closed for a period of months, the system changes dramaticly, and many important biotic components of the saltmarsh start to die out.

EFFECTS OF DUNE OVERWASH

During the storm of January 1988, sand was deposited into the channel south of the estuary mouth, cutting off tidal circulation. All invertebrates and fishes living in this channel were completely displaced by the sand plume that flowed over this site. The saltmarsh vegetation, comprised primarily of pickleweed (*Salicornia virginicus*) was buried. Approximately 80 meters of this channel were completely filled with sand; the remaining 700 meters were at least 40% filled[2]. To restore tidal flow, 1000 cubic yards of sand were dredged from this channel in the fall of 1988[6].

Figure 1. The Tijuana Estuary depicting the Pacific Ocean to the left, coastal dune habitat and saltmarsh with channel arms extending top to bottom. Approximate scale is 1:20,000. Photo by Aerial Photobank, Inc., San Diego, Ca.

Ironically, this sedimentation occurred only where the dune profile was low. Here, several 0.5-m high hummocks sparsely vegetated with beach burr (*Ambrosia chamissonis*) are maintained by the U.S. Fish and Wildlife Service for optimum California Least Tern (*Serna antillarum*) nesting habitat.

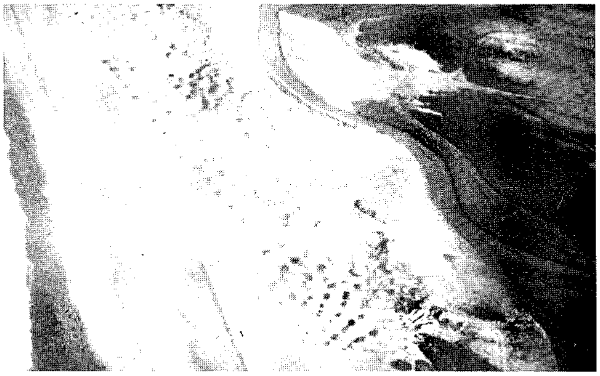

Figure 2. A newly constructed barrier dune after the 1982-83 storm season. From right to left one sees the Pacific Ocean, coastal strand, the sculpted dune, and saltmarsh with the south channel open to tidal circulation. Photo by Stow.

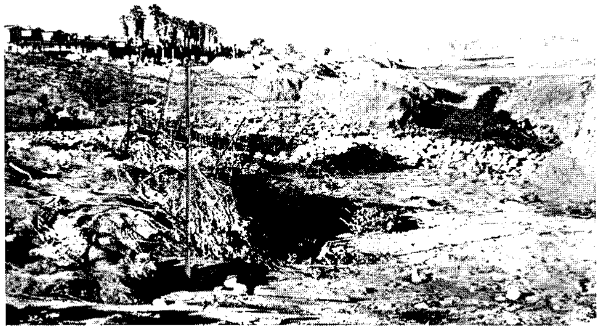

Figure 3. Overwashed dunes after the January 18, 1988 storm. Extensive stems of the sand verbena (Abronia maritima) can be seen draped on the fence enclosure. Photo by Zedler.

Figure 4. During the 1988 storm, overwash sand flowed into a main channel south of the estuary mouth. The Pacific Ocean is in the top of this photo, thus sand flowed from the beach down into the saltmarsh. To the left of this overwash fan are the sculpted dunes and the south channel below this. Photo by Stow.

In other areas where the 2 to 3-m high dune was restored with previously dredged material (Figure 2) , extreme wave generated erosion occurred. Deep gullies were made in the dune and sand plumes flowed inland. The majority of native dune vegetation planted for stabilization of the barrier dune were lost in this storm, some to sand burial, while others exposed to breaking waves were stripped of all aboveground biomass at the substrate surface (Figure 3).

Other species of plants, although not physically removed by storm waves, suffered heavy mortality from the effects of seawater inundation. This maritime stress has the effect of "sterilizing" the dune environment. Inland glycophytic plant seedlings germinate closer to the surfline with each successive year void of storm overwash. These species, gradually creeping toward the shore are eliminated following inundation. Physiological responses of certain native dune species to this stress and to sand erosion/accretion and seaspray deposition have been studied by Fink[1].

In addition to the elimination of glycophytes from the dune, many native perennial dune plant species were extirpated as a result of this storm. Species lost were the beach evening primrose (*Camissonia cheiranthifolia*), goldenbush *(Isocoma venetus)*, and beach lotus (*Lotus nuttalianus*). Mortality likely resulted from problems associated with increased internal solute concentrations (osmoregulation). Other species of perennial plants better adapted to this harsh environment such as the sand verbena (*Abronia maritima*) and the beach burr (*Ambrosia chamissonis*) were temporally set back due to physical removal of much of the aboveground biomass, but resprouted within 8 weeks. The latter two species could be termed "seasonal halophytes" due to the ability to withstand all maritime stresses present in the strandline environment.

Although severe overwash can be devastating to coastal organisms, there are some benefits to the ecosystem associated with overwash. Aside from eliminating exotic glycophytic plant species (weeds), overwash adds minerals elements to the sand substrate. Seawater inundation is a significant input to the mineral budget, which may produce a fertilizer effect[3,4]. Wrack, deposited along the entire dune during the storm, added scarce organic matter to the sand substrate.

The loss of saltmarsh habitat by wave generated sedimentation was offset somewhat by a net gain in coastal strand and dune habitats. Although over 75 percent of the saltmarsh habitat has been destroyed in California[5] and is one of the most productive ecosystems, coastal dunes are even rarer due to their ease of development. In San Diego County they provide habitat for such endangered species as the California least tern (*Sterna antillarum*), the San Diego horned lizard (*Phrynosoma coronatum blainvillei*), and the sand dune tiger beetle *(Cicindela latesiguata latesiguata)*.

SUMMARY

In summary, there were many impacts of the January 18, 1988 storm on the Tijuana Estuary. Sedimentation of one of the main channels caused local extinction of the invertebrates and fish here as well as loss of important saltmarsh habitat (less than 2 acres total for this storm and the 1982-83 storms). With continued sealevel rise, more habitat will be lost during future storm events. The stabilizing dune vegetation experienced high mortality as a result of the storm, although this was a species-specific response based mainly on relative tolerance to seawater inundation. The former topographically heterogeneous coastal dune with numerous microsites was reduced to a sand plain, an earlier successional stage characterized by a few extremely hardy species of plants and animals. In addition, overwash contributed nutrients as wrack and seawater ions as well as eliminating weedy inland glycophytes, which compete for scarce water and minerals.

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Experimental Ocean Platform Survives Extreme Storm Waves

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Port Hueneme, California

INTRODUCTION

THE NAVAL CIVIL ENGINEERING LABORATORY executed an ocean test program to collect environmental and response data for evaluating the performance of small ocean platforms moored in deep water. The test program, with its specially-built, 100-ton, semisubmersible platform deployed off southern California, was operational during the 17–18 January 1988 storm. This storm produced wave heights approaching the survival conditions used in designing this experimental semisubmersible. Environmental and platform response parameters were measured through the peak of the storm. The data shows that the response for an extreme storm event can be much larger than for annual storm events.

EXPERIMENT DESCRIPTION

Small semisubmersible platforms moored in deep water are proposed as ocean facilities for Navy tracking ranges. To design these unique ocean platforms, one needs to calculate the response of these floating platforms to extreme storm conditions. Nonlinear computer models, which couple the dynamics of the hull with that of the mooring legs, were developed for simulating the response of these proposed ocean platforms to various environmental events. The accuracy of these computer models must be validated against real experimental data from an extreme environmental event.

To collect this environmental loading and structural response data, NCEL executed a two year ocean-based Motion Measurement Experiment (MME) using a specially-designed semisubmersible platform. A large-scale, at-sea experiment was desirable to a small-scale, laboratory experiment because hydrodynamic properties cannot be truly represented for extreme seas in a laboratory model basin.

The MME was conducted at a site 25.3 nautical miles south-southeast of Port Hueneme, California at coordinates 33°44.8'N, 119°02.5'W. In addition to the semisubmersible, the MME included a 10-meter discuss wave buoy supplied by the National Data Buoy Center (NDBC) and a vertical current meter array supplied by the Naval Oceanographic Office (NAVOCEANO). Consisting of 15 vector-averaging current meters, the NAVOCEANO array collected 15-minute averages of current velocity versus depth. The NDBC buoy, commonly known as the Santa Monica Basin Buoy #46025, collected hourly scalar and directional wave spectra, wind speed and direction, temperatures, and barometric pressure. Because the directional wave system was being repaired, only non-directional wave spectra is available for 17-Jan-88.

The MME semisubmersible was deployed within four nautical miles of the NDBC buoy and the NAVOCEANO array. The semisubmersible hull consisted of 5-ft. diameter, 33-ft. long columns connected by 4.5-ft. diameter, 50-ft. long pontoons. It displaced 96.4 long-tons at 20 foot draft. The hull was moored in 2,910 feet of water using a three-point spread mooring. Each mooring leg consisted of a chain pendant, polyester line, anchor chain, and an anchor. Design details are given in Ref. 3.

The semisubmersible was instrumented with a motion sensing package, a solid state compass, two wave staffs, a long baseline acoustic positioning system, two electromagnetic current meters, several shackle load cells, and three wind speed sensors as shown in Fig. 1. Sampled at 3.333 Hertz, time-series data from over 40 sensor channels was normally acquired aboard the semisubmersible for five hours every weekday. Data acquisition times were extended when storms were expected.

17–18 JANUARY 1988 STORM

Although a large magnitude storm had not been predicted for 17 January 1988, the data acquisition system had fortunately been set to operate during this particular day. Excellent environmental loading and response data was collected continuously from 0800 17-Jan-88 until failure of the motion package at 0500 18-Jan-88.

Data from the NDBC wave buoy showed a rapid build-up of the storm in the vicinity of the MME as shown in Fig. 2. In Fig. 2, significant wave height is defined as the average height of the highest one-third of all waves. Similarly, peak wave period is defined as the wave period associated with the maximum value of the wave energy spectrum. The significant wave height rose from 10 feet to 26.2 feet in less than 6 hours. Prior to the storm, the wave energy was concentrated in moderately-high, long-period swell. As the storm approached, the wave energy shifted to short-period wind waves. As the storm increased in strength, the wave energy intensified into very-high, long-period storm swells.

The unmanned MME semisubmersible was designed for a maximum significant wave height of 27.1 feet just 0.9 feet larger than produced by the 17-Jan-88 storm. Based upon extreme probability theory of random seas, 44 feet is the largest single wave that could theoretically occur in an area where the significant wave height measured 26.2 feet.

Wave heights relative to the moving semisubmersible are measured by wave staffs attached to the semisubmersible hull. Traditional wave time history traces for a fixed point are produced by adding platform motions to the wave staff time history[1]. Fig. 3 shows a wave time history trace containing one of the largest waves that actually passed through the MME semisubmersible. From peak to trough this wave measured 42 feet, 9 feet more than the height of the semisubmersible hull. Moving in compliance to the waves, the hull sustained only minor damage from wave slamming against the bottom of the deck.

The spectral energy of the waves as measured by the wave staffs are compared against that measured by the NDBC buoy, Fig. 4. A very close comparison is shown, independently confirming the large wave energies measured by the NDBC buoy in this storm.

SEMISUBMERSIBLE PLATFORM RESPONSE

Directionality of the storm can be assessed from the movement of the MME semisubmersible within its watch circle. Fig. 5 shows a trace of the semisubmersible center of gravity in the horizontal plane from 0900 hours 17-Jan-88 to 0500 hours 18-Jan-88. The semisubmersible moved first easterly, then southwesterly, and finally southeasterly just prior to the peak of the storm. This low frequency movement was due to the time-dependent combination of environmental loading on the semisubmersible from wave, wind and currents acting from different directions. The random, higher frequency motions of the semisubmersible are representative of the response of a semisubmersible to the wave forces created by a storm-generated directionally spread sea.

The semisubmersible platform was designed to be compliant but remain stable during extreme waves[2]. This stability is demonstrated in Fig. 3. In large, long period waves, the hull heaves up and down in phase with the wave and thus avoids wave slamming. On the other hand, the hull rolls and pitches 90 degrees out of phase with the wave and thus avoids rolling over. The platform remains rotationally stable even in wave heights approaching the survival limit.

The semisubmersible hull was also designed to minimize motions during everyday wave conditions for normal Navy tracking operations. In smaller, short period waves, the hull remains essentially still while the waves pass through. Unlike conventional semisubmersibles, the smaller MME semisubmersible hull was designed to have natural periods near wave periods. The MME semisubmersible has natural periods of 10.8, 13.0, and 13.0 seconds in heave, pitch, and roll, respectively. Resonant motion amplification is kept to a minimum by hydrodynamic damping.

During the extreme storm of 17-Jan-88, the semisubmersible platform experienced the largest mooring line tensions of the entire experiment, due mostly to large current and wave drift. Dynamic mooring line tensions were only slightly higher for the 17-Jan-88 storm than for previous storms which produced significant wave heights that were less than one-third as high. However, maximum platform yaw was over seven times larger in the 17-Jan-88 storm than previously measured. The dynamics of small semisubmersibles moored in deep water is undoubtedly a nonlinear process.

CONCLUSION

For experimental purposes, we designed the MME semisubmersible to have dynamic natural frequencies of motion near those of the expected peak wave frequency for the MME site. This way we could measure the performance of the semisubmersible to random waves with peak periods above and below peak resonant response. We also sized the MME semisubmersible so that the one-year probable wave heights would create motions that would be near the limit for normal Navy operations.

At-sea tests are always risky in the sense that you may have to wait for a hundred or so years to capture that one extreme event. We were, however, fortunate to capture an event of truly large proportions in only two years of testing. The 17-Jan-88 storm produced a significant wave height that was much larger than expected and a peak wave frequency that was centered about the natural periods of the semisubmersible hull.

Although rare, the winds, waves, and currents generated by this storm represent a loading environment that is orders of magnitude above the annual expected events. Designers of ocean platforms, piers, and other coastal structures must not forget that it is these extreme events, with their associated nonlinear response uncertainty, that will determine the survivability of the structure.

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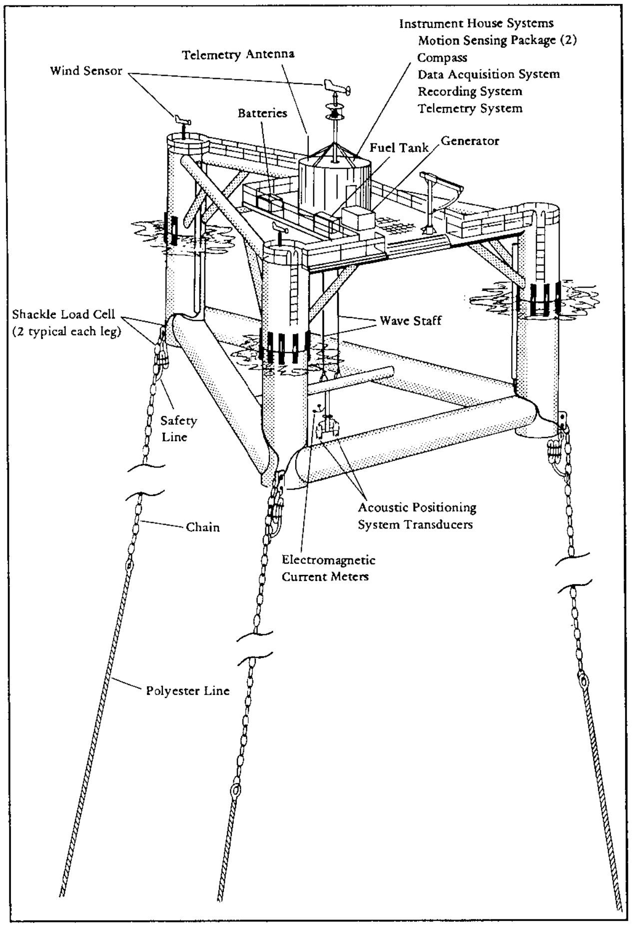

Figure 1. MME semisubmersible showing key environmental and platform motion sensors.

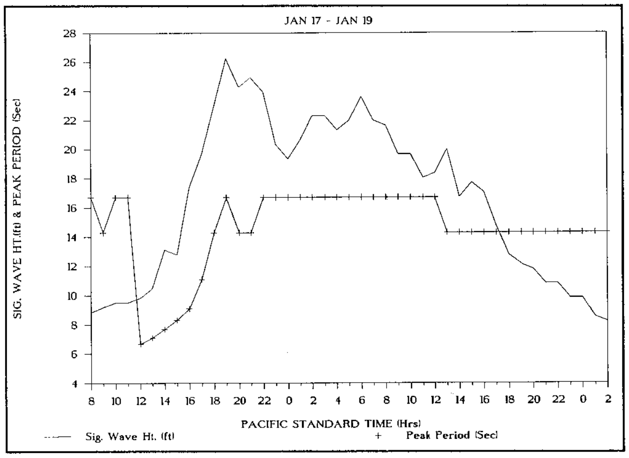

Figure 2. NDBC wave height and period data from Santa Monica Basin Buoy #46025.

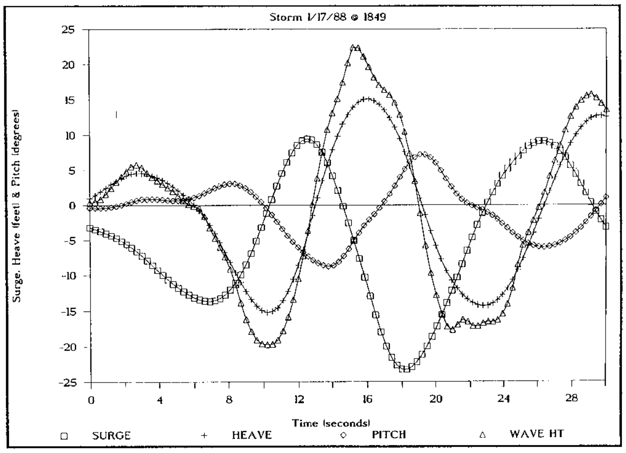

Figure 3. MME semisubmersible motions resulting from largest recorded wave.

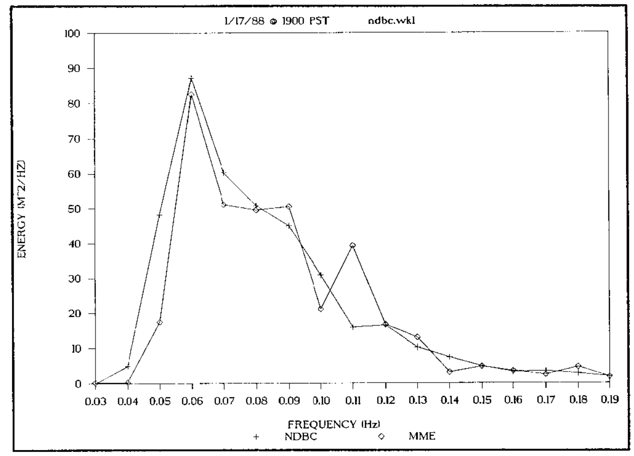

Figure 4. Comparison of wave spectral densities measured by MME wave staff and by NDBC buoy.

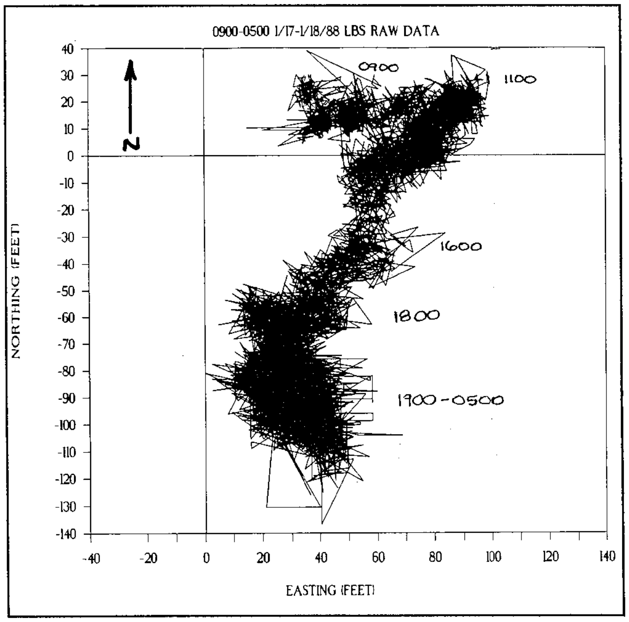

Figure 5. Watch circle movement for MME semisubmersible through duration of storm.

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