## CHAPTER 25

# WAVE CLIMATE CYCLES AND COASTAL ENGINEERING PRACTICE

Douglas L. Inman,[1] Scott A. Jenkins,[1] M. Hany S. Elwany[1]

## Abstract

El Niño-Southern Oscilllation (ENSO) events are major factors in changing wave climate at coastal sites. These events are triggered by extreme anomalies in the global seasonal climate; and in recent years they have become quasi-predictable from certain antecedent conditions. Judicious application of the global concepts leading to (ENSO) events will improve our understanding and prediction of wave climate.

## Introduction

Design of coastal structures and planning for beach remedial systems depend upon statistics determined from the study and measurement of past events and upon models using those statistics as primary inputs. The value of the statistic is usually assumed to depend solely upon the accuracy and duration of the observational series. This leads to common statistics such as a "design wave" height based on a recurrence history that defines the storm of the decade and century, and to shoreline changes based upon simple statistics such as the mean and standard deviation of beach width.

The limitation of our statistic is usually not the quality or resolution of the observations it is based upon, but rather that the statistics do not take into consideration the episodic nature of larger,

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[1] Center for Coastal Studies, Scripps Institution of Oceanography, La Jolla, California 92093-0209

controlling systems that govern the intermediate to long-term wave climate and sediment budget. For example, wave climate is an end product of meteorological climate and subject to the cyclicities and uncertaintities associated with that subject. Beach width is an end effect of the position within a littoral cell and is subject to all of the factors that influence the littoral sediment budget, including source, transport paths and sinks of sediment, as well as the variability in wave climate. Also, in the case of beaches, there is an element of inertia that causes beach erosion to be influenced more by the successive occurrence of clusters of average storms rather than by the isolated occurrence of a single extreme storm.

Climatic events such as El Niño-Southern Oscillation (ENSO) effect wave climate on a world-wide basis by altering the global atmospheric circulation paths, introducing periods of abrupt chaotic or episodic change. El Niños are harbingers of more intense wave climate along the temperate west coast of the Americas, but result in milder wave climates for the temperate east coasts of the Americas (Inman and Masters, 1994; Neelin et al 1994). El Niños also modify rainfall, causing droughts in some areas and flooding and maximum sediment yield in others. Along the southern California coast decades of relatively stable, mild wave climate are interrupted by El Niño events characterized by groups or clusters of intense storms and heavy rainfall. The El Niño of 1982/83 and its associated cluster storms completely denuded beaches that had been stable for the preceding 30 years. Thus, it is apparent that the usual statistical techniques based upon limited record lengths for predicting beach width and littoral drift rates and directions would lead to conclusions that are invalid for episodic periods of significant wave climate change.

## Seasonal Climate: An Introduction to ENSO Events

The seasonal variations in the exposure of the hemispheres to the sun produce interannual changes in the duration of daylight and the angle of the sun's irradiance. These effects modulate solar heating, resulting in the interannual variation of the earth's atmospheric pressure field which in turn introduces seasonal climatic effects. Interannual variations are enhanced by the higher convective effects of land and the greater concentration of land mass relative to water in the temperate latitudes of the northern hemisphere. In January, a large intense area of high pressure forms over the Asian continent (Figure 1a). This occurs because the convective slopes of Asia are inclined away from the sun with short periods of daylight that shutdown upslope convection, resulting in subsidence of air mass and an increase in pressure at ground level. In July, the convective slopes are inclined towards the sun with longer periods of daylight that increase solar irradiance and fuel upslope convection and lower surface pressure. Note that, in contrast to a rigid-lid system, the free motion of air in the convective atmosphere results in an inverse relation between temperature and pressure.

The northeast monsoons of southern Asia maximize in January, mainly in response to downslope anticyclonic flowing air caused by subsidence under the large area of Asian high pressure (Figure 1a). The cold descending air converges with tropical air to form a wet monsoon. The northeast monsoon in the Indian Ocean is less intense because of lower pressure gradients and the blocking effect of the Asian and African continental mountains. During July, the combination of upslope flow towards the low pressure area over the Himalaya mountains and the cyclonic geostrophic flow generates a strong southwest monsoon over the Indian Ocean (Figure 1b). This brings heavy rainfall over India and the high Ethiopian plateau (Quinn, 1992). The latter causes the Nile River floods that maximize during July. In contrast to the Indian Ocean, the southwestern monsoon is weak and relatively dry over southeast Asia because of lower pressure gradients and blocking by high inland topography.

## The ENSO System

Upon occasion the typical seasonal weather cycles discussed above are abruptly and severely modified on a global scale. These intense global modifications are signalled by anomalies in the pressure fields between the tropical eastern Pacific and Malaysia known as the *El Niño/Southern Oscillation* (ENSO) (e.g., Diaz and Markgraf, eds., (1992). The intensity of the oscillation is often measured in terms of the *Southern Oscillation Index* (SOI), defined as the monthly mean sea level pressure anomaly in mb normalized by the standard deviation of the monthly means for the period 1951-1980 at Tahiti, minus that at Darwin, Australia (Figure 2). A

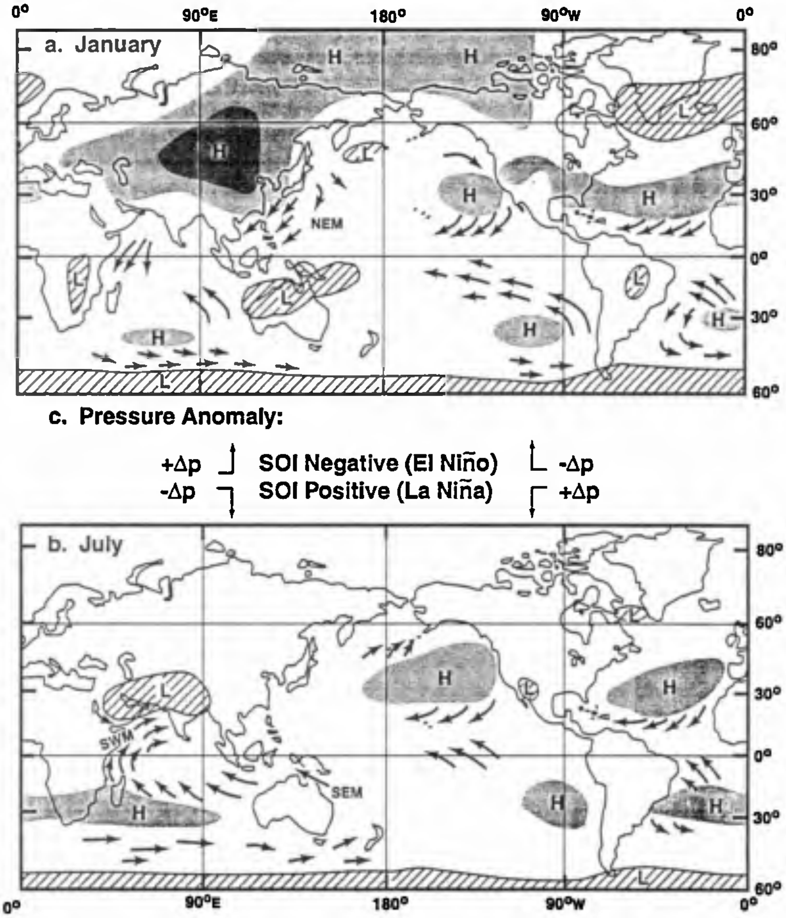
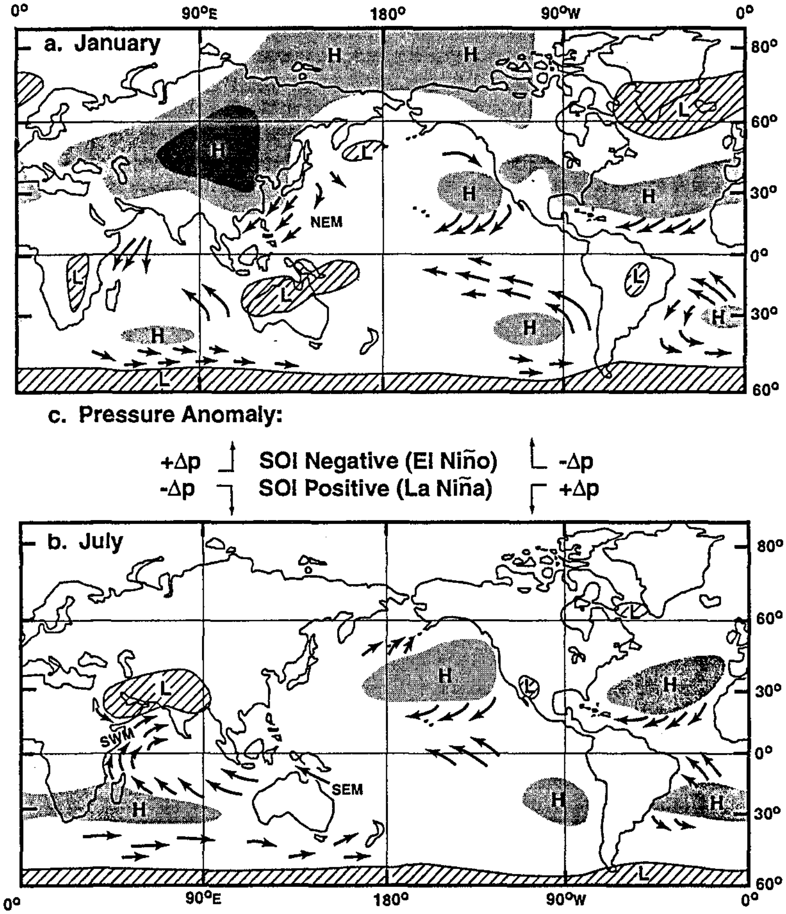



Figure 1. Seasonal pressure and winds for (a) January and (b) July. Contours of 1020 mb and 1000 mb are shown around areas of high (H) and low (L) pressure respectively. Prevailing winds are indicated by arrows: NEM, SEM, SWM designate northeast, southeast and southwest monsoons. (c) The pressure anomaly, $\Delta p$ centered around longitudes 105° E and 105° W for negative and positive Southern Oscillation Indices (SOI).

Asian low pressure area will be intensified, spinning up a strong southwestern monsoon in the Indian Ocean, causing increased rain in India and over the Ethiopian plateau. In July, the air flow over the northern Indian Ocean is dominated by the large Asian low pressure system centered over Afghanistan. This intensifies the southwesterlies and draws the *intertropical convergence zone* (ITCZ) north over the Ethiopian plateau. The ITCZ is the zone of collision between the converging tradewinds of the northern and southern hemispheres. Its primary features are surface doldrums and vertical convection with considerable cumulus development, rain and thunder storms. For intense La Niñas, the resulting convergence of air masses in the ITCZ brings heavy rainfall that causes floods on the Nile River (Quinn, 1992). Application of $-\Delta p$ anomaly to the southern hemisphere tropics in the vicinity of 105° E lowers the pressure over northern Australia and New Guinea. This modifies the pattern of the southeast monsoon and brings heavy monsoonal rainfall to Australia (e.g., Nicholls, 1992).

Of course, the above suggestions based on an intensified seasonal pattern are vastly oversimplified and tell us nothing about why or when ENSO events occur or how long they will last. However, climatic events characterized by intense El Niños and La Niñas affect wave climates on a world-wide basis in the sense that atmospheric circulation paths are altered globally (Neelin, et. al., 1994; Philander, 1989). Spectral analysis of coral growth rates shows that over the past century El Niño events have occurred with recurrence periods centered approximately on 3 and 7 years with more intense events occurring every decade or so (Cole et al, 1992; 1993). Although the events are not clearly understood, there is evidence that ocean-atmosphere interactions act as an oscillator which drives large-scale ocean waves known as equatorial Kelvin waves. However, this oscillator interacts with Earth's annual cycles, producing nonlinear resonances (Jin et al, 1994; Tziperman et al, 1994). The ENSO cycles jump irregularly among these nonlinear resonances, exhibiting chaotic behavior. Thus, there may be relatively long periods of uniform annual climate response, interrupted by periods of abrupt change.

El Niños are harbingers of more intense wave climates along the temperate west coast of the Americas, but may result in milder measured in terms of the *Southern Oscillation Index* (SOI), defined as the monthly mean sea level pressure anomaly in mb normalized by the standard deviation of the monthly means for the period 1951-1980 at Tahiti, minus that at Darwin, Australia (Figure 2). A

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negative SOI (lower pressure at Tahiti, higher pressure at Darwin) is known as an El Niño or warm ENSO event, because of the arrival

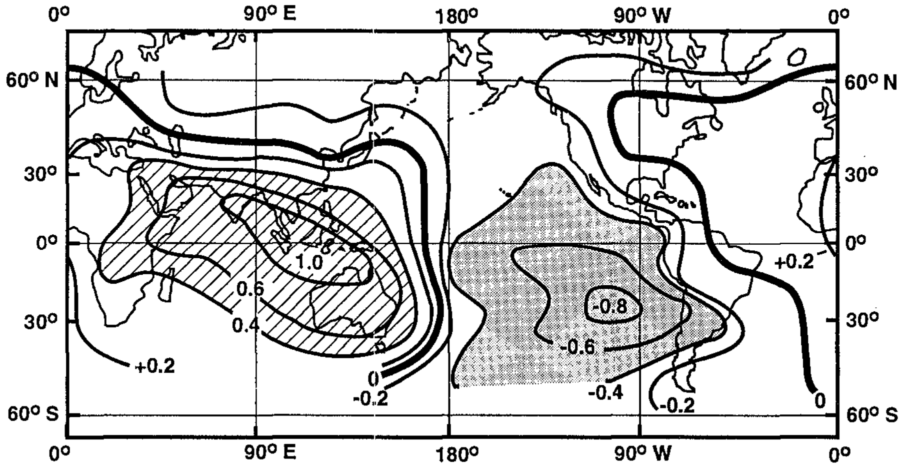


Figure 2. Global distribution of the correlation coefficient of annual pressure anomalies with simultaneous pressure anomalies at Jakarta (107° E longitude). Redrawn from Berlage (1957) and centered on 180° to show the southern oscillation.

of unusually warm surface water off the coast of Peru at the time of Christmas; hence, the term El Niño. Warm water also occurs along the coast of California and both regions experience unusually heavy rainfall. A positive SOI is known as La Niña and it signals the occurrence of colder than normal surface water in the eastern Pacific, but stronger southwest monsoons in the Indian Ocean with heavy rainfall in India and in the Ethiopian plateau. The latter causes flooding of the Nile River. Thus, the terms warm and wet vs cold and dry ENSO events that accompany El Niños and La Niñas respectively apply to the waters and coastal areas of the tropical-subtropical eastern Pacific Ocean and not necessarily to other parts of the globe.

It has been shown that the pressure changes associated with ENSO events are global in extent, and follow a pattern of alternate positive and negative correlation coefficients centered around wave climates for the temperate east coasts of the Americas (Dolan et al, 1990 and Seymour, 1996). As El Niño events and groups of intense storms (referred to as "cluster storms") alter the wave climate, models of the nearshore must be adjusted to these changes in oder to account for the abrupt and often long-lived coastal changes induced by these events.

The El Niño system

El Niño systems involve a complex set of interactions between the atmospheric and ocean circulation at tropical to middle latitude. The large-scale wind patterns and the companion mid-latitude high pressure systems described previously have a complementary feature in the ocean circulation referred to as "gyres". The gyres are the dynamic equivalent of the mid-latitude highs in the atmosphere, and are the result of an elevated sea level in the center of the ocean basin caused by a convergence of the Ekman drift from the trades and the mid-latitude westerlies. A large pool of warm water is established in the western Pacific which is ultimately regulated by the strength of the tradewind-driven component of gyre circulation.

This warm pool extends from the Philippine Islands south to the mid-Australian coast (Figure 3). Associated with these prevailing conditions is a stationary area of low atmospheric pressure, centered on Darwin, Australia, as compared with the relatively higher sea level pressure in the eastern Pacific from Tahiti to the coast of the Americas. El Niño events are associated with the release to the east of the warm water pool and a reversal of the relative pressure fields at Darwin as compared with Tahiti and the coast of the Americas (Figure 1a,c). These changes in the pressure fields in the lower layers of the atmosphere redirect the upper level jet streams that steer the tracks of traveling storms and markedly alter the wave climate of the world's coastline. The sequences within an El Niño event are illustrated in Figure 3 by numbers (1) through (5). The trade winds setup and confine a pool of warm surface water on the western side of the equatorial Pacific Ocean (1). Fluctuations in the prevailing trade wind intensity may release a series of eastward-flowing pulses of warm water. The warm El

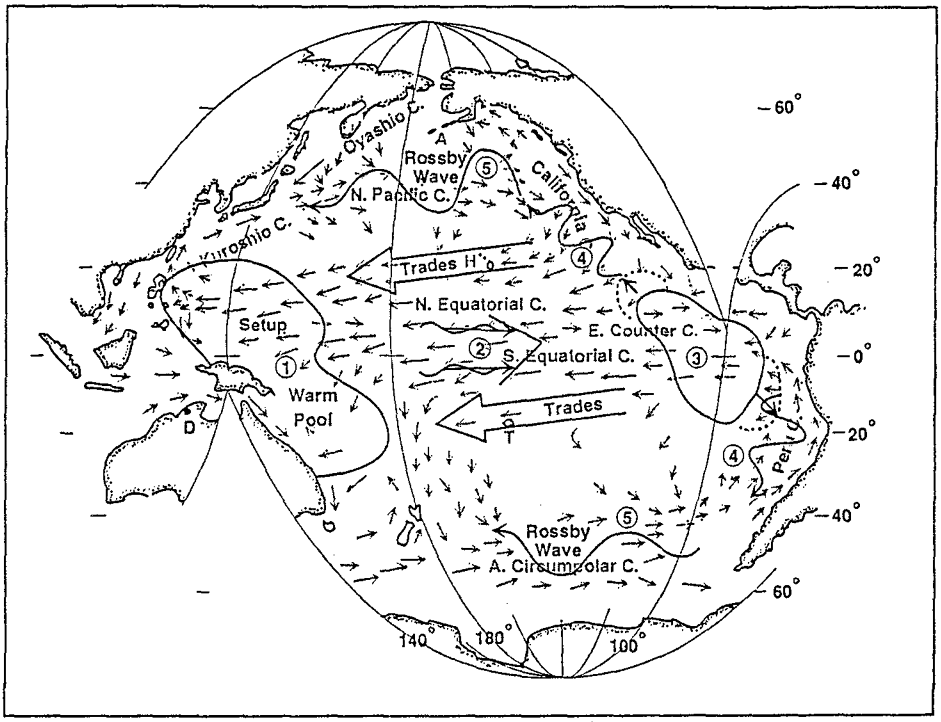


Figure 3. Schematic illustration of the five sequences leading to a fully developed El Niño event. See text for description.

Niño event begins when the trade winds relax and release a large "slosh" from this warm water pool which travels to the east along the equator (2). These sloshes travel as soliton-like internal features that are low-mode, baroclinic Kelvin waves channeled in the equatorial wave guide by the north-south gradients in planetary vorticity. Planetary vorticity is the spin imparted to a fluid particle by the local surface-normal vector component of the earth's angular velocity. These Kelvin waves have a phase speed determined by the density difference, $\Delta\rho$, at the thermocline, such that their phase speed is order:

$$C = [(\Delta\rho/\rho_2)gh_1]^{1/2} = 150 \text{ cm/sec},$$

where $h_1$ is the depth of the thermocline. The equatorial Kelvin waves pump warm water into the eastern equatorial Pacific (3), where it is spread poleward by barotropic Kelvin waves with topographically trapped modes propagating along the continental margins (4). These waves oppose the flow of the California and Peru currents. In turn, the shelf-trapped Kelvin waves appear to excite Rossby planetary waves that propagate slowly to the west against the flows of the North Pacific Current and the Antarctic Circumpolar Current (5). In addition to slowing the ocean current system, the Rossby waves induce sea surface temperature anomalies which modify surface pressures in the lower atmosphere that ultimately decrease the intensity of the westerlies, further slowing the overall circulation of water in the large Pacific gyres.

Sequences (1) through (5) in the El Niño event are all interactive among themselves and with the atmospheric circulation in very complex ways that are poorly understood. The conditions triggering the beginning of an El Niño event or those leading to its demise are not yet known. However, it is clear that, once started, the Kelvin-Kelvin-Rossby sequences all provide positive feedback that enhance each other and work toward a spin-down in the intensity of the prevailing anticyclonic oceanic gyres.

## Changing Wave Climate

ENSO events leading to significant changes in seasonal trends of wave climate are usually associated with SOI values greater than about $\mp$ 0.5. Figure 4 shows hemispheric contour plots of the pressure height anomalies (meters) for SOI positive (La Niña) and SOI negative (El Niño). Pressure gradients cause winds, and height anomalies show where persistent pressure gradients occur. The strongest pressure gradients occur along the boundaries of the height anomalies. The height anomalies in the figure show the mean location and intensities of the pressure changes during the ENSO events, and their boundaries indicate the likely location of storm paths. Figure 4a (La Niña) shows large areas of high pressure over the North Pacific and eastern North Atlantic. These high pressure areas would enhance storm tracks as shown by the two arrows for waves apporaching North America and Europe. The El Niño condition is characterized in Figure 4b by a large area of negative height anomaly over the North Pacific ocean and a relaxation in intensity but an increase in area of the positive height anomaly in the eastern North Atlantic. Thus, the La Niña/El Niño pattern over the North Pacific is bipolar and would be expected to give distinct changes in the storm track locations for the two conditions. In contrast either extreme would tend to enhance storm tracks approaching the coasts of Europe and the southeastern Mediterranean coast.

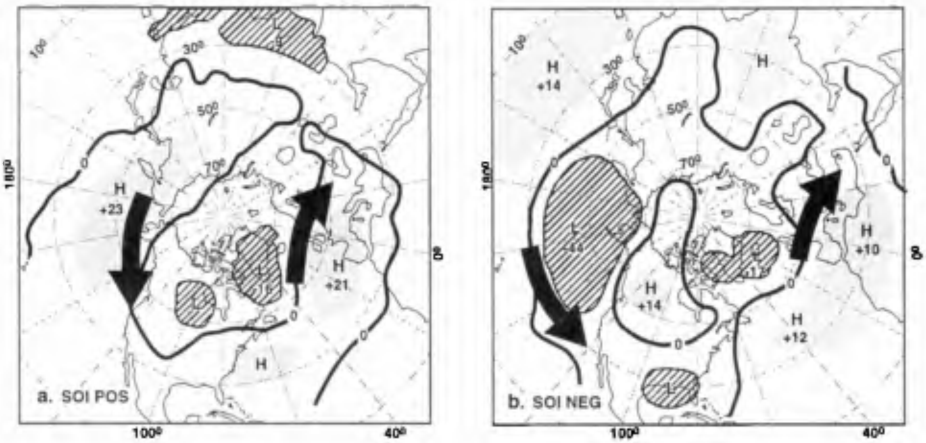


Figure 4. Height anomalies of the 700 mb atmospheric pressure surface derived from averaging winters (October-March) between 1947 and 1992 with preceding June-November for 11 SOI of +0.5 or greater (a) and for 12 SOI of -0.5 or less (b) (data from Redmond and Cayan, 1994). Shading and hatching indicate areas of negative (L) and positive (H) anomalies with maximum departure in meters. Arrows show position of storm-track enhancement associated with the anomalies.

Along many coasts, there are decades of relatively stable weather interrupted by shorter periods characterized by more variable weather, often accompanied by severe storms. The most recent period of mild-stable weather along the southern California coast occurred during the 30 years between the mid-1940's and mid-1970's when mild La Niña type weather prevailed. Winters were moderate with low rainfall (Figure 5), and winds were predominantly from the west-northwest. The principal wave energy was from Aleutian lows having storm tracks which usually did not reach southern California (Figure 4a). Summers were mild and dry with principal wave energy coming from the southern hemisphere.

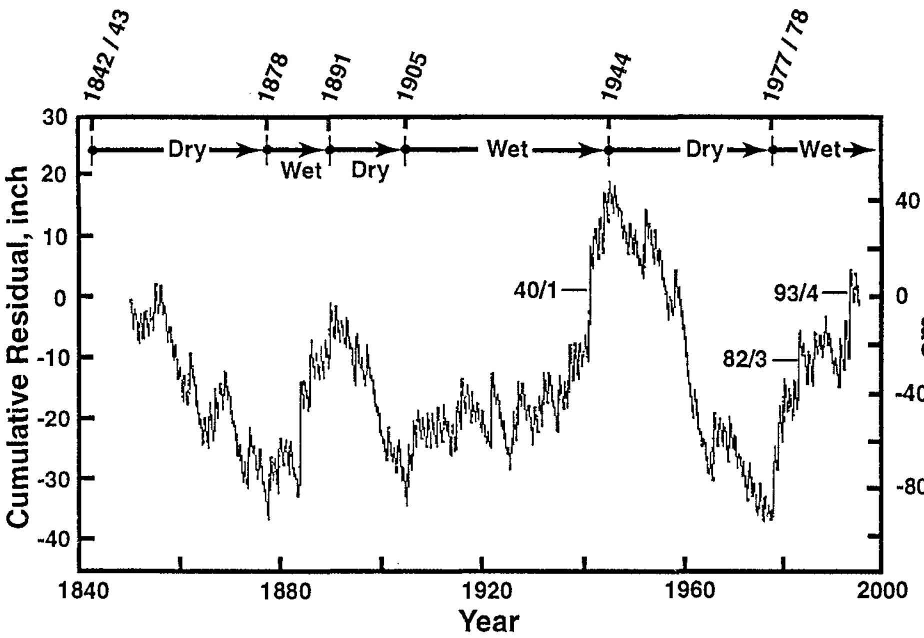


Figure 5. Cumulative residual rainfall in San Diego illustrating wet and dry periods that correlate with El Niño trends.

The wave climate in Southern California changed, beginning with the El Niño years of 1979/80 and 1982/83. The prevailing northwesterly winter waves have been replaced by waves approaching from the west (Figure 4b), and the previous southern hemisphere swell waves of summer have been replaced by tropical storm waves from the waters off Central America. The net result appears to be a decrease in the southerly component of the longshore transport of sand that prevailed during the preceding thirty years (Inman and Masters, 1994). Previous southward drift rates of 200,000 $m^3$/yr. have decreased to 50,000 $m^3$/yr. and have reversed direction for protracted periods of time.

## Conclusions

The clue to successful application of time series to engineering practice lies in long record lengths, and in the identification of supposedly anomalous trends. These anomalous trends can be identified by observables that either have intrinsically long record length or correlate with certain cause and effect mechanisms. For example, rainfall records, tree rings, railroad surveys and old newspaper articles can be used to correlate beach width and wave erosion with past El Niño's. Fluctuations in rainfall and wave intensity both follow the ENSO cycle which links them. For the modern records, a number of techniques are available to help elucidate this problem of cause and effect, including spectral and cross-spectral approaches and numerical progressions such as those resulting in cumulative residuals ( Figure 5).

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