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RELATIVE SEA LEVEL CHANGE FROM TIDE GAUGE RECORDS OF WESTERN NORTH AMERICA

K. O. Emery and D. G. Aubrey

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Abstract. Negligible success of investigators in relating tide gauge records of the west coast of North America to eustatic changes of sea level is the result of tectonic movements of the land reference level beneath the tide gauges. The vertical tectonic movements are caused by horizontal movements of oceanic crustal plates. Sinking of 12 mm/yr at Cordova, Alaska, is associated with intense subduction at the east end of the Aleutian Trench; rising by 6 mm/yr at Skagway may be caused by resistance to lateral crustal movement toward the filled trench; rising of 1 mm/yr in southern Alaska (uplift above slow subduction); little vertical movement between Sitka and Mendocino Fracture Zone (translation and slow subduction including fracture zones and thick sediments); sinking of 1 mm/yr west of the San Andreas fault (translation); and sinking of 2 mm/yr along northwestern Mexico (effects of cooling of late rifted crust and only diagonal subduction). Superimposed on this tectonism due to plate motion is broad scale isostatic adjustment (both rise and fall) resulting from deglaciation. Removal of rigid plate motion deltas helps resolve subplate tectonic processes. Higher-frequency (0.05-0.5 cpy) sea level changes as well as large-scale pressure fluctuations and wind stress events are associated with El Niño/Southern Oscillation. An apparent increase in relative sea level rise near 1935, also observed in other regions, remains to be explained.

Introduction

Tide gauges originally were established to indicate times of flooding and ebbing tides to aid sailing ships to enter and leave harbors, but later their records yielded information about longer-term changes of relative sea level. Hourly averages of tide height throughout an entire year showed year-to-year shifts ascribable only to general change in level of the ocean surface or of the land foundation beneath the tide gauge platform. Early compilation by Marmer [1927] of these relative shifts recorded on U.S. gauges was continued by others at the U.S. Coast and Geodetic Survey. Hicks and Shofnos [1965] and Hicks and Crosby [1974] showed that at most U.S. stations the average annual shift was between 2.0 mm rise and 1.0 mm fall of relative sea level but that several Alaskan stations exhibited average falls as much as 13.5 mm/yr. Slopes of regression lines, standard errors, variability, and smoothed curves for entire durations of station record and for the common time span between 1942 and 1972 were listed, but there was little discussion about causes of the changes. Comparison of records from different sites was complicated by differences in time spans of record at the stations and by effects of exceptional changes at 5- to 20-year intervals caused by oceanic and atmospheric factors. Other workers also have plotted tide gauge records for U.S. stations and for worldwide ones [e.g., Gornitz et al., 1982; Barnett, 1983a], but almost invariably with the stated or implied assumption that the records reveal eustatic changes of sea level and that the main analytical requirement was to balance the poor distribution pattern of the tide gauges.

Uplift of crusts of Scandinavia and Canada after melt of their glacial loads is well known from the presence of raised and tilted marine and lake terraces, but less well recognized are tide gauge indicators of vertical land displacements caused by lateral movements of crustal plates. In an effort to estimate the relative roles of tectonic movements of land and eustatic rise of sea level caused by return of glacial meltwater, Emery [1980] made regression analyses for 247 tide gauge stations of the world, finding a range of relative sea level change between at least +13 and -13 mm/yr. Such a wide range means that tectonic warps at the tide gauge sites have paramount importance for the general trends. After elimination of tide gauge stations at sites having a rise of land, the remaining stations recorded a median annual rise of sea level (or a fall of land level) of about 3.0 mm/yr. This change involves tectonic, eustatic, and periodic meteorological and oceanographic factors. The first step in evaluating the relative roles of these factors is to make detailed analyses of changes of level in regions that have numerous well-tended tide gauges. In addition, a need was evident to apply statistical methods beyond simple linear regressions to avoid biases and errors caused by periodic variations in water level, gaps in records, differences in time spans of records, and uneven distribution of stations along the coasts of the world.

In a recent review, Cartwright et al. [1985] discussed aspects of changes in relative mean sea level. Among the factors discussed was global geodynamics, with a strong emphasis on glacioisostatic rebound at the expense of plate tectonics and related issues. Although Cartwright et al. [1985] correctly identify the importance of land motion in interpreting tide gauge records, tectonism is not addressed leaving a large gap that the present study is designed to fill.

A first attempt at this statistical approach [Aubrey and Emery, 1983] was for the Pacific and Atlantic coasts of the United States using mean annual sea levels through 1979 supplied by the National Oceanic and Atmospheric Administration. Results for the Atlantic coast indicated the presence of three coastal sections having

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different trends of sea level changes, probably crustal blocks warped by tectonic movements and differently affected by glacial rebounds. Stations of the Pacific coast exhibited considerable irregularity that was considered due to movements of blocks, but interpretation was limited by the fewer stations and the probable smaller size of crustal blocks along the Pacific than the Atlantic coast. This article is a return to the Pacific coast problems after having gained experience in evaluating tectonic controls over changes in relative sea level in other parts of the world and after incorporating additional records especially from stations along the west coasts of Canada and Mexico.

Statistical Analyses

Mean annual sea levels at Pacific coast United States, Canadian, and Mexican tide gauge stations were provided by D. Pugh of the Permanent Service for Mean Sea Level at Merseyside, England. Forty-five Pacific coastal stations in the three nations had records of 13 or more years duration, but only 38 were within the geological provinces of Figure 1b and two of these were eliminated for regression because their Student t confidence limits (±1 mm/yr) for least squares regression were below 0.80. The remaining 36 stations (Table 1, Figure 1a) lie along the mainland between latitudes 19°30' and 60°33'N. Complications due to sinking of land at Long Beach prior to unitization of the large oil field there were avoided by eliminating the part of the record before 1963. Similarly, a 14-m uplift along a fault at Yakutat in 1899 [Tarr and Martin, 1912] occurred prior to the tide gauge record there.

Regression analyses showed that rise in mean annual relative sea levels ranges from +5.2 to -3.2 mm/yr, or (as in Figure 2) the change in land level ranges from -5.2 to +3.2 mm/yr. Between Manzanillo and Sitka a best fit line through the points that show average annual change approximates 0.75 mm rise/yr./1000 km north-northwestward along the coast, but there are many irregularities along the profile (Figure 2). Between Sitka and Skagway the rise of land level change is much steeper, reaching 17.6 mm/yr by regression, and beyond Skagway to Cordova it falls to -12.2 mm/yr.

Temporal eigenanalysis (details of methodology given by Aubrey and Emery [1986a] for 34 of the 36 stations showed that 79% of the variation in mean annual levels is in the first two functions (Figure 2, Table 2). The first function exhibits a change of slope from nearly horizontal prior to 1930-1935 (almost the same date as observed for records of the U.S. East Coast [Braatz and Aubrey, 1986], to a slope of -0.005/yr for the time span after 1935. The first and second spatial eigenfunctions, plotted at the bottom of Figure 2, were multiplied by the slope of their respective temporal functions and summed to obtain synthetic mean annual relative sea level change (expressed as land level change in Figure 2). Note that the results by eigenanalysis are parallel with those from regression analysis with the exception that the highest rates are muted by eigenanalysis (see also comparison in Figure 1c).

Annual changes of relative sea level are far from uniform, as revealed by the plots of Figure 4 made for 10 of the longer-term tide gauge stations of Figure 1. The changes appear to be cyclical, with higher sea levels corresponding with dates of El Niños that appear at intervals averaging about 6-7 years. Monthly mean relative sea levels (Figure 5) depict similar results but with more detail because of reduced averaging. Many El Niño/Southern Oscillations (ENSOs) are clearly identified in these monthly anomalies, although the El Niños of 1929 and 1939 exhibit weak sea level signatures.

These examples illustrate the presence of variations in relative sea levels (or land levels) that range from secular, or long-term, ones to others that are quasi-periodic, or short term. Low-frequency and high-frequency variations are discussed separately in the following sections as befitting their very different causes.

Low-Frequency Geologic Factors

Average annual changes of relative sea level along the Pacific mainland coast are too large and too varied to be accounted for by errors in tide gauge measurements of simple eustatic rise caused by returned meltwater and by changing ocean temperature. Most obvious are the sharp changes at Juneau, Skagway, and Yakutat compared with change in the opposite direction at Cordova (Figure 2). Significant also are less extreme changes between Sitka and Manzanillo. These smaller changes appear at first impression to be erratic, but their general trend is that of a general low gradient or even of several nearly horizontal levels with a step between San Francisco and Crescent City. Such gradients in relative sea level change along the coast suggest dominant control by vertical movement of the land through tectonism or isostatic adjustment rather than by shift of sea level alone. A similar conclusion favored large systematic changes of land level in Japan, which Aubrey and Emery [1986a] ascribed to effects of underthrusting of the Pacific and Philippine oceanic plates beneath the Japanese continental plate.

Examination of plate movements along the Pacific mainland coast of North America should clarify whether they may provide a rational explanation for the changes of relative sea (land) level along that coast. Much of the pertinent information for these plate movements was described by Atwater [1970], who built upon previous work derived largely from magnetic reversal patterns measured aboard surface ships and confirmed by cores from the Deep Sea Drilling Project. In brief summary, sometime before Late Jurassic a north-south spreading belt began to form the present Pacific Ocean, possibly by rifting of a former continent (named Pacifica by Nur and Ben-Avraham [1977]. Oceanic crust emplaced along this belt spread laterally eastward and westward from the original position of the belt. At about the same time another north-south spreading belt began as the Mid-Atlantic Ridge in the Atlantic Ocean, accompanying a westward movement of North America. As a result, the North American plate of continental crust overrode the earliest Pacific oceanic crust at the

TABLE 1. West Coast of North America Station Data

Station Name	Latitude	Longitude	Begin Year	End Year	Total Years
United States (Aleutian Island)					
Massacre Bay+	52°50'N	173°11'W	1943	1966	24
Sweeper Cove+	51°51'N	176°39'W	1943	1975	33
Unalaska+	53°53'N	166°32'W	1955	1975	21
United States (Alaska)					
Cordova*	60°33'N	145°46'W	1964	1983	19
Yakutat (YA)	59°33'N	139°44'W	1940	1983	44
Sitka	57°30'N	135°20'W	1938	1983	46
Skagway	59°27'N	135°19'W	1944	1973	31
Juneau (JU)	58°18'N	134°25'W	1936	1983	45
Ketchikan (KE)	55°20'N	131°38'W	1919	1975	61
Canada (Pacific)					
Prince Rupert	54°19'N	130°20'W	1933	1977	39
Queen Charlotte	53°15'N	132°40'W	1957	1977	16
Bella Bella	52°10'N	128°80'W	1962	1977	16
Port Hardy*	50°43'N	127°39'W	1965	1977	12
Alert Bay	50°35'N	126°57'W	1948	1977	30
Point Atkinson	49°20'N	123°15'W	1914	1977	44
Vancouver	49°17'N	123°70'W	1910	1977	51
Fulford Harbour	48°46'N	123°27'W	1960	1977	18
Victoria (VI)	48°25'N	123°22'W	1909	1977	69
Tofino	49°90'N	125°55'W	1962	1977	16
United States (Pacific)					
Neah Bay	48°22'N	124°37'W	1934	1983	50
Friday Harbor	48°33'N	123°00'W	1934	1983	50
Seattle (SE)	47°36'N	122°20'W	1899	1983	85
Astoria	46°13'N	123°46'W	1925	1983	59
South Beach*	44°38'N	124°30'W	1967	1983	17
Crescent City (CC)	41°45'N	124°12'W	1933	1983	52
San Francisco (SF)	37°48'N	122°28'W	1905	1983	79
Alameda	37°46'N	122°18'W	1939	1983	45
Avila	35°10'N	120°44'W	1945	1969	26
Rincon Island*	34°21'N	119°26'W	1962	1983	21
Santa Monica	34°10'N	118°30'W	1933	1983	43
Los Angeles (LA)	33°43'N	118°16'W	1923	1983	62
Long Beach	33°47'N	118°15'W	1963	1983	21
Newport Bay	33°36'N	117°53'W	1955	1983	29
La Jolla (LJ)	32°52'N	117°15'W	1924	1983	59
San Diego	32°43'N	117°10'W	1906	1983	78
Mexico (Pacific)					
Ensenada	31°51'N	116°38'W	1956	1982	25
La Paz*	24°10'N	110°21'W	1952	1966	15
Guaymas*	27°55'N	110°54'W	1952	1965	14
Manzanillo (MA)	19°30'N	104°20'W	1954	1982	26
Salina Cruz+	16°10	95°12	1952	1979	27

* Not included in eigenanalysis.
\+ Not included in regression analysis.

eastern side of the Pacific spreading belt until by now only fragments of that crust remain. In fact, part of the spreading belt itself has been overridden so that the East Pacific Rise has been consumed between the head of the Gulf of California and Cape Mendocino. It reappears at the Mendocino Fracture Zone as the Juan de Fuca Ridge, which in turn has been overridden by the North American plate in western Canada north of Prince Rupert (Figure 1b).

Most of the oceanic crust west of the spreading belt (the Pacific plate, Figure 6b) is intact, with a maximum width of about 9000 km that was formed during about 160 m.y. of seafloor spreading (an average rate of 5.6 cm/yr). Most oceanic crust east of the spreading belt (originally the same width as the present crust west of the spreading belt if spreading was symmetrical as is typical) has been lost by subduction beneath the North American and South American plates. Widest of the remaining fragments is the Nazca plate off South America

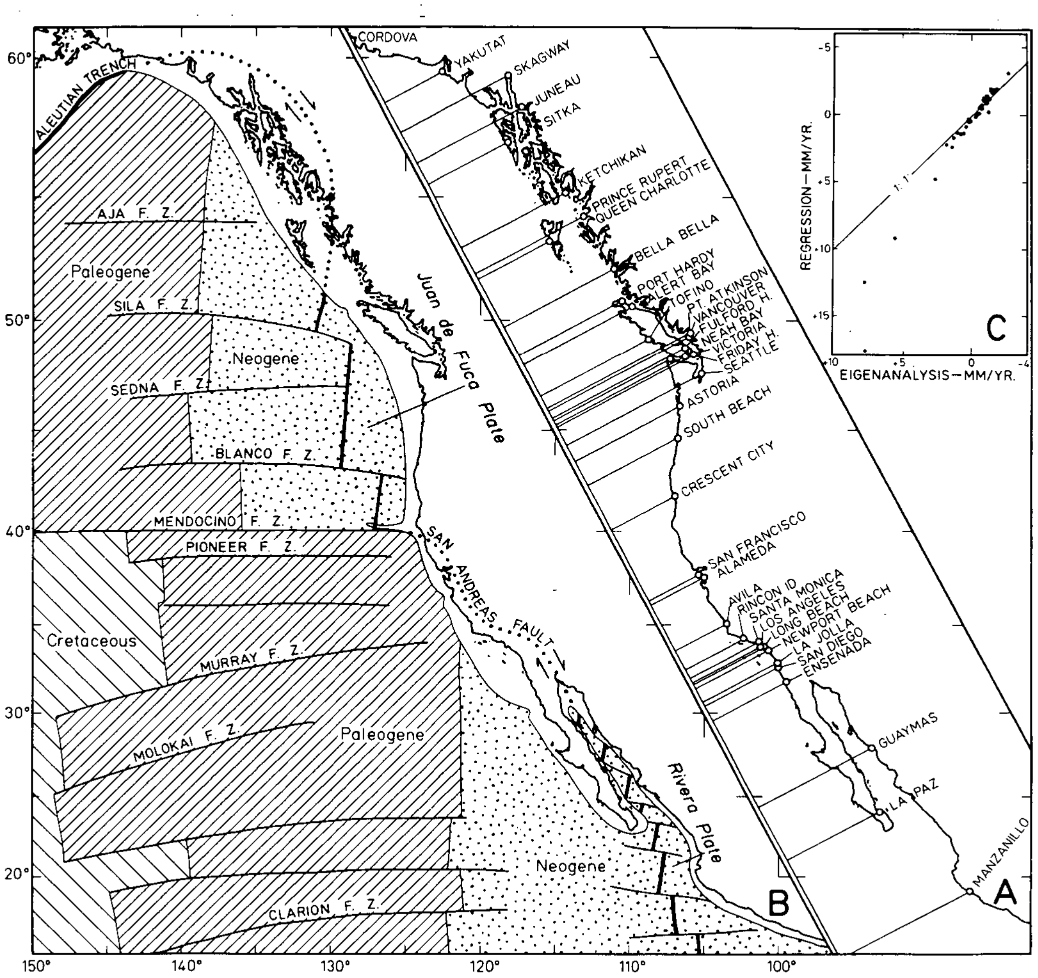

Fig. 1. Geographical patterns. (a) Positions of tide gauge stations (circles) and their projections to a line that trends N20°W for subsequent plotting of data. (b) Major fracture zones, spreading belts, San Andreas fault system, and ages of oceanic crust [King, 1969; Atwater, 1970; Pitman et al., 1974; Heezen and Fornari, 1975]. (c) Relation of relative land level change computed from regression analysis and eigenanalysis. The straight line represents the relation if results from the two methods had been identical.

south of the equator; its oldest remaining part next to the continent is early Eocene. The next fragment (Cocos plate) extends from the secondary east-west Galapagos spreading belt northward to latitude 18°N; its oldest crust is again early Eocene. A northward extension, the Rivera plate, occupies the eastern side of the Gulf of California (Figures 1b and 6a) but contains no oceanic crust older than late Miocene [Karig et al., 1978]. Next to the north was the former Farallon plate [Figure 6b] that extended to near the Mendocino Fracture Zone but became entirely consumed by subduction about 10 m.y. ago. The last remaining part of the original oceanic crust east of the main spreading belt is the Juan de Fuca Plate (Figures 6a and 6b), whose oldest remaining part is Miocene and whose northern limit is near Prince Rupert (Figure 1b). The part of this original plate north of that limit and all of a former Kula plate (Figure 6b [Grow and Atwater, 1970]) northwest of it have been lost to subduction beneath the North American plate to the northeast and along the Aleutian Trench to the northwest [Ben-Avraham and Cooper, 1981].

The subduction beneath the North American plate of an area of oceanic crust nearly equal to that of the present North Pacific Ocean influenced the continent in many ways [Maxwell, 1974] including vertical movements of the continental margin. That these movements persist to the present is reasonable in view of the many earthquakes along the coasts of this region and by an average rate of oceanic crust emplaced during the Neogene and Quaternary equaling 4.1 cm/yr, as estimated from the average width and 22.5 m.y. duration of emplacement of oceanic crust of that time span (mapped by Heezen and Fornari [1975].

Comparison of vertical movements of land shown by the regression and eigenanalysis profiles of Figure 2 with plate movements inferred from map patterns of Figures 1b and 6a is instructive. The largest fall of land level is at Cordova, which is just north of the eastern extension of the Aleutian Trench, the present main belt of subduction of the northern Pacific plate. Less

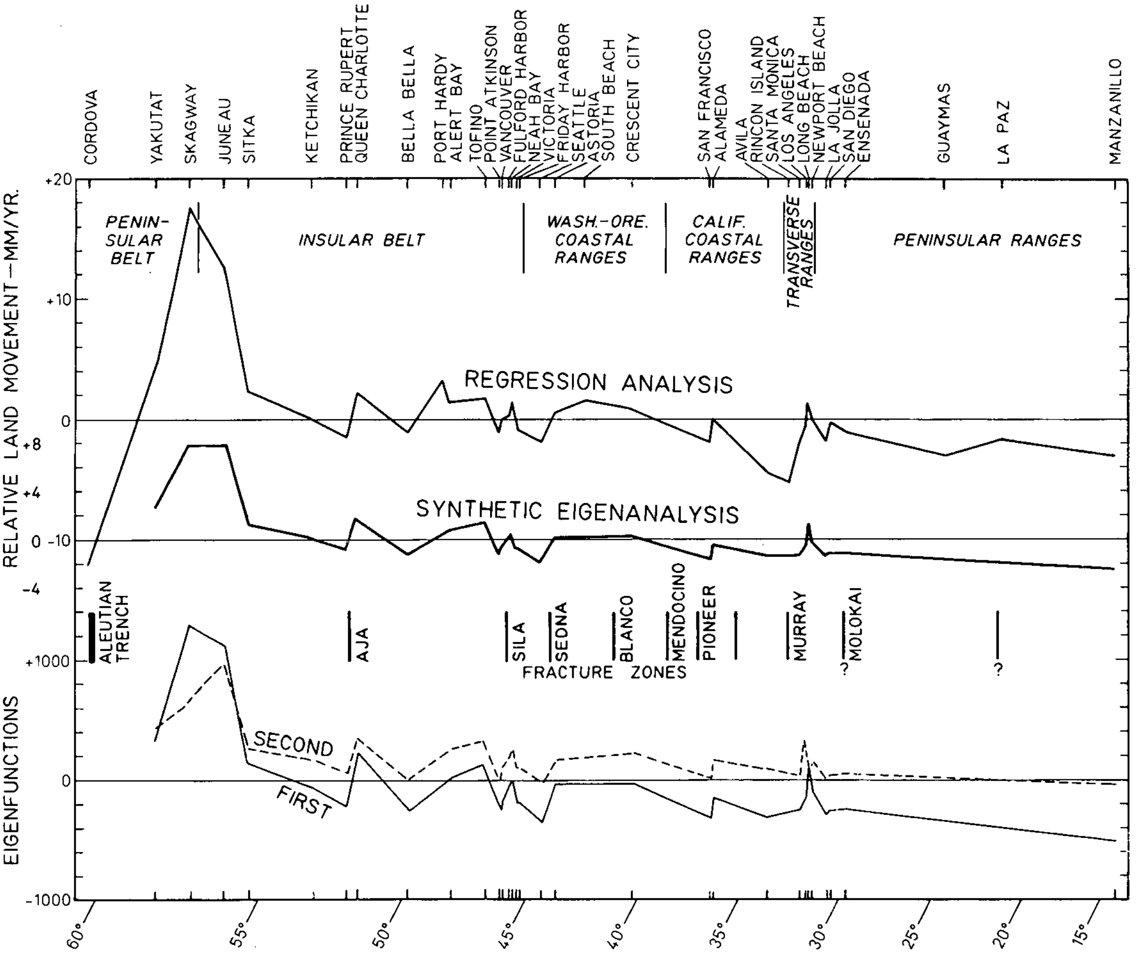

Fig. 2. Results of linear regression and eigenanalysis of data uncorrected for rigid plate motions and their relation to geological structures.

subduction occurs at the eastern end of the Aleutian Trench [Von Huene, 1972] than farther west; nevertheless, oceanic sediments at the east are thick, the crust is depressed, and deformation may have begun only during the Pliocene. The relationship accords with the Hilde and Uyeda [1983] observation that the depth of trenches is a function of the age and rate of plate subduction especially in regions having little sediment supply. The considerable uplift of land at Yakutat, Skagway, and Juneau is in a region of intense faulting [King, 1969] south of the Aleutian Trench extension, and perhaps it is partly due to resistance to underthrusting into the eastern Aleutian Trench of the Pacific plate and its adjacent continental crust (Figure 6a).

Between Sitka and the Mendocino Fracture Zone (the latter projecting eastward to the coast between Crescent City and San Francisco) the land level changes little (mostly between +1 and -1 mm/yr), perhaps in accordance with underthrusting of the Juan de Fuca plate (east of the spreading belt) beneath the North American plate. This

TABLE 2a. Percent of Variance in Sea Levels Explained by Dominant Eigenfunctions: Original Series

Eigenfunction	Percent of Variance
1	68.2
2	10.8
3	7.2
4	3.3
5	2.5
6	1.8
Total	93.8

TABLE 2b. Percent of Variance in Sea Levels Explained by Dominant Eigenfunctions Residual Series (Original Minus Rigid Plate Model)

Eigenfunction	Percent of Variance
1	68.0
2	13.7
3	6.0
4	4.1
5	1.9
6	1.6
Total	95.3

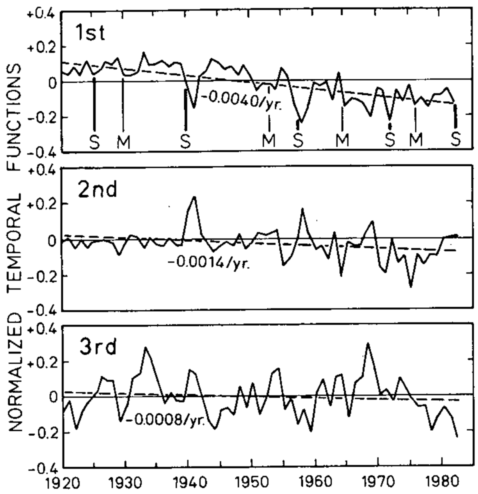

Fig. 3. Temporal eigenfunctions between 1920 and 1982. Of the total variability in the data set, 68.2% is accounted for by the first function 10.8% by the second, and 7.2% by the third. Significance tests presented by Priesendorfer et al. [1981] show the first three eigenvectors to be significant at the 95% level, although the applicability of these tests to small populations is marginally valid. Note the break in trend at about 1935 exhibited by the first function. Vertical lines denote dates of the chief El Niños (anti-Southern Oscillations [Quinn et al., 1978]); S, strong, M, moderate. Sign of temporal function is arbitrary and by itself implies neither rise nor fall of relative sea level.

underthrusting probably is most important south of Prince Rupert east of the spreading belt, but between Sitka and Prince Rupert it must be reduced by left-lateral strike-slip movement along a complex system of faults (Figure 1b [King, 1969]). Irregularities may be associated with the underthrusting of fracture zones, especially eastward extensions of the Sila and Sedna ones that appear to intersect the coast in a section having many tide gauge stations.

Farther south, between the Mendocino Fracture Zone and the Gulf of California, land levels are falling in accordance with the fact that underthrusting of oceanic crust ceased there when the spreading belt became overridden by the North American plate about 10 m.y. ago; much but not all subsequent movement was taken up by left-lateral strike-slip motion along the San Andreas fault [Atwater, 1970]. The one part of this coastal unit that exhibits uplift is the Transverse Ranges (Figure 2, top; the San Gabriel and San Bernardino mountains), which may be bounded by the eastward extension of the Murray Fracture Zone. They also have long been known from repeated precise leveling to be undergoing uplift of about 5 mm/yr [Gilluly, 1949], probably a result of oblique compression at the bend of the San Andreas fault (Figure 6a [Crowell, 1968]). Last, at the south is the segment between the head of the Gulf of California and latitude 15°S (the southern limit of Figures 1 and 6). Three tide gauge stations are present, and all denote a sinking land level on both sides of the gulf (Figure 6a), which may indicate that uplift caused by subduction there is less important than sinking produced by crustal cooling [Pitman, 1978] of the recently (3-5.5 m.y. ago [Curray et al., 1982]) rifted continental crust.

Recent work has focussed on identification of suspect terranes [see Coney et al., 1980], indicating that much of the North American continent consists of allochthonous blocks.

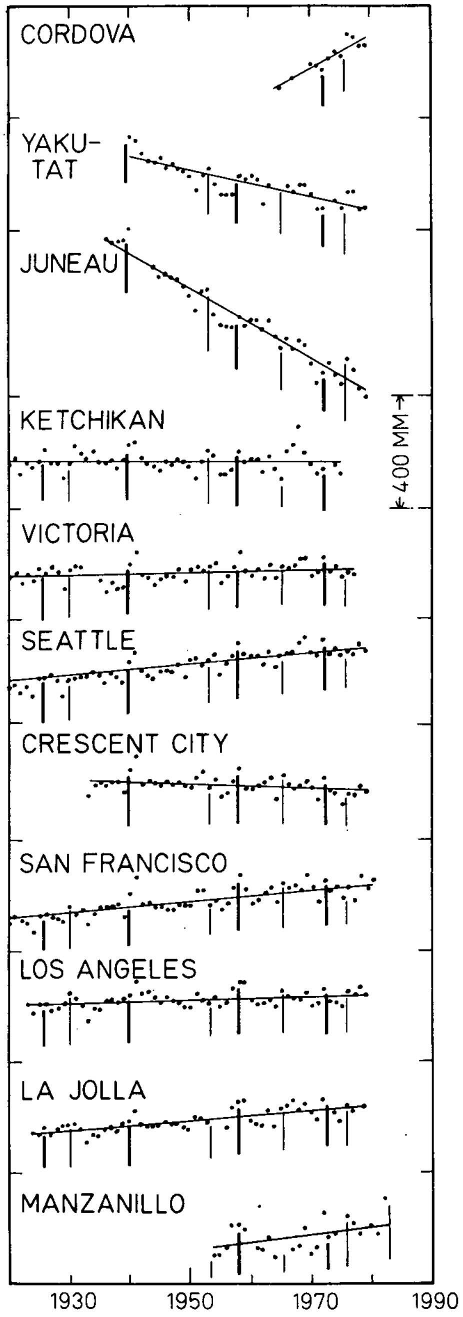

Fig. 4. Annual relative sea levels at 10 long-term tide gauge stations in the region of Figure 1 and Table 1. Linear regression lines reveal periodic departures from the general trends. El Niños indicated as in Figure 3.

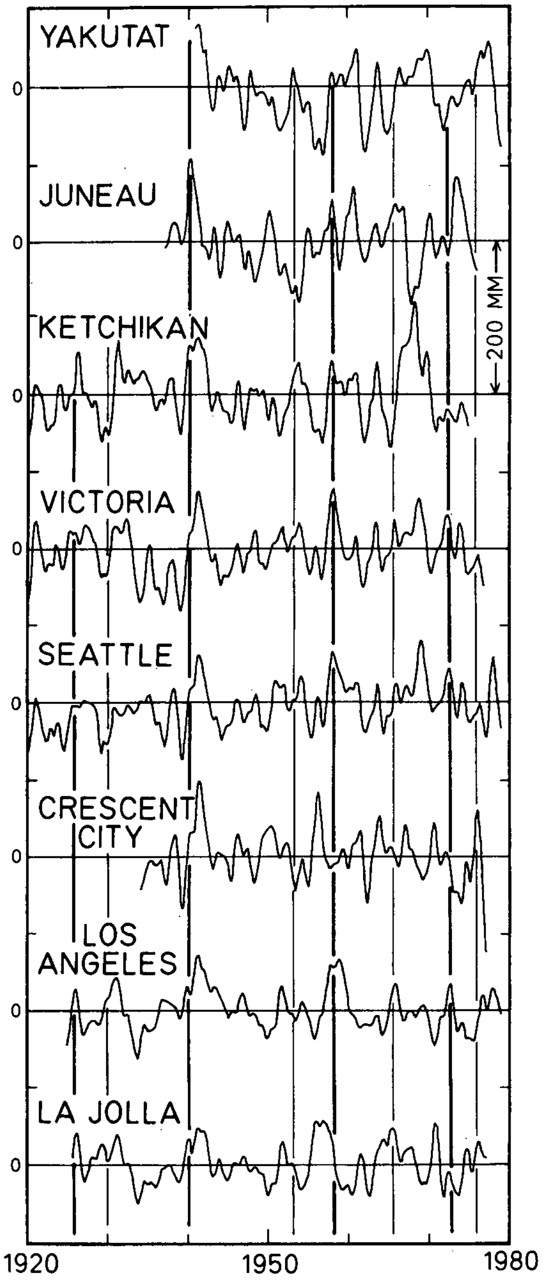

Fig. 5. Same as Figure 4 except data are triple 6-month running mean averages of monthly relative sea level data (mean monthly values have been removed to eliminate seasonal effects). This averaging is identical to that of Quinn et al. [1978] and is discussed by Aubrey and Emery [1986a].

These subplate blocks may be reflected in relative sea level behavior, as suggested by Figure 2. To more clearly distinguish rigid plate from subplate scale motions, additional modeling was performed. The oceanic plates were separated into three sectors corresponding to the following plates: northern Pacific plate (Yakutat to Bella Bella); Juan de Fuca plate (Bella Bella to Crescent City); and southern Pacific plate (Crescent City to La Paz). Within each of these sectors, relative sea level was modeled as

$$\eta'(x,t) = a_0 + a_1x + (a_2 + a_3\ x)t$$

where $\eta'(x,t)$ is plate motion at point x for time t, while a_0, a_1, a_2, and a_3 are constants for each plate. Tide gauge data from each of the three sectors were modeled by least squares. The resulting rigid plate model was then subtracted from the original relative sea level data, $\eta(x,t)$, to yield a residual series:

$$\eta^*(x,t) = \eta(x,t) - \eta'(x,t)$$

Regression results of the residual series are similar to patterns of the original series, lacking only the low wave number component (Figure 7). Spatial patterns of relative land movement remain essentially unchanged from those of Figure 2.

Eigenanalysis was performed on the residual series, as it had been for the exploratory investigation of original relative sea level series. Relative sea level histories reconstructed from eigenanalysis of residuals (Figure 7) are similar to analogous results from the original series. The rigid plate approximation does not reduce the spatial variability of relative sea levels. Similarly, temporal eigenfunctions (Figure 8) from the residual series are remarkably similar to those of the original time series (Figure 3).

Residual relative sea levels exhibit considerable spatial variability. Although some of this is a result of statistical uncertainties, part may reflect tectonic processes at a subplate scale. E. Uchupi and D. G. Aubrey (unpublished manuscript, 1986) related allochthonous terranes to sea level trends, identifying strong correlations between subplate scale tectonism and relative sea level records. Their results reinforce the strong control exerted by tectonism on tide gauge records.

Vertical crustal movement resulting from isostatic adjustment to deglaciation is superimposed on vertical changes due to plate motion (Figure 7). Peltier [1986] has modeled deglaciation of North America during the past 18,000 years. His results indicate a pattern of relative land movement markedly different from the tide gauge results (Figures 2 and 7). West of Skagway, isostatic adjustment leads to sinking of land. Between Skagway and Astoria, land is rising at rates up to 1.6 mm/yr, while between Astoria and Avila, land is sinking at rates reaching 0.8 mm/yr. South of Avila, isostatic response is negligible (less than 0.4 mm/yr). Removal of this broad scale isostatic adjustment neither makes tide gauge results more uniform nor alters interpretation of plate influence. Although contributing to relative sea level changes, isostatic processes are masked by tectonism associated with relative plate motions.

Eustatic rise caused by return of meltwater and change in water temperature is another low-frequency factor that can influence relative sea levels. This factor certainly was important after the time of maximum glaciation until about

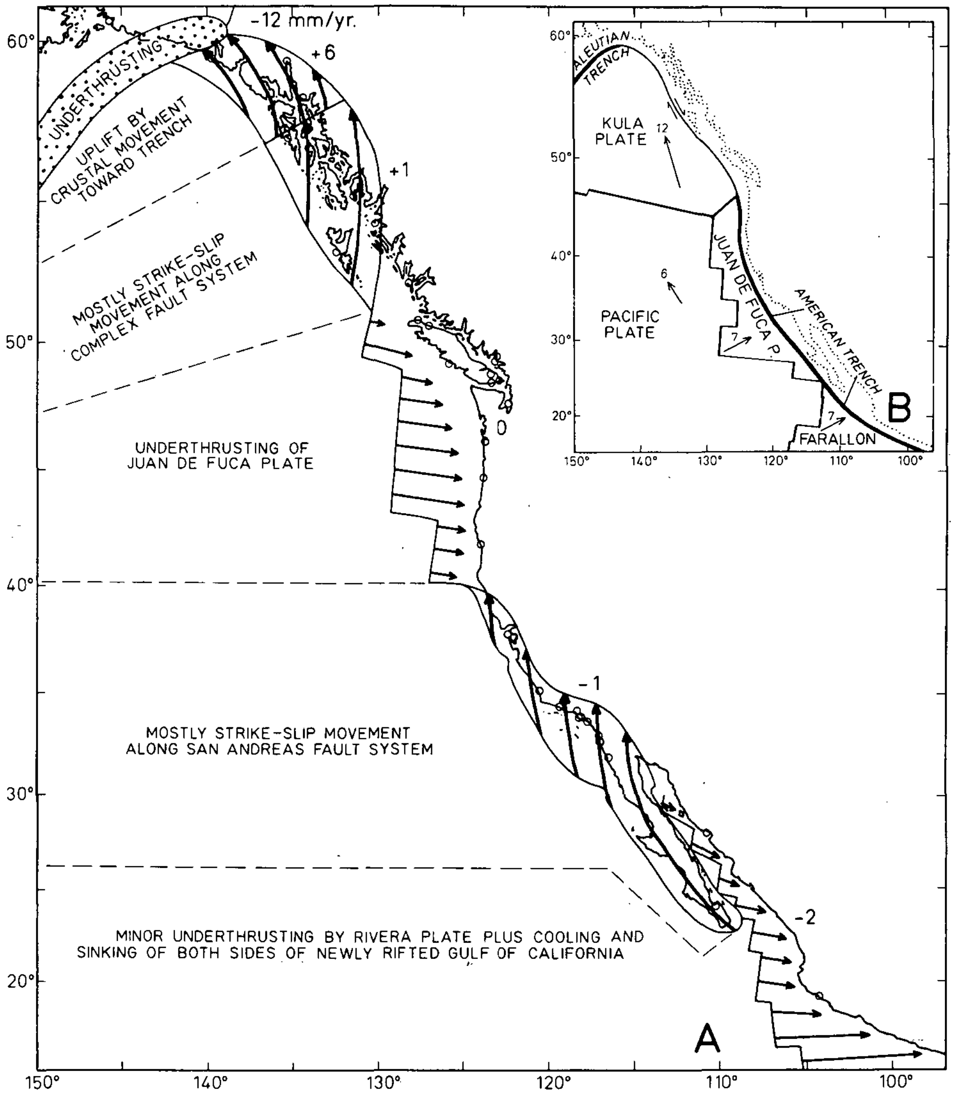

Fig. 6. Plate movements. (a) Present relative plate movements that control most of the changes of land level recorded by tide gauges (Figure 2; eigenanalysis). Underthrusting at the Aleutian Trench: -12 mm/yr at Cordova. Uplift by largely strike-slip movement toward trench at Skagway and Juneau: +6 mm/yr. Little change between Sitka and Prince Rupert: +1 mm/yr. Less change between Prince Rupert and Mendocino Fracture Zone: 0 mm/yr. Largely strike-slip movement between Mendocino Fracture Zone and Gulf of California: -1 mm/yr. Slight underthrusting but marked sinking of newly rifted crust between head of Gulf of California and latitude 15°N: -2 mm/yr. (b) Distribution and net movement of plates at boundary between Eocene and Oligocene (38 m.y. ago) assuming North America to be stationary; present shore shown by dots. Adapted from Atwater [1970, Figure 18b]. Present positions of the plates as given in Figure 1b and in text.

6000 years ago, but later after most of the ice had melted it became less important than tectonic changes of land level. There is no doubt that a present eustatic rise of sea level exists, but it occurs as a bias of unknown magnitude to the tectonic effects on land levels. Presently, we cannot evaluate the eustatic rise of sea level, although we hope to be able to do so in the near future.

High-Frequency Oceanic Factors

Low-frequency relative sea level signals are dominated by tectonic processes, with an unknown contribution from absolute sea level rise. Inspection of the temporal eigenfunctions (Figure 3) and individual station data (Figures 4 and 5) reveals many superimposed high-frequency fluctuations. Although the linear trend in relative sea levels defines the space scales of tectonic, isostatic, and eustatic changes, higher-frequency changes reflect oceanographic, steric, and hydrological influence.

Sea level fluctuations along western North America at frequencies greater than 1 cpy have been studied extensively in the past [Roden, 1960, 1966; Clarke, 1977; Osmer and Huyer, 1978; Enfield and Allen, 1980; Chelton and Davis, 1982;

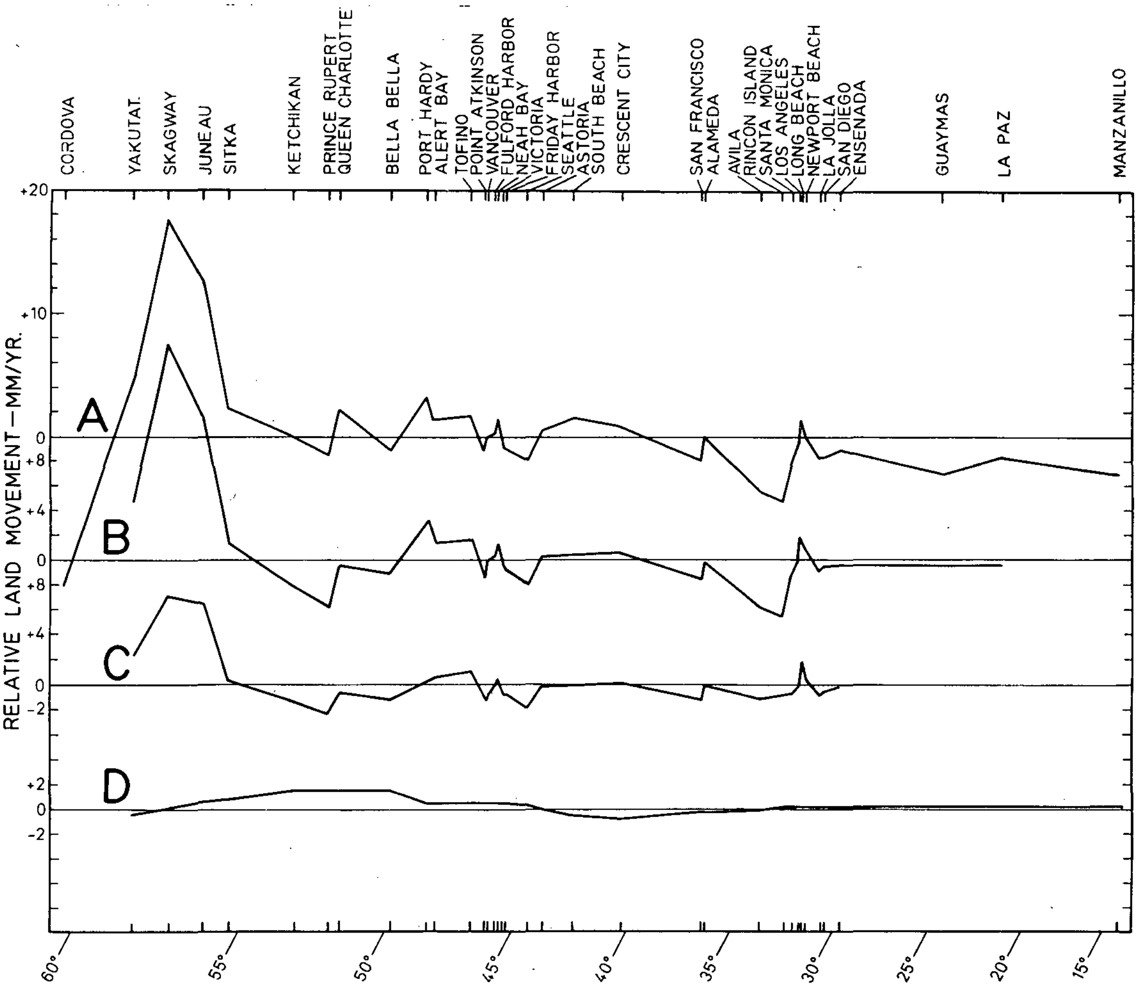

Fig. 7. Plate movements from tide gauge data. (a) Linear regression results of original data at each station (same as Figure 2, top). (b) Linear regression results of residual tide gauge data at each station (original data minus rigid plate model). (c) Composite relative sea level trends from eigenanalysis of residual data of Figure 7b. (d) Peltier's [1986] isostatic adjustment due to deglaciation of the earth following the Wisconsinan glaciation. This glacioisostatic signal is poorly correlated with any of the above curves.

Allen and Denbo, 1984]. Interannual variability also has been examined in detail [Roden, 1966; Chelton et al., 1982], with particular emphasis on the El Niño/Southern Oscillation phenomenon [Wyrtki, 1977, 1985; Emery and Hamilton, 1985; Chelton and Enfield, 1986].

One of the most comprehensive studies [Chelton and Davis, 1982] documented variability in relative sea level using monthly averaged tide gauge data for 20 stations from Alaska to Mexico during the interval 1946-1974. Many of their observations are germane to the present study. Their primary conclusions about higher-frequency (0-6 cpy) changes include the following:

1. The well-documented inverse barometer effect [Robinson, 1964] accounts for 50-60% of monthly sea level variability north of San Francisco but only 10-15% of the variability south of San Francisco.

2. Of the residual relative sea level variabilty, interannual contribution is dominated by the El Niño/Southern Oscillation, which propagates at a phase speed of approximately 40

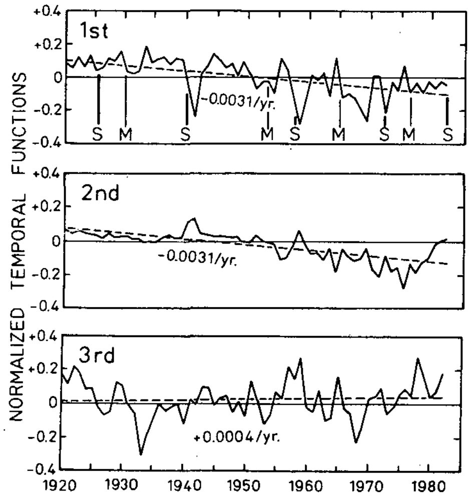

Fig. 8. Temporal eigenfunctions as in Figure 3 except formed from residual tide gauge data following removal of rigid plate approximation.

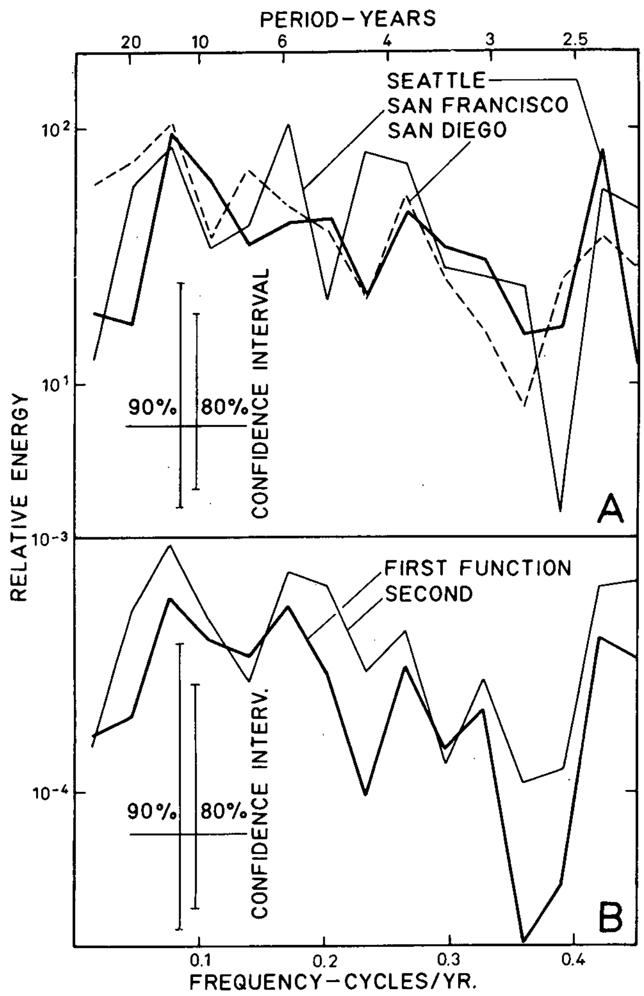

Fig. 9. (a) Spectra of relative sea levels at Seattle, San Francisco, and San Diego, for the period 1900-1982. Spectral estimates have 6 degrees of freedom, with confidence limits shown. (b) Spectra of the first two temporal eigenfunctions (Figure 3), for the period 1920-1982. Estimates have 4 degrees of freedom, with confidence limits indicated. The first function accounts for 68.2% of the variability in the data, while the second accounts for 10.8%.

cm/s, leading to a lag of 9-10 months between Acapulco and Adak.

3. Much of the remaining variance is ascribable to other dynamical causes, such as response to basin-wide wind stress. Many stations between Washington and San Francisco exhibit high-frequency relative sea level variability unrelated to the dynamical models tested.

The present study examines relative sea levels at 38 stations from Mexico to Alaska, reporting for a minimum of 15 years between 1920 and 1982. Eigenanalysis was performed on annual averages of hourly tide gauge data that were neither detrended nor corrected for the inverted barometer effect. Eigenfunctions were derived from the correlation matrix instead of the covariance matrix [see Aubrey and Emery, 1986a].

The three dominant temporal functions (Figure 3, accounting for 68, 11, and 7% of the total variance in the data, respectively) document the high-frequency variability in relative sea levels. This higher-frequency variability may be caused by direct steric response to large-scale pressure anomalies [Davis, 1976; Chelton and Davis, 1982], El Niño/Southern Oscillation events, and wind stress events. Spectra of these temporal functions (Figure 9) reveal little of direct dynamical significance because of the short record length and time-varying statistics (nonstationarity) of the signal. The spectra are energetic in low frequencies, with some higher-frequency variability of unclear origin. Although this energy between 0.4 and 0.5 cpy is not aliased, it is not evident in the results of Chelton and Davis [1982].

Individual station data (Figures 4 and 10) reflect this large variability in relative sea levels. At Seattle and San Diego, two stations having the longest interval of measurement, fluctuations correlate, but significant differences exist. Spectra of three station data (Seattle, San Francisco, San Diego, Figure 9) reveal similar, but not as predominant, lower-frequency energy. Again, with the poor time sample and limited stationarity these spectra provide little insight into dynamical mechanisms for relative sea level variability. The high-frequency peak (0.4-0.5 cpy) may be related to the inverse barometer effect, since spectra of relative sea level data having the barometric effect removed [Chelton and Davis, 1982] do not contain this same peak. Cross spectra between stations show some significant interannual coherence, but results are difficult to interpret because of poor stationarity.

The influence of El Niño/Southern Oscillation on these data was examined using the Southern Oscillation index of Quinn et al. [1978], as was done by Aubrey and Emery [1986b] for Australia. Chelton and Davis [1982] used the El Niño index of Allison et al. [1972] for their shorter record. For the longer data set (1920-1982), all moderate and strong El Niños are evident in monthly averaged relative sea level anomalies from San Diego and Seattle (Figure 10), while the effects are not as clear in yearly averaged sea levels of Alaska and Canada (Figure 4). Part of this difference is due to use of a yearly averaging interval that smears the El Niño signal (this effect is absent in Figure 5), and part is due to the 10-month time lag for El Niño propagation from Mexico to Alaska. Detailed examination of stations of northern and western Alaska reveals no El Niño signature; here strong atmospheric pressure fluctuations and wind stress mask the weak El Niño.

Eigenanalysis clarifies the large-scale response of the western North American coast to El Niño (Figure 3). During the El Niños of 1925-1926 (strong), 1929-1930 (moderate), 1939-1941 (strong), 1953 (moderate), 1957-1958 (strong), 1972 (strong), and 1976 (moderate), the coherent part of the relative sea level signal as represented by the first temporal eigenfunction depicts a uniform strong deviation (in this illustration a negative deviation, because of the sign convention adopted here). Thus the El Niño exhibits a strong but not unique control on relative sea levels.

Details of the response of relative sea levels

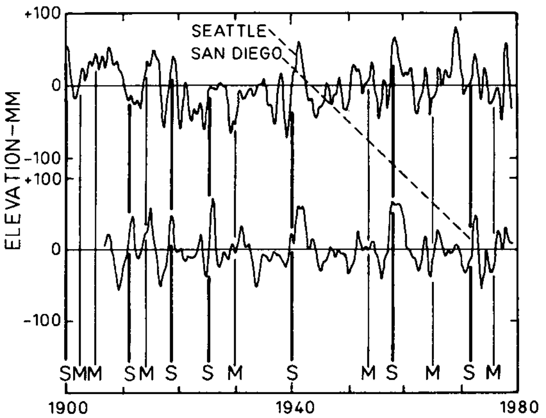

Fig. 10. Relative monthly mean sea levels at Seattle and San Diego for the period 1900-1982. El Niño/Southern Oscillation indices are as in Figure 3. Both San Diego and Seattle sea levels respond in phase to this El Niño forcing, although ENSO response is but a small fraction of total sea level variance. Tide data for San Diego are not exactly as provided by Permanent Service for Mean Sea Level. A 100-mm jump in water level has been removed from data preceding 1926, providing a close correspondence for records from San Diego and nearby La Jolla.

to atmospheric and sea level forcing are not examined in greater detail here because it is beyond the major focus of this study. Chelton and Davis [1982] provided more detail on these relationships.

Clear in both eigenanalysis results (Figure 3) as well as individual station data (Figure 10) is an apparent increase in rate of relative sea level rise centered near 1935. Examination of the longest station data as well as the shorter records used for eigenanalysis reveals this behavior. Prior to 1935, relative sea level change was low, increasing after 1935. Simple two-segment linear statistical models demonstrate a significant (greater than 95% level of confidence) change in slope at this time. This change cannot be explained by available data. It may represent a steric response to the greenhouse effect, a low-frequency (period order of 100-years) mode of relative sea level variability unresolved by the short record length, poor tide gauge measurements prior to 1935, or a change in ice volume. Meier et al. [1985] lent no support for the ice volume theory, while Barnett [1983b] found no steric effect on this time scale. Interestingly, Barnett [1984] did find a similar effect in his studies; Emery and Aubrey [1985] reported the same change in Scandinavia; while Braatz and Aubrey [1986] observed this acceleration in rate of change along the U.S. east coast at the same time. More investigation of this phenomenon is required to identify its causes.

Conclusions

Relative sea level records derived from tide gauges reveal a rich spectrum of motions, varying from extremely low-frequency (less than 0.05 cpy) to about one-half cycle per year. Eigenanalysis of yearly averaged sea levels for 36 stations along the western North American coastline defines coherent patterns of relative sea levels, improving previous estimates of the coherent large-scale spatial pattern.

Low-frequency changes (frequency less than 0.05 cpy) exhibit along-coast variation, with a range of relative sea level rise or fall (with respect to land) between -8 mm/yr (subsidence) and +3 mm/yr (emergence). Although Chelton and Davis [1982] cited possible contributions to this geographic trend from cooling of the North Pacific Ocean waters [White et al., 1979] and from isostatic rebound due to deglaciation, the primary contribution is remarkably consistent with large-scale tectonics of this region. Active subduction, seafloor spreading, and fracture zone slippage impose considerable alongshore variability of land movement relative to sea level. Since the seafloor is young, competition between tectonic uplift/subsidence and thermal subsidence produces a relative sea level signature which makes identification and evaluation of a eustatic component uncertain.

Previous attempts to estimate global eustatic changes from short contaminated tide gauge records [Emery, 1980; Barnett, 1983a, 1984; etc.] have a severe tectonic bias illustrated by the variation in relative sea level changes. Tectonic bias is illustrated elsewhere by vertical isostatic movements (Scandinavia [Emery and Aubrey, 1985], and Australia [Aubrey and Emery, 1986b]) and horizontal plate movements (Japan [Aubrey and Emery, 1986a]), so estimates of eustatic sea level changes during the past century must await elucidation and identification of regional tectonic trends. Tide gauge indications of vertical movements of land associated with plate tectonics represent modern continuations of long-term trends previously known only from geological studies of ancient strata and structure. Confirmation of these modern plate movements inferred from tide gauge records is now beginning to be provided by space-based measuring systems such as very long baseline interferometry and satellite laser ranging between fixed points on different continents [Carter et al., 1985; Kerr, 1985].

Higher-frequency (0.05-0.5 cpy, and higher) fluctuations reflect oceanic and atmospheric processes, as discussed by Chelton and Davis [1982] for the northeastern Pacific. The present study documents the large spatial coherence of El Niño/Southern Oscillation along western North America, with the nine accepted major El Niño events between 1920 and 1982 clearly depicted in the signals. Although northern response to El Niño is weaker than southern response, the ENSO events exert a strong control on yearly averaged relative sea levels. Also contributing to these higher-frequency variations are atmospheric pressure fluctuations, wind stress forcing, and some as yet unidentified dynamical factors.

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D. G. Aubrey and K. O. Emery, Woods Hole Oceanographic Institution, Woods Hole, MA 02543

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