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Overview of Sea Level Rise and Some Implications for Coastal California

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This document was prepared by the staff of the California Coastal Commission to provide information about sea level rise and to investigate possible effects to the California coast from a possible acceleration of sea level rise. This report has not been approved by the Commission.

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Overview of Sea Level Rise and Some Implications for Coastal California

Introduction

The coast is formed by the intersection of water, land and air. This boundary area is very dynamic and constantly changing. In California and other tectonically active locales, the changes to all three coastal components are regularly apparent. These changes occur on many different time scales. Changes in land elevation can be through gradual uplift or subsidence, or abrupt change through a seismic event. Other changes in land elevation can occur as gradual erosion, or rapid bluff collapse. Wind forces change constantly. Low pressure storm fronts change air pressure and can cause a short, one or two day long increase in water elevation; more major weather systems, like El Niños, can lower atmospheric pressure for many months. Finally, the water level is constantly changing from variations in atmospheric pressure and tides. Within this context, changes in sea level are regular elements of the coastal environment.

Historically, global sea level has been rising at a rate of 0.5 to 0.6 ft per century (15 to 18 cm per century). Over the past 10 to 15 years there has been a growing concern that increased in emissions of carbon dioxide and other greenhouse gases will cause an increase in global temperature, often called global warming. One likely effect of global warming would be an acceleration of the rate of sea level rise. Many of the physical consequences of this acceleration in sea level rise are apparent -- low-lying coastal beaches and wetlands could be drowned, and coastal infrastructure, such as wharves, piers, breakwaters and levees could be too close to the water level to work effectively. Increased coastal storm damage and salt-water intrusion are other, less apparent consequences.

The California Coastal Commission is one of the statewide agencies responsible for planning and regulation within the California Coastal Zone. The entire coastal zone may be affected significantly by future changes in sea level. This report provides an overview of geologic and historic changes in sea level that help put the projections of future sea level change into context. It discusses some of factors affecting global and local changes in sea level and the differences between mean sea level and the various tidal components. And, finally, it discusses the trends in sea level, possible consequences of increased sea level and the various responses to a future increase in sea level.

Geologic and historic changes in sea level

Sea level varies greatly during periods of glacial advance and retreat. Glacial and interglacial periods can be recognized by evidence of different vertical locations for overall sea level. During glacial cooling periods, vast amounts of water are stored as ice in land bound glaciers. Ocean levels are lower because so much water has been trapped in glaciers and the remaining ocean water is cold and dense. As the glacial period ends and an interglacial period begin, glaciers melt and retreat. The ocean level rises as glacial ice melts and the water flows into the ocean. Also, the increase in temperature causes the ocean water to warm and expand. Figure 1 shows the changes in sea level that have occurred through the past three glacial cycles.

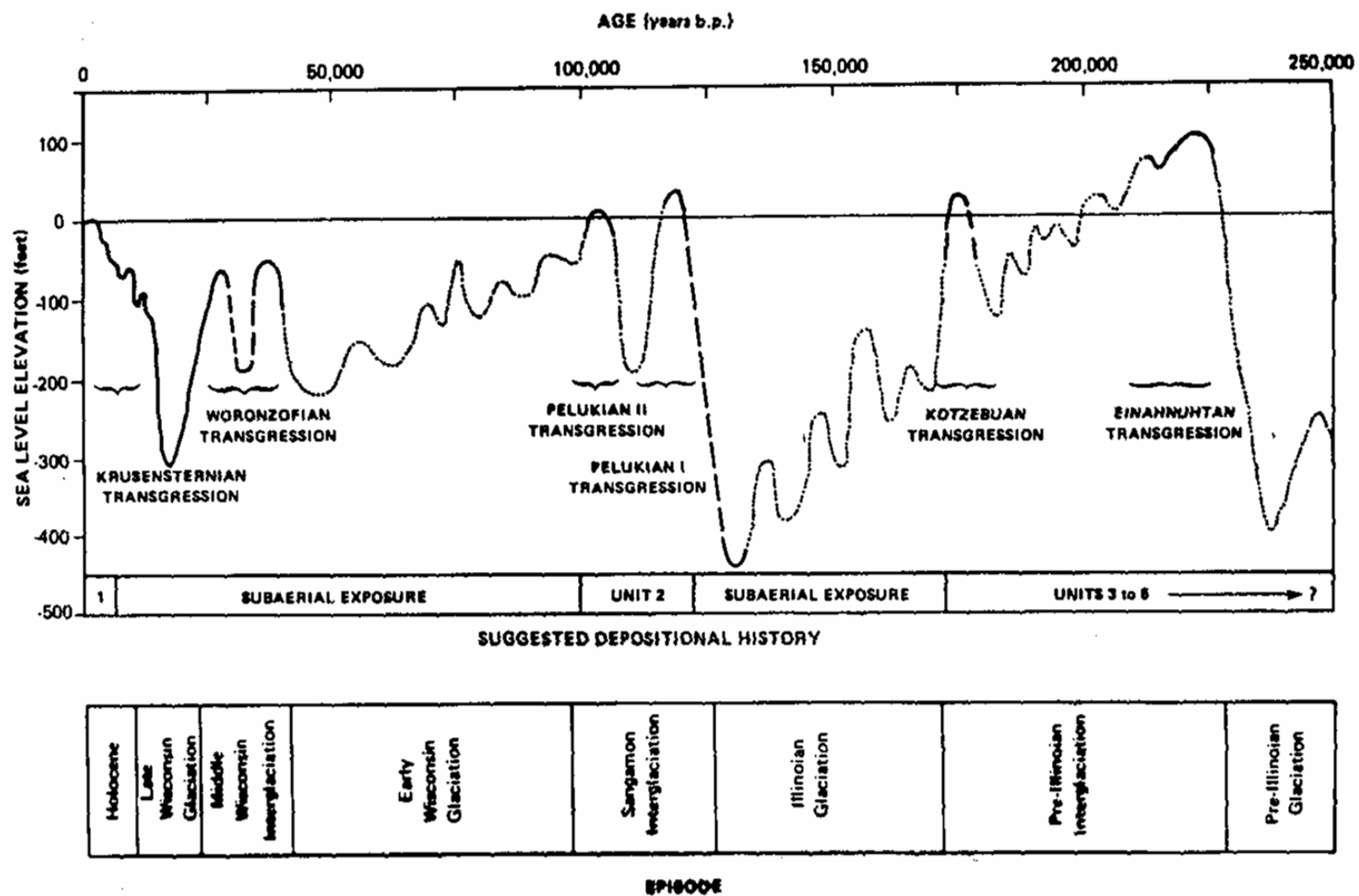


FIGURE 1
Sea Level Rise Since Pre-Illinoian Glaciation (250,000 B.P. to Present)

The most recent glacial period, the Late Wisconsin Glaciation, was followed by rapid sea level rise. From 18,000 years before present to 8,000 years before present, sea level rose rapidly at about 3 ft (0.9 m) per century (Chorley et al., 1984, page 399). Over the past 8,000 years the glacial melting has slowed significantly and the changes in sea level have slowed as well.

The growth of glaciers added a massive amount of weight on the underlying landmass. As the glaciers melted, the weight on the landmass was removed. The weighting and unweighting of the landmass causes downwarp and rebound. The modern day eastern United States coast, from Maine to Maryland or Virginia, and the Great Lakes are classic examples of land masses that are experiencing effects of the combined sea level rise and glacial rebound.

During the major glacial transition periods, the glacial effects tend to dominate the changes in sea level. In the major interglacial periods, such as the current period, changes in sea level are more sensitive to temperature changes and show decadal and century long fluctuations. In the last millennium there were two small cooling periods (the Medieval Advance, about 1200 AD to 1400 AD, and the Little Ice Age, about 1550 AD to 1800 AD), accompanied by glacial growth and a drop in sea level (Chorley et al., 1984, page 399).

Estimates of geologic and early historic changes in sea level have been based mainly on inferred evidence – uplifted marine terraces, submerged shelves, sediment and ice cores, epic stories, and others. Actual measurements of sea level and temperature have been available for only the past few centuries. Galileo invented the thermometer in the 1660's and this started the first concerted effort to record temperature. Since 1860, there has been an international program to measure global temperature. Figure 2 shows these records of global temperature; over the past 140 years, there has been a general trend of temperature increase. The mean surface temperature of the earth has increased 0.6° to 1.2°F. (0.3 to 0.7°C.) since the late 1800's.

Information sea level rise has been developed mainly from the tidal records that are maintained for many coastal ports and harbors. These records provide information on relative sea level rise – the change in water level relative to the land position. Tide measurements combine the changes in water elevation with the changes in land elevation. A relative rise in sea level can occur if the actual water level increases faster than the land elevation rises, if the water level drops more slowly than the land elevation drops, or if water rises or is constant as land drops. The overall global change in sea level, called eustatic sea level, is estimated by isolating the changes in water level from tide records. This worldwide, or eustatic, rise has been about 0.5 to 0.6 ft (15 to 18 cm) over the past century.

Along much of the California coast, the effects of this global rise in sea level have been dampened by uplift of the land and tectonic forces. Relative sea level rise has been less than the rate of eustatic sea level change, since much of the California coast is experiencing uplift often due to tectonic forces. The coastal marine terraces inland of the California shoreline are evidence of this uplift. Some uplift or subsidence events occur fairly slowly; in other cases this change can be very rapid. The Ferndale Earthquake caused localized uplift of over 3 ft (0.9 m). Fluid withdrawals from some southern

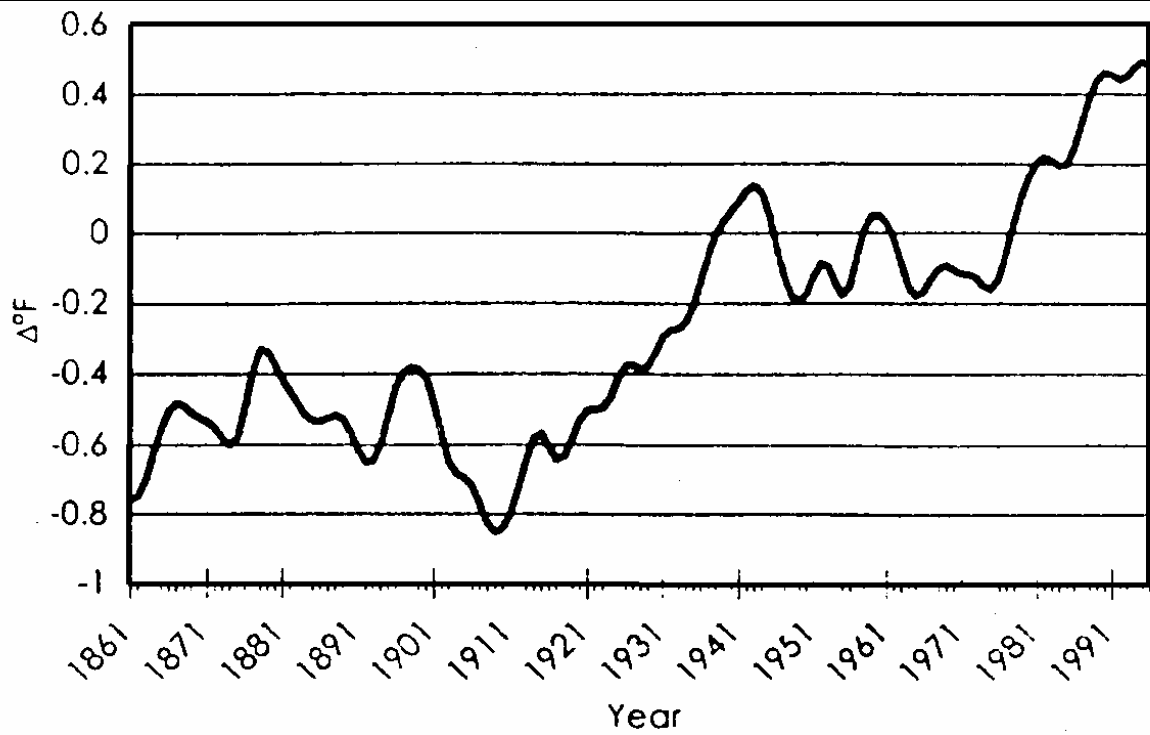


FIGURE 2
Global Temperature Changes 1861 – 1996

Source: International Panel on Climate Change (IPCC), 1995 (Updated)

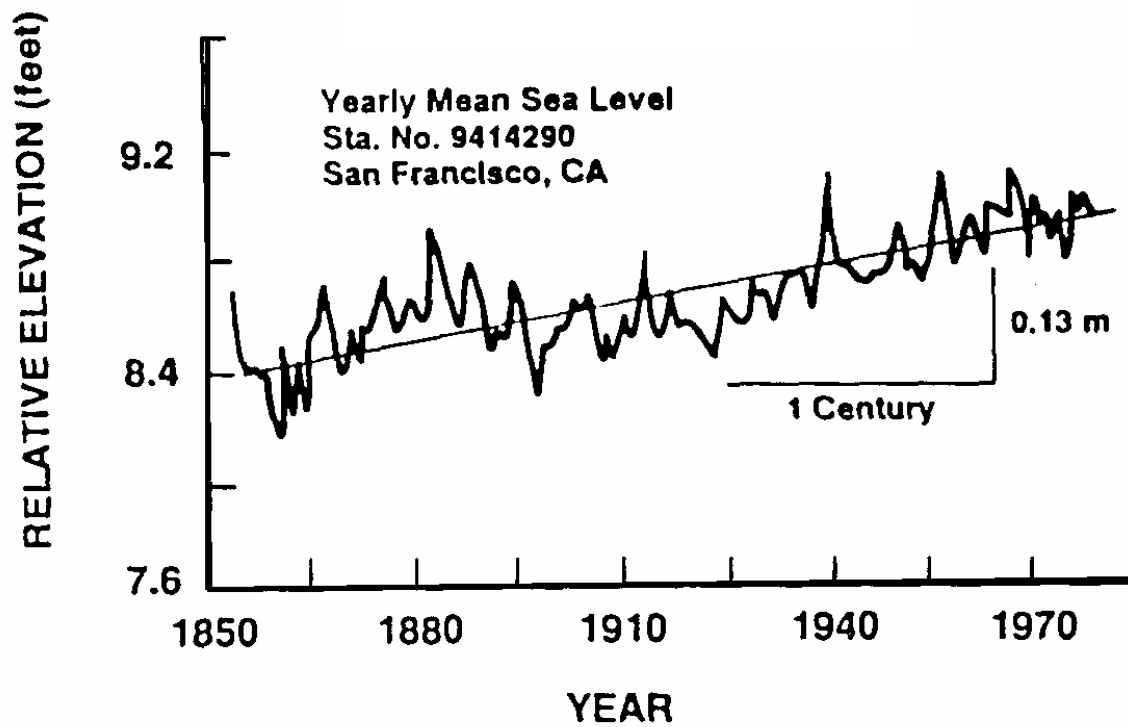


FIGURE 3
Sea Level at San Francisco: 1955 to 1980

SOURCE: Hicks et al. (1983)

California oil fields can cause gradual localized subsidence (sinking of the land surface). The near shore area of Long Beach experienced up to 10 ft (3 m) of subsidence before fluid reinjection halted or slowed this effect.

Figure 3 shows the long-term annual mean sea level record for San Francisco, indicating a rise in sea level of 0.43 ft/100 yr (0.13m/100 yr). Figure 4 and Table 1 show trends in relative mean sea level for various California tidal stations. The trends, provided by the Permanent Service for Mean Sea Level and the National Oceanic and Atmospheric Administration, differ slightly for some stations, due to the different treatment of discontinuous records and the different time periods used in each record. The negative trends, such as at Crescent City, CA, indicate that the landmass at Crescent City is rising more quickly than sea level, and the actual water level is dropping relative to the land.

Difference between mean sea level and various tidal components

Mean sea level is just one component of the tidal record. A full tidal record will provide information on all the tidal constituents – higher high water, lower high water, higher low water, lower low water, extreme high and low water, and mean sea level. For day to day activities, the tidal range and elevations of the high and low tide are often far more important than the elevation of mean sea level. For design of wetland restoration projects, the intertidal zone is more critical than the elevation of mean sea level. However, none of the studies of changes in sea level had examined either the historic or future changes in the various tidal components that go into mean sea level. Only a few studies have looked at the historic changes in the tidal range and a recent study (Flick, Murray and Ewing, 1999) is the first to look at the historic tidal ranges throughout the US. A major finding from this study was that all the tidal components have not changed uniformly. While tidal records for all the stations in California except Crescent City show an increase in mean sea level, some show an increase in tidal range and others show a decrease.

In San Francisco, both the diurnal¹ and mean² tide ranges have increased since 1900. The diurnal range increased at a rate of 0.199 ft/100 yr (0.061 m/100 yr), and the mean range at a rate of 0.192 ft/100 yr (0.0585 m/100yr). The rise in mean sea level has been about 0.72 ft/100 yr (0.219m/100 yr) while the rise in MHHW and MHW for the same period have been 0.85 ft/100 yr (0.259 m/100 yr) and 0.82 ft/100 yr (0.250 m/100 yr). Table 2 shows the trends in Mean Sea Level and Tidal Range for 11 major California tidal stations. Detailed graphs for all the California stations are provided in Appendix A. These findings also reinforce the wave element of tides. It appears that the tidal wave (not to be confused with a tsunami wave that is often incorrectly called a tidal wave) changes over time, possibly due to changes in ocean temperature, water density or depth of the thermocline.

Regardless of the cause, the results highlight the importance of clarifying specific concerns. If the concern is with the future viability of a wetland, the project should be considered in light of the changes to the tidal range between lower low water and higher high water. Project studies should look at the changes to these components in addition to, or possibly in place of, the changes to mean sea level. For projects where storm damage

¹ The range between mean higher high water and mean lower low water.

² The range between mean high water and mean low water.

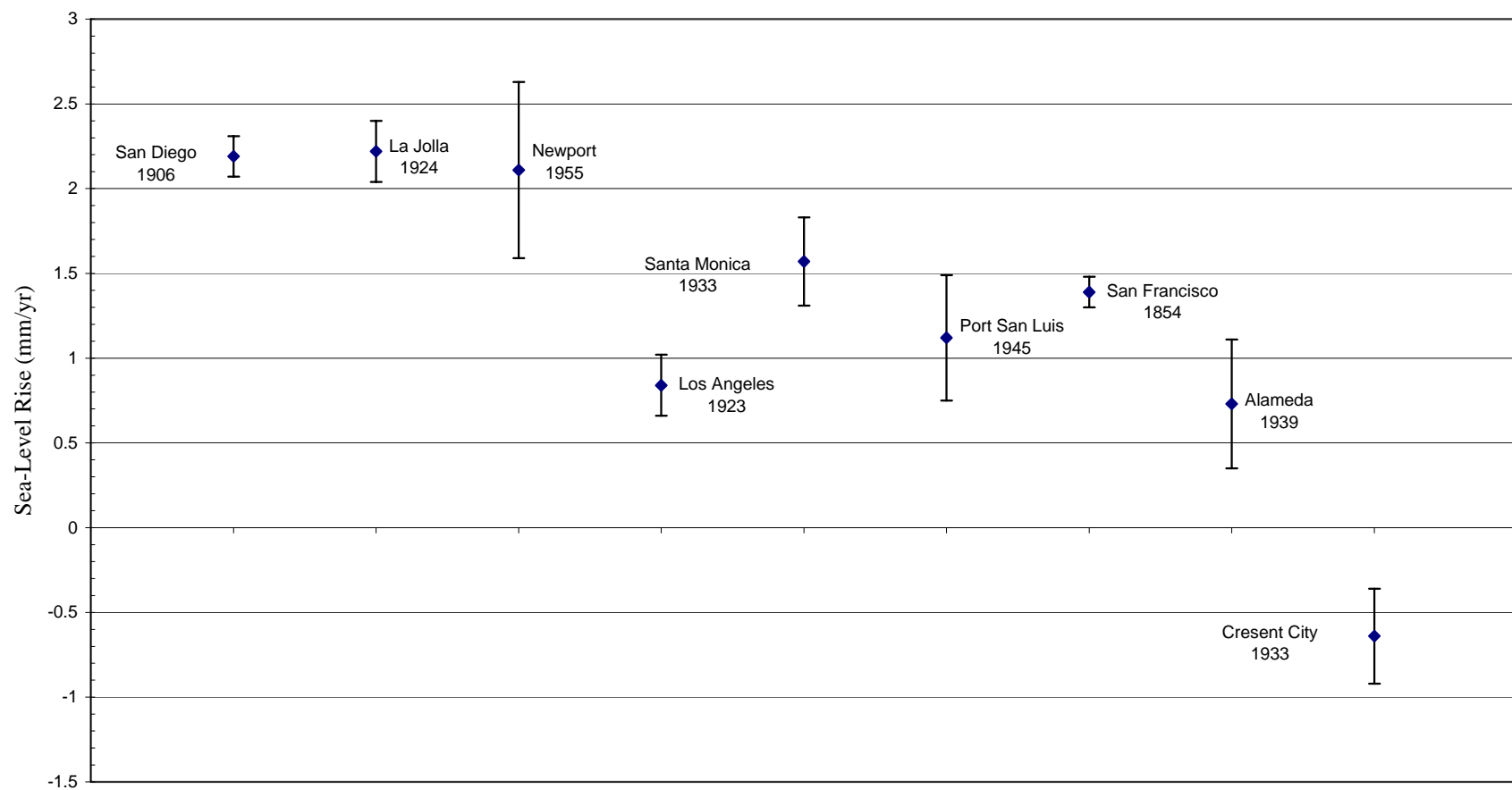


FIGURE 4
Relative Sea Level Trends for Selected Locations In California
From Date of Station Operation to 1993

Source: Calculated from NOAA's Oceanographic Products and Services Division Data; <http://www.opsd.nos.noaa.gov/seatmds.html>

STATION NAME	PSMSL ³		NOAA ⁴	
	Years	Trend & Error (mm/yr.)	Years ⁵	Trend & Error (mm/yr.)
CRESCENT CITY	1933 – 1997	-0.57 +/- 0.25	1933 - 1998	-0.64 +/- 0.28
N. SPIT, HUMBOLDT BAY	1985 - 1997	10.74 +/- 2.68		
POINT REYES	1975 - 1997	2.81 +/- 1.39		
SAN FRANCISCO	1855 - 1997	1.41 +/- 0.09	1854 – 1998	1.39 +/- 0.09
ALAMEDA N. AIR STA.	1940 - 1997	1.09 +/- 0.36	1939 – 1998	0.73 +/- 0.38
SAN MATEO	1985 - 1987	16.50 +/- 30.89		
MONTEREY	1974 - 1997	3.20 +/- 1.11		
PORT SAN LUIS	1946 - 1995	1.04 +/- 0.30	1945 – 1998	1.12 +/- 0.37
RINCON ISLAND	1962 - 1989	3.57 +/- 0.94		
SANTA MONICA PIER	1933 - 1997	1.69 +/- 0.24	1933 – 1998	1.57 +/- 0.26
LOS ANGELES	1924 - 1997	0.92 +/- 0.17	1923 - 1998	0.84 +/- 0.18
ALAMITOS BAY ENT.	1954 - 1965	8.12 +/- 2.85		
NEWPORT BAY	1956 - 1990	1.65 +/- 0.57		
LA JOLLA (SCRIPPS PIER)	1925 - 1997	2.27 +/- 0.17	1924 - 1998	2.22 +/- 0.18
SAN DIEGO	1906 - 1996	2.16 +/- 0.11	1906 - 1998	2.19 +/- 0.12

TABLE 1
TRENDS IN MEAN SEA LEVEL FOR VARIOUS CALIFORNIA TIDAL STATIONS

³ Permanent Service for Mean Sea Level

⁴ National Oceanic and Atmospheric Administration

⁵ Number of years with valid records. Some stations did not have continuous records for all years of operation and years with sporadic records were not used in computing the Mean Sea Level trend.

Station Name Number	Start End	MSL			HHW-MLLW			HHW-RLW		
		Ft/100y	Yrs	Trend	Ft/100y	Yrs	Trend	Ft/100y	Yrs	Trend
CALIFORNIA STATIONS										
San Diego, San Diego Bay (9400170)	1926 1999	0.758	71	Up	-0.144	71	Down	-0.105	71	Down
La Jolla, Pacific (9400230)	1934 1999	0.750	69	Up	0.122	69	Up	0.153	69	Up
Los Angeles, Outer Harbor (9400660)	1923 1999	0.299	75	Up	0.083	75	Up	0.113	75	Up
Santa Monica, Pacific (9400840)	1933 1999	0.529	55	Up	0.032	54	--	0.085	54	Up
Port San Luis, Pacific (9402110)	1972 1999	0.843	27	Up	-0.213	27	Down	-0.262	27	Down
Monterey, Monterey Harbor (9403450)	1973 1999	0.990	25	Up	-0.632	25	Down	-0.499	25	Down
San Francisco Bay (9404290)	1855 1999	0.475	133	Up	0.189	81	Up	0.192	81	Up
Alameda, San Francisco Bay (9404750)	1939 1999	0.365	48	Up	0.447	48	Up	0.410	48	Up
Point Reyes, Drakes Bay (9405030)	1975 1999	1.329	24	Up	-0.433	24	Down	-0.460	24	Down
Fort Chicago, Suisun Bay (9405140)	1976 1999	2.384	22	Up	1.157	22	Up	0.945	22	Up
Crescent City, Pacific (9409750)	1933 1999	-0.163	59	Down	-0.040	59	--	-0.058	59	Down

TABLE 2
TRENDS ON MEAN SEA LEVEL AND TIDE RANGE

Source: Flick, Murray and Ewing, 1999

is a concern, the projects should examine higher high water and extreme high water, rather than mean sea level. Mean sea level is not the only, or maybe even the correct, water level statistic for coastal engineers and planners to consider.

Future trends in sea level rise

Future trends in all the tidal components will depend on a number of factors – all of which have their own uncertainties. Despite the significance of individual tidal components to the daily changes to the coast and to the function of coastal systems, all existing projections of future sea level address mean sea level as the only component. In most situations, changes in mean sea level will provide a good first order approximation for changes in the other tidal constituents. Furthermore, the range provided in most projections can cover the variation in the individual constituents.

State-of-the-art climate models are predicting that global temperature may rise by 2 to 9° F (1 to 5°C) over the next 100 years (Field et al., 1999). There is a large uncertainty in these estimates of future temperature change and even greater uncertainty about the sea level response to this warming. Over the past century, global temperature has increased about 1° F (0.6° C) and mean sea level has risen by 0.5 to 0.6 ft (15 to 18 cm) globally (IPCC, 1996 and NOAA Tidal Records). There is strong certainty that a future rise in global temperature of 2 to 9° F (1 to 5°C) will be accompanied by a rise in sea level. There is uncertainty as to the rate and amount of rise that could occur by any specific time in the future. Future sea level will depend, among other factors, upon:

- Future global temperature
- Lag time between atmospheric changes and oceanic reactions
- Thermal expansion of ocean water
- Effects of atmospheric temperature changes on Antarctica, Greenland and other glaciers
- Local subsidence and uplift

One method for viewing future sea level rise has been through the development of scenarios – of a high rate of sea level rise, a medium rate and a low rate. Figure 4 shows one set of scenarios for future changes in global sea level. These scenarios have been used by the Environmental Protection Agency, the International Panel on Climate Change and many other groups to provide a range of consequences that can be anticipated from various future increases in sea level.

A second method for viewing future sea level rise is to develop probability-based estimates. Table 3 provides some estimates of sea level rise for various California locations and provides a probability that this level will be met or exceeded at certain times. These values were developed from an Environmental Protection Agency methodology that merges together historic local changes in sea level with projected future changes (Titus and Narayanan, 1995). As both figures show, it is very likely that, by 2050, much of the California coast will experience coastal water levels that are 1 foot (0.3 meters) higher than they are currently. By 2100, it is very likely that water levels will be 3 feet (0.9 meters) higher than they are currently. Such a rise in sea level can have profound effects on the coast.

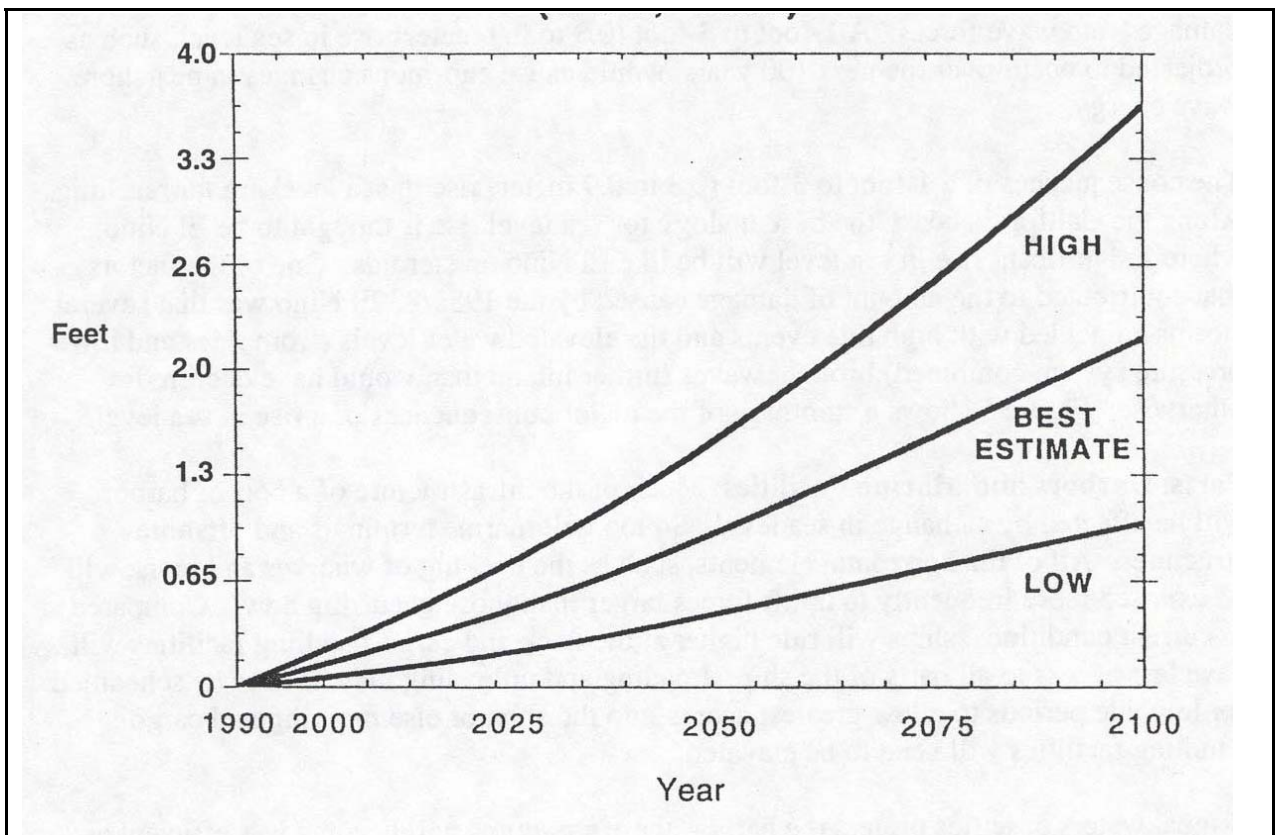


FIGURE 4
Global Sea Level Rise 'Business-As-Usual' Scenario

Source: IPCC, 1990

Potential consequences of sea level rise

The most obvious consequence of a large rise in sea level will be changes in areas that are submerged. Lands that now are only wet at high tide could be wet most of the day. Structures that are built above the water, like docks and piers, will be closer to the water, or eventually submerged. A second consequence will be an increase in wave energy. Wave energy is a factor of wave height. Wave heights along the California coast are influenced greatly by bottom depths and for most locations along the coast, the heights of nearshore waves are “depth limited”. When the water depth increases, the wave height can be higher. Thus, higher waves impact the coast during high tide than during low tide. Wave energy increases with the square of the wave height. Thus, a 2-foot (0.6-meter) wave would have 4 times the energy of a 1-foot (0.3-meter) wave. Small changes in water level can cause significant changes in wave energy and the potential for shoreline damage from wave forces. A 1-foot to 3-foot (0.3 to 0.9 meter) rise in sea level, such as projected to occur over the next 100 years, would cause enormous changes in nearshore wave energy.

The consequences of a 1-foot to 3-foot (0.3 to 0.9 meter) rise in sea level are far reaching. Along the California coast, the best analogy for sea level rise is thought to be El Niño, where a significant rise in sea level will be like El Niño on steroids. One of the factors that contributed to the amount of damage caused by the 1982/83 El Niño was that several storms coincided with high tide events and the elevated water levels (from tides and low pressure system combined) brought waves further inland than would have occurred otherwise. Figure 5 shows a summary of the major consequences of a rise in sea level.

Ports, Harbors and Marine Facilities: Much of the infrastructure of a port or harbor will be affected by a change in sea level. So too will marine terminals and offshore structures. All of the horizontal elements, such as the decking of wharves and piers, will be exposed more frequently to uplift forces larger than those occurring now. Compared to current conditions, ships will ride higher at the dock and cargo-handling facilities will have less access to all parts of the ship. Loading and unloading may have to be scheduled for low tide periods to allow greatest access into the ship, or else mooring and cargo handling facilities will need to be elevated.

If breakwaters or jetties protect the harbor, these structures will become less efficient as water levels increase. The breakwaters and jetties will need to be enlarged and heightened to keep up with the rise in sea level, or the harbor will have to accept a higher level of overtopping and storm surge, and a higher probability of storm damage. The increase in water level could also increase the tidal prism of the harbor, resulting in increased scour at the foundations of any structures in the harbor. So, it may also be necessary to reinforce the base of the breakwater or jetty to insure stability. Benefits that could occur from a rise in sea level would be the opportunity for harbors to accommodate deeper draught ships and a decrease in dredging to maintain necessary channel depths.

LOCATION	cm Rise by 2025 (Probability)		cm Rise by 2050 (Probability)		cm Rise by 2100 (Probability)	
San Diego	7.4 (90%)	3.0"	12.6 (90%)	5.0"	24.1 (90%)	9.5"
	12.4 (50%)	4.8"	22.6 (50%)	8.9"	49.1 (50%)	19.3"
	19.4 (10%)	7.6"	35.6 (10%)	14.0"	90.1 (10%)	35.5"
La Jolla	7.0 (90%)	2.8"	12.0 (90%)	4.7"	23.0 (90%)	9.0"
	12.0 (50%)	4.7"	22.0 (50%)	8.7"	48.0 (50%)	18.9"
	19.0 (10%)	7.5"	35.0 (10%)	13.7"	89.0 (10%)	35.0"
Newport	6.7 (90%)	2.6"	11.4 (90%)	4.5"	21.9 (90%)	8.6"
	11.7 (50%)	4.6"	21.4 (50%)	8.4"	46.9 (50%)	18.5"
	18.7 (10%)	7.4"	34.4 (10%)	13.5"	87.9 (10%)	34.6"
Los Angeles	2.8 (90%)	1.0"	4.8 (90%)	2.0"	9.8 (90%)	3.9"
	7.8 (50%)	3.0"	14.8 (50%)	5.8"	34.8 (50%)	13.7"
	14.8 (10%)	5.8"	27.8 (10%)	10.9"	75.8 (10%)	29.8"
Santa Monica	6.3 (90%)	2.5"	10.8 (90%)	4.3"	20.8 (90%)	8.1"
	11.3 (50%)	4.4"	20.8 (50%)	8.2"	45.8 (50%)	18.0"
	18.3 (10%)	7.3"	33.8 (10%)	13.3	86.8 (10%)	34.2"
San Francisco	4.6 (90%)	1.8"	7.8 (90%)	3.1"	15.3 (90%)	6.0"
	5.6 (50%)	2.2"	17.8 (50%)	7.0"	40.3 (50%)	15.9"
	16.6 (10%)	6.5"	30.8 (10%)	12.1"	81.3 (10%)	32.0"
Alameda	3.5 (90%)	1.4"	6.0 (90%)	2.4"	21.0 (90%)	8.3"
	8.5 (50%)	3.4"	16.0 (50%)	6.2"	46.0 (50%)	18.1"
	15.5 (10%)	6.1"	29.0 (90%)	11.4"	87.0 (10%)	34.3"
Crescent City	-2.1 (90%)	-0.8"	-3.6 (90%)	-1.4"	-5.6 (90%)	-2.2"
	2.9 (50%)	1.1"	6.4 (50%)	2.5"	19.4 (50%)	7.6"
	9.9 (10%)	3.9"	19.4 (10%)	7.6"	60.4 (10%)	23.8"

TABLE 3
Estimates of Sea Level Rise at Various California Locations, through the Year 2100⁶
(with Probability that Threshold will be met or exceeded)

⁶ Developed from EPA estimates of historic rates of sea level rise and estimated sea level rise, both provided in Titus and Narayanan (1995) "The Probability of Sea Level Rise (EPA 230-R-95-008).

FIGURE 5

Major Consequences of Sea Level Rise

Ports and Harbors

- Wharves can experience more uplift from waves -- increased storm damage
- Ships will higher than the docks -- cargo facilities will be less efficient
- Breakwaters and Jetties will have less freeboard – increased storm damage
- Channels will be deeper -- decreased need for dredging
- Tidal prism will increase -- greater scour of all foundations

Seawalls and Other Engineered Structures

- More regular exposure to wave energy -- increased storm damage
- Exposure to deeper water -- greater foundation scour

Groundwater

- Increased salt water intrusion to coastal aquifers

Wetlands

- More areas will be inundated
- Saltwater/freshwater interface & zone of brackish water will migrate inland
- Tidal prism will increase – potentially greater scour and removal of sediment
- Gains or losses in area will depend on:
 - Ability of wetland to migrate inland
 - Ability of wetland to migrate up, with greater trapping of sediment
 - Overall change in tidal range

Beaches

- More area will be inundated
- Rule of thumb is that 1' of rise will cause about a 50' to 100' beach loss

Coastal Bluffs

- More regular exposure to wave energy -- increased bluff retreat
- Exposure to deeper water -- greater scour and undercutting

Seawalls and other engineered shoreline protection: Figure 6 shows the possible effects to a seawall from a rise in sea level. The foundation would be exposed to greater scour and the main structure would be exposed to greater and more frequent wave forces. As with breakwaters and jetties, these structures will need to be reinforced to withstand these greater forces, or a lower level of protection will have to be accepted for the backshore property.

Wetlands: Coastal wetlands will be greatly modified by changes in sea level; however, the consequences will vary with the different wetland areas. Overall there will be greater areas of inundation. The change in the intertidal area will depend on local topography, the future change in tidal range, and the ability of the wetland to migrate both up and inland. Historically many wetlands have accommodated the rise in sea level by increasing the base elevation. Sediment collects in the roots and vegetative mass of the wetland and provides a substrate for new growth. If the rate of sediment entrapment equals the rate of sea level rise, the wetland will remain fairly constant. If the rate of sedimentation exceeds the rate of sea level rise, the wetland will convert to a wet meadow or other system with more supratidal vegetation. If the sediment rate is less than the rise in sea level, the wetland will become intertidal and subtidal habitat.

Wetland changes also will be affected by inland development. Historically, wetland areas migrated both upward and landward as they were inundated. If the inland area has a slope and soil composition that can support a wetland and is not already developed, then inland migration may be possible. If there is a steep bluff or some type of fixed development, such as a highway or bulkhead, inland of a wetland, inland migration will not be possible and the wetland area will diminish over time.

Another physical change to wetland in response to a rise in sea level is an increase in the tidal currents, with the potential for increased scour. Also, for estuarine systems there will be a shift in the location of the salt water-freshwater interface, and an inland movement of the zone of brackish water. Figure 7 shows some of the possible changes to a wetland when landward migration is not possible.

Various climate change models have attempted to examine changes in run-off and sedimentation from global warming. Two global circulation models predict both increases in the number of storm events entering the US from the Pacific and an increase in run-off state-wide. There is considerable uncertainty about the effects to hydrological cycles, particularly on the regional level. Over the next 25 to 35 years, average annual run-off is expected to increase in California by about 25%; by the end of the century, it is expected to increase by over 100%. (Wolock and McCabe, 1999; cited in Boesch, et al., 2000) These increases could increase vertical stratification in the water column and could affect circulation in estuaries, lagoons and nearshore coastal areas. Increased run-off could also increase transport of nutrients, suspended sediments and bedload to the coast. Since inland dams and reservoirs limit many sediment supplies in California, the effects from increased run-off and sediment loadings will vary significantly, based on individual watershed characteristics.

Beaches and Coastal Bluffs: Open coastal landforms like beaches and bluffs will be exposed to greater and more frequent wave attack. There will more potential for erosion and shoreline retreat. For gently sloping beaches, the general rule of thumb is that 50 to

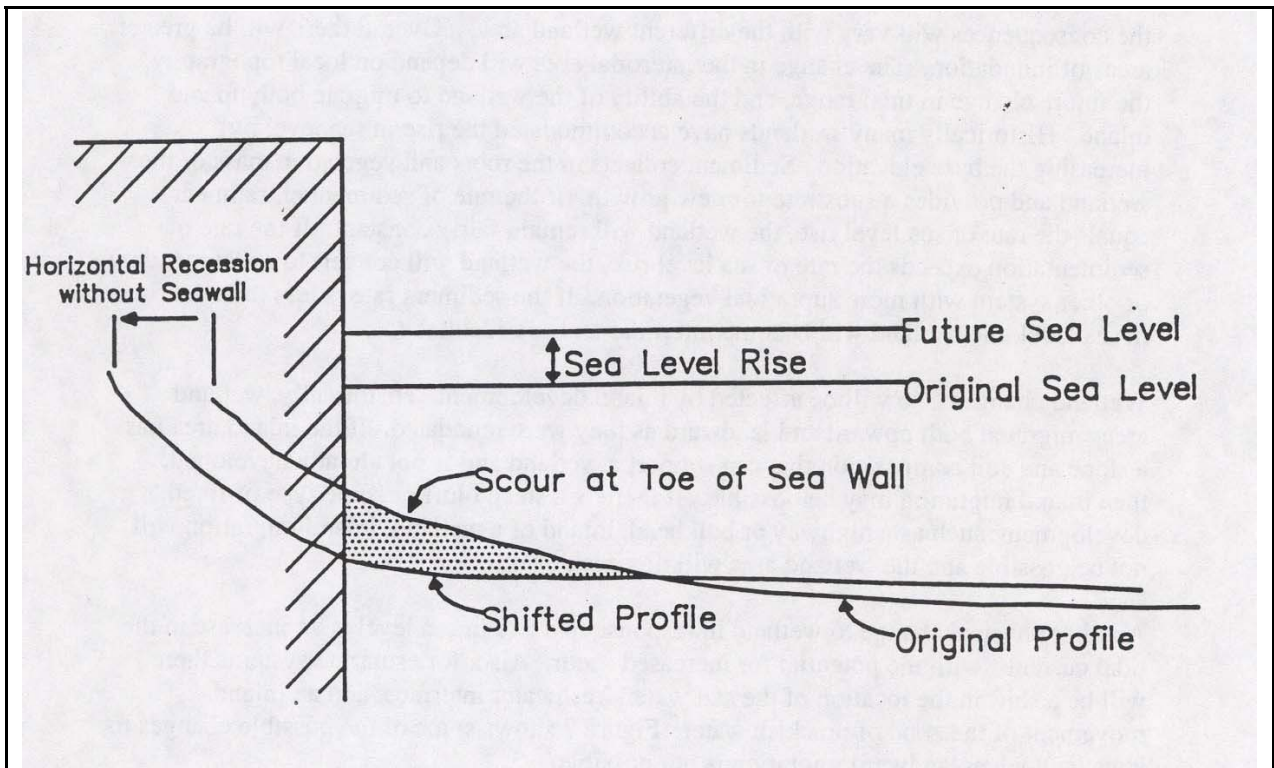
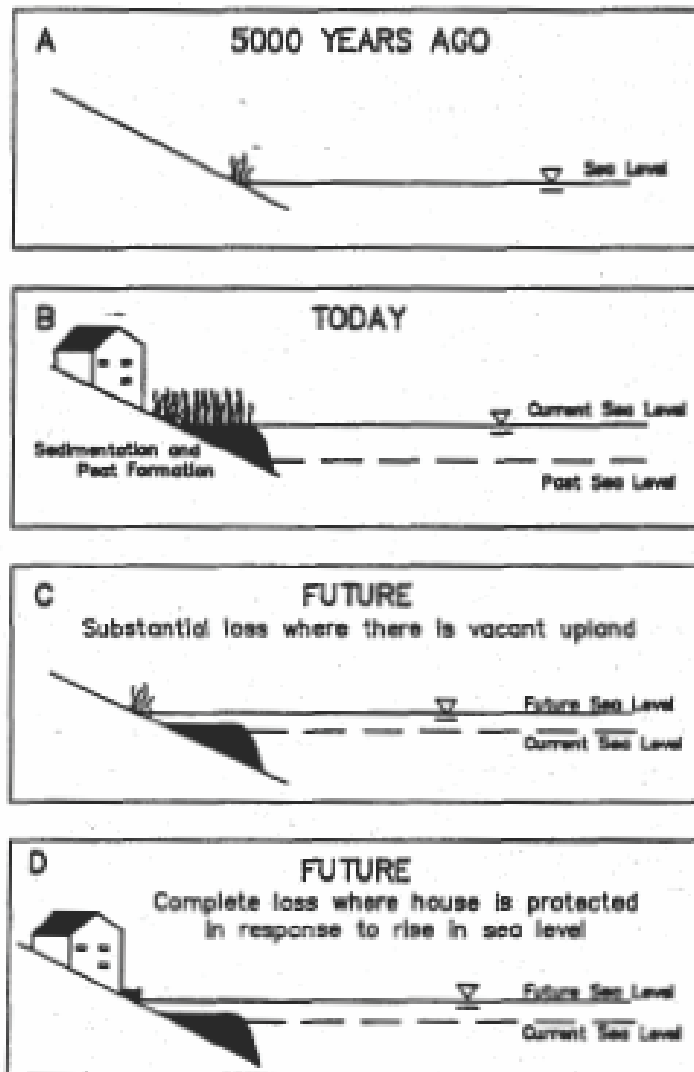


FIGURE 6
Scour at Seawall Toe

Source: Dean and Maurmeyer, 1983



Coastal marshes have kept pace with the slow sea level rise characterizing the last several thousand years. The wetland areas expanded as more lands were inundated (A and B). If future sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of seawalls may prevent new marsh area from forming and result in a total loss of marsh in some areas (D).

FIGURE 7
MARSH EVOLUTION AS SEA LEVEL RISES

SOURCE: Titus, 1988

100 feet of beach width will be lost from use for every foot of sea level rise. Figure 8 shows some of these changes.

Some global circulation models predict significant increases in run-off from coastal watersheds in California. (Wolock and McCabe, 1999; cited in Boesch, et al., 2000) Along sections of the coast where sediment supplies are not restricted by dams or reservoirs, these increases in run-off could increase supplies of sediment to the coast. The amount of increase in sediment supply would not necessarily correlate with the percent increase in run-off; the quantitative changes to sediment supply cannot be determined at this time. Additional studies at the watershed level would be necessary to provide even a general estimate of how sediment supply could change for possible changes in run-off.

Overall Severity and Economic Effect: As of 1999, over 25 million people lived in the coastal counties of California. By 2025, the coastal population is expected to grow by 27%, to over 32 million people (NPA, cited in Boesch, et al., 2000). Over the same time period, coastal counties are expected to have a 20 to 60% increase in economic growth, except for San Diego which is expected to have a 60 to 90 % growth (ibid.). California's ocean-dependent industries contributed \$17.3 billion to the state economy in 1992, including both direct and indirect effects (California Research Bureau, in Resources Agency, 1997). An increase in sea level rise will affect many of these activities and many of the effects will be adverse. Figures 9 and 10 indicate those areas of the coast where a long-term rise in sea level rise would be most severe and the areas that would experience the greatest economic losses. The economic losses also are relative and are based on the current patterns in land use and development of coastal lands. Overall, the effect on the coast is perhaps best shown by Figure 11. The coast is at the intersection of increased development pressure, water elevation, wave energy and coastal erosion.

Responses to Sea Level Rise

Responses to a rise in sea level will vary. The actions that can be taken in response to sea level rise include hard engineering (such as seawalls, revetments, breakwaters, levees and other structures built to protect inland areas), soft engineering (such as beach nourishment or vegetated buffers), accommodation/adaptation, and retreat. There may be appropriate times for each response to be considered. However some responses, such as soft engineering or retreat, are often best applied on a large or multi-lot scale, while hard engineering often can be applied to individual properties, regardless of the actions taken on surrounding properties.

Due to the uncertainty associated with sea level change and the fact that this is but one of the factors that will affect the coast in the future, most of the experts who are developing sea level response scenarios are recommending that solutions be as flexible as possible. A second recommendation is for "no regret" solutions that will be beneficial for many reasons and not just to accommodate a single prediction of future sea level rise (Mageean, Constable, and Van Arsdol Jr., 1998).

Hard engineering has been the default response to many coastal hazards. Hard structures provide a barrier between ocean and the property that is being threatened. As sea level rises, it can be expected that many property owners and communities will consider hard

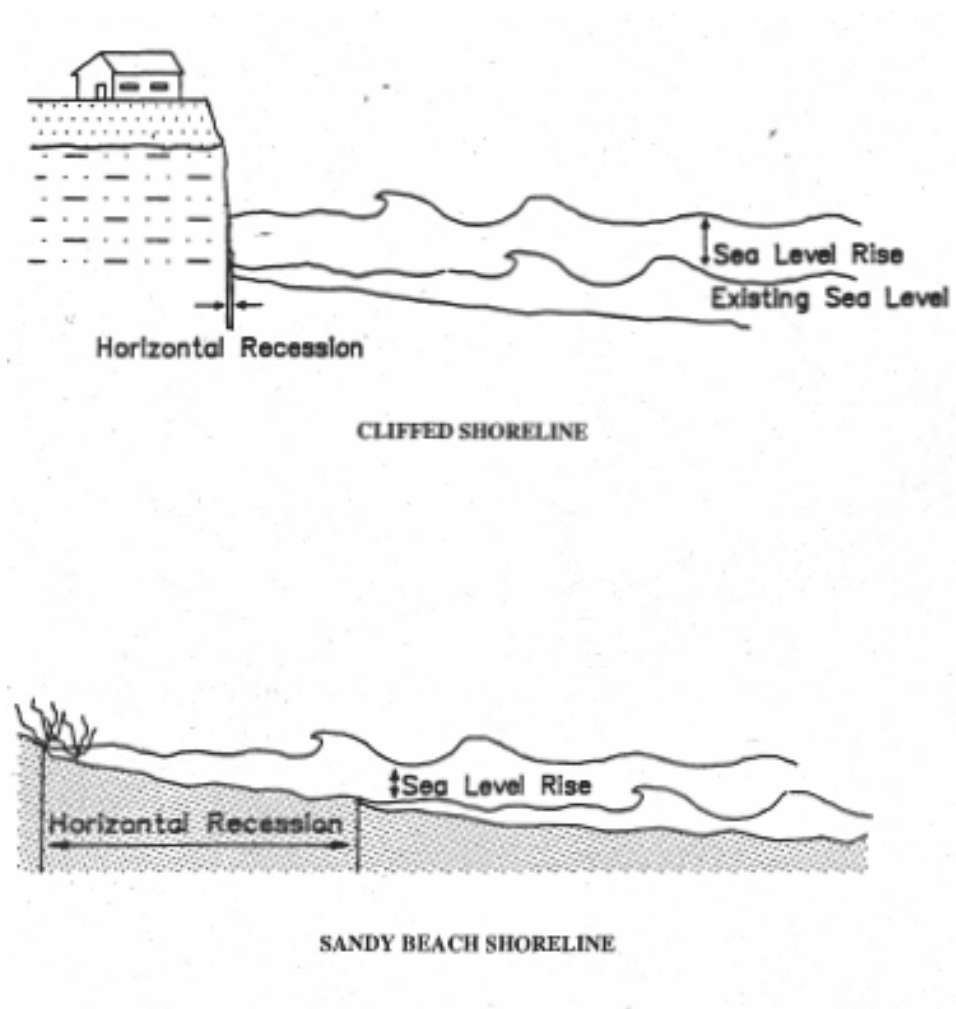
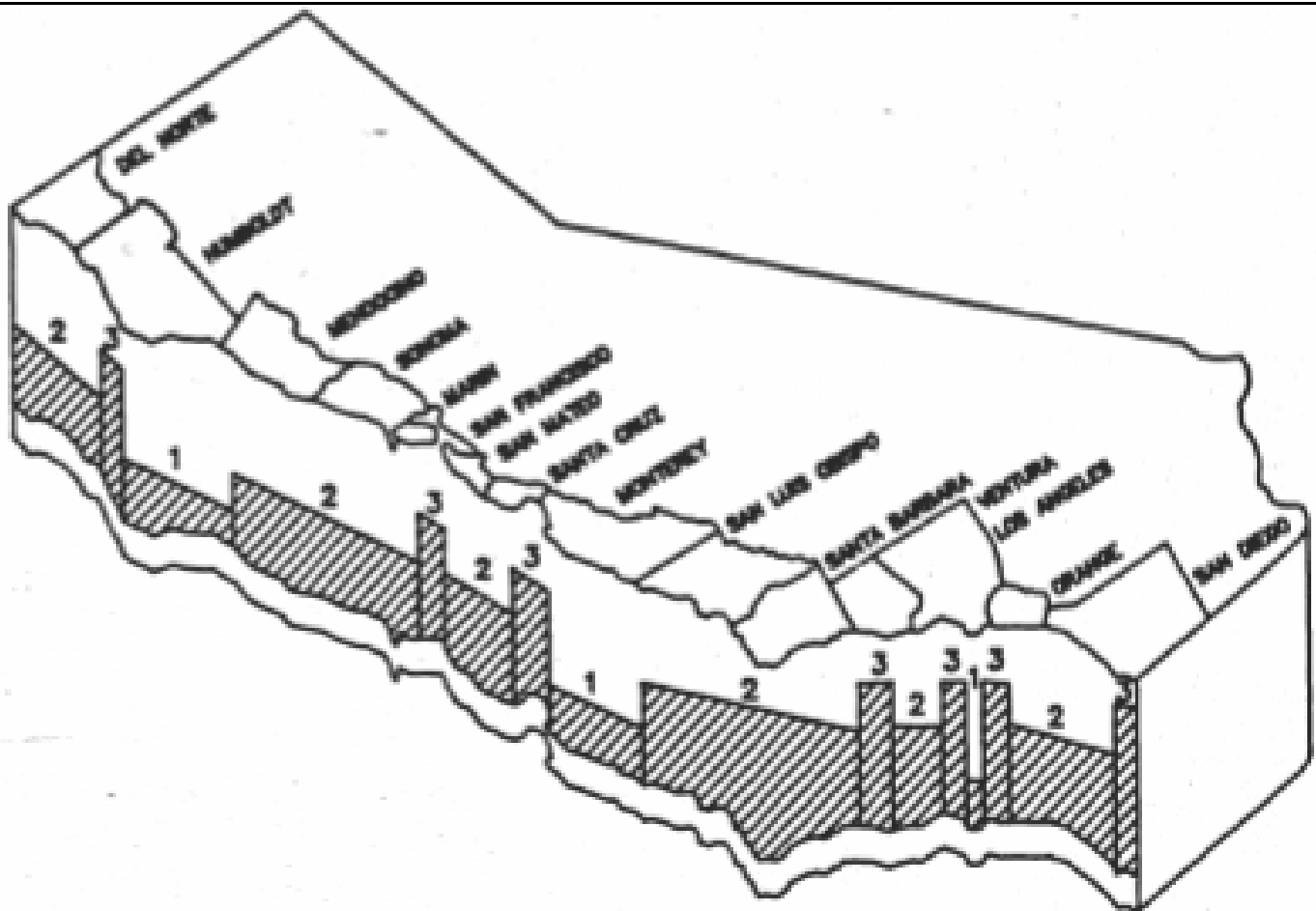


FIGURE 8
EXAMPLES OF DROWNED VALLEY COASTS



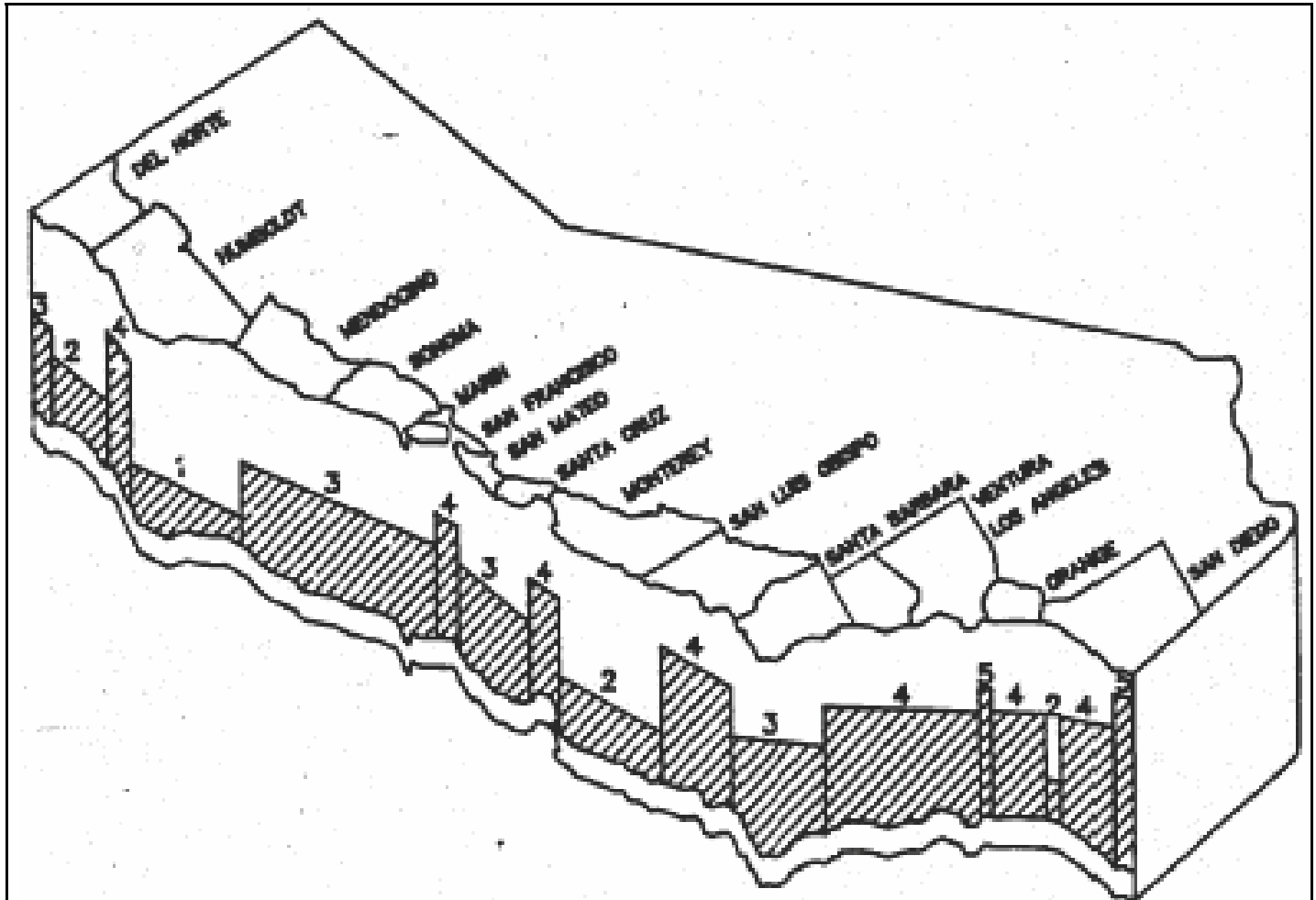
The relative severity of impact is an estimate of the extent of flooding, erosion and cliff retreat that is likely to occur from a 3-foot rise in sea level by the year 2100.

The greatest impact is expected to occur in low-lying areas that will be completely inundated, indicated as Impact Level 3.

Less impact is expected to occur at broad beaches or cliffs protected by talus, indicated by Impact Level 2.

The least impact is expected to occur at steep coastal cliffs comprised of resistant rock units, indicated as Impact Level 1.

FIGURE 9
RELATIVE SEVERITY OF IMPACT FROM
ACCELERATED SEA LEVEL RISE



Relative economic loss estimates the comparative extent of property damage that is likely to occur from a 3-foot rise in sea level by 2100. This assumes that no major shoreline protection projects are undertaken to counter the effects of sea level rise.

The greatest losses are expected to occur where extensive urban infrastructure has been located on or near a beach, coastal bluff or harbor, indicated as Impact Level 5.

The least impact is expected to occur where the coastline can migrate landward unimpeded by structures or development, indicated by Impact Level 1.

FIGURE 10
RELATIVE ECONOMIC LOSS FROM
ACCELERATED SEA LEVEL RISE

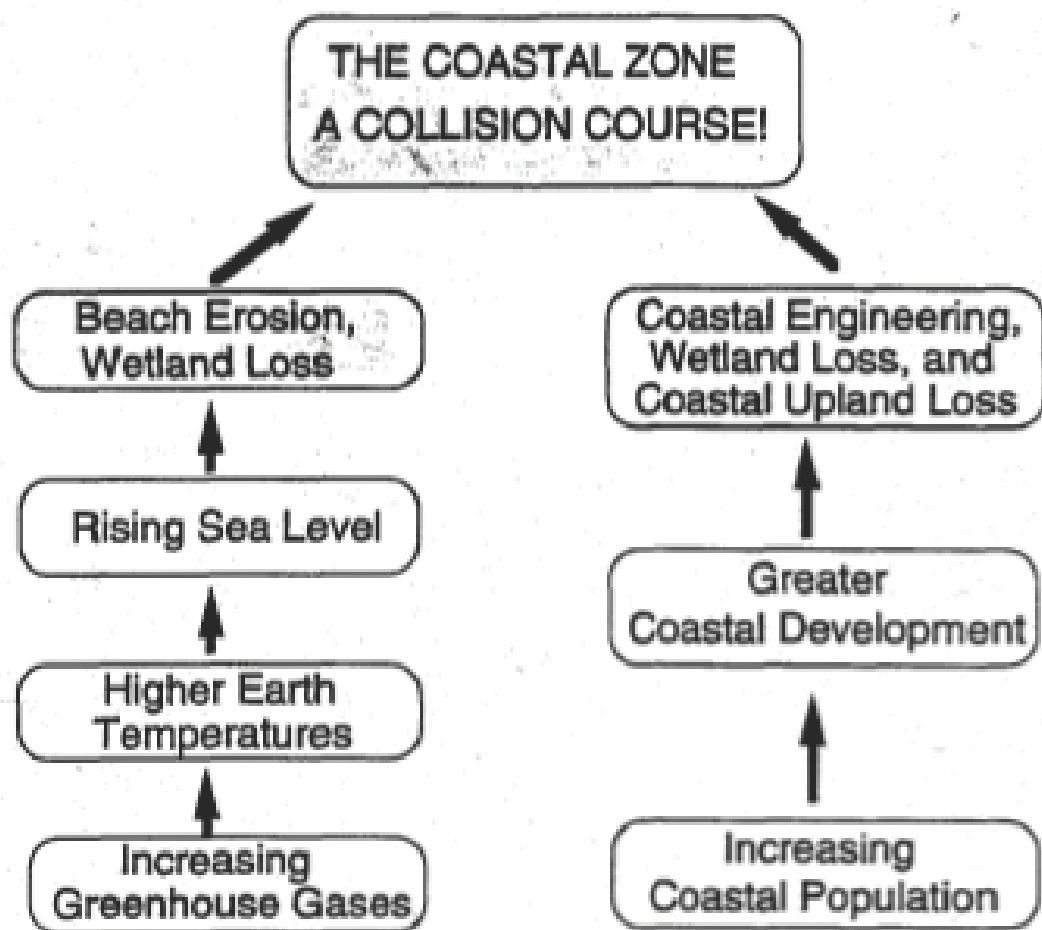


FIGURE 11
THE COASTAL ZONE ON A COLLISION COURSE

SOURCE: Leatherman, 1993

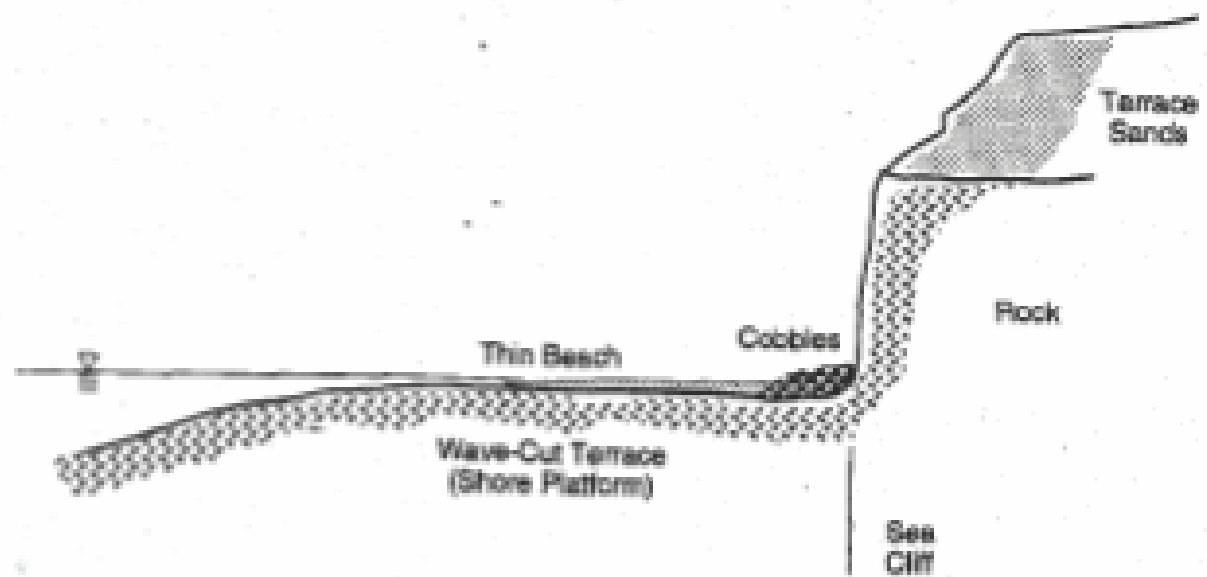
engineering as a response to future increases in sea level. Existing structures would be fortified to withstand new wave conditions. New seawalls, bulkheads, revetments, breakwaters and levees could be considered for those areas of the coast that are not now armored. This is consistent with the general response to erosion caused by each El Niño, where property owners have reinforced the armoring that already existed and introduced armoring in areas that had not yet been protected. When local subsidence decreased the effectiveness of the Redondo Breakwater, a new layer of armor rock was placed in it to bring it back to its former level of protection and efficiency. Thus, the hard engineering responses have been used historically to address changes in sea level or to potential damage from storms. In most situations, armoring can be designed to protect against future storm conditions. For large increases in sea level, the direct cost of this engineering will be enormous, possibly causing property owners to question the reasonableness of the continued investment in armoring.

Soft engineering is usually thought to be beach or dune nourishment or the creation of perched beaches. Over the short-term, beach nourishment will continue to be a very effective way to protect the backshore and at the same time provide access and a recreational beach. A single beach nourishment effort is not a permanent response; it must be maintained on a regular basis to remain effective. This can allow an opportunity for periodically reviewing the effectiveness of this response. Beach nourishment can provide some level of protection while keeping open other options. A perched beach, as shown in Figure 12, is an effective way to maintain access and a recreational beach. Natural beaches depend upon sand from a zone of active transport that extends offshore to water depths of about 35' below mean lower low water. A perched beach reduces the offshore dimension of the beach and can provide a cost-effective way to maintain the dry sand component of the beach without also building up the vast offshore portion.

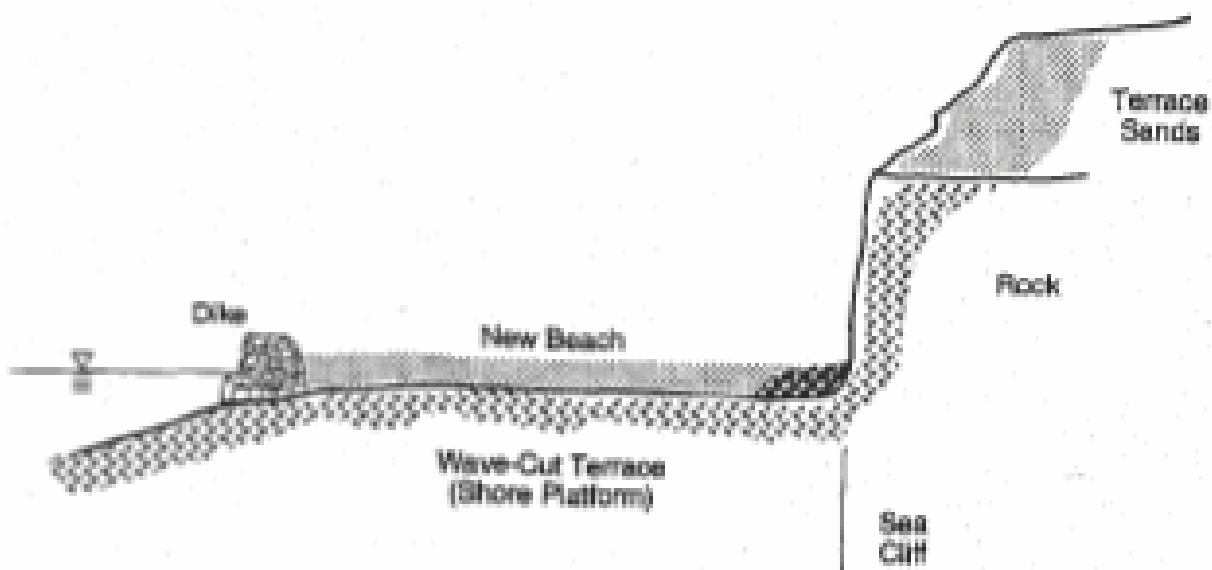
Both hard engineering and soft engineering options are ways to work against sea level rise. The hard engineering options will strengthen existing bluffs or structures so that they will be able to withstand the increased energy of a higher sea. The soft engineering responses will provide a buffer between the waves and the backshore and thus reduce the energy and damage that would occur at the backshore.

Accommodation/adaptation: Another approach is to accommodate or adapt to the changes. If structures are at risk, they can be raised so they will not be inundated. If agricultural lands are at risk, there may be options to switch to salt tolerant vegetation. Islands or spits could be elevated to keep pace with sea level rise. These approaches often require more “hands-on” involvement. Accommodative/adaptive responses are rarely one-time actions; to be most effective they require continued flexibility and modification to meet the ongoing conditions.

Retreat: A final response to a rise in sea level is retreat. Wetlands have demonstrated this historically as an effective response to sea level rise. Retreat has also been used in some situations to protect development or movable property. During the 1982/83 El Niño storms, a mobile home subdivision in Pacifica lost the seawardmost row of lots. The response was to pull the facilities landward and reduce the number of available sites. During the storms of 1997/98, a different part of Pacifica was attacked by waves and 10 homes were eventually removed from the blufftop. In southern Big Sur, portions of Pacific Coast Highway have been threatened by bluff retreat. Small amounts of revetment have been built to protect the most threatened portions, but the overall plan is to relocate several miles of the road to a safer, more inland location. Such examples of retreat may be more common in the future, as the threat from coastal erosion becomes more pervasive and the long-term costs of in-place protection increase.



EXISTING BEACH



**FIGURE 12
PERCHES BEACH**

Source: Flick, R.E. ed. 1994

Planning and Regulatory Responses for Sea Level Rise

There are a number of ways the California Coastal Commission currently addresses sea level rise in its planning and regulatory process. For new development, the Commission requires setbacks to assure site stability for foreseeable future conditions and review engineering designs. It also can establish wetland buffers to allow future inland or upland migration of wetlands. Various permits have notified current and future property owners that the conditions at a site may worsen with time and have applied a condition for assumption of risk and/or conditions that prohibit future seawalls. For example, for an oil development project in Hermosa Beach, the Commission required fluid re-injection to prevent subsidence, combined with a monitoring program to insure that the re-injection was effective.

On the planning side, the Commission has been involved with several state, regional or local studies of shoreline change that have improved overall understanding of the components that contribute to shoreline retreat and erosion. The 1999/2000 NOAA Coastal Fellowship Program in Opportunities for Beach Nourishment will help identify areas where beach nourishment can be most appropriate. The Commission has had a very strong public education program and this can be used to provide information on sea level rise, as well as other coastal hazards. Finally, the Commission can coordinate with the California Coastal Conservancy to promote acquisition of lands in high hazard areas.

States have not passed special regulations to address sea level rise. Most coastal states have coastal programs that address sea level rise in a manner that is similar to California's -- they modify or adapt current regulatory mechanisms to cover the effects of sea level rise. Texas has a rolling easement program that relocates the public land boundary to the current line of vegetation. Figure 13 is a pictorial variation of this effort and how it could apply to sea level rise. States like South and North Carolina and Massachusetts have prohibited the construction of any hard shoreline armoring. This limits the responses that can be used to address sea level rise to soft engineering, accommodation and retreat. Maine has regulations that prohibit rebuilding structures that have been damaged by storms if the new structure could reasonably be expected to be damaged within the next 100 years. This regulation covers damage from sea level rise or other coastal hazards.

Many coastal have research programs for studying coastal processes and identifying hazards associated with sea level rise. Oregon and Massachusetts have detailed coastal hazard mapping efforts that can provide information on a range of coastal hazards for specific coastal areas, or even individual parcels in some cases. Florida has a statewide shoreline monument program and the state performs regular, comparable beach surveys to obtain information on beach conditions and beach profiles. These research efforts provide current and historic shoreline information against which future shoreline change can be evaluated.

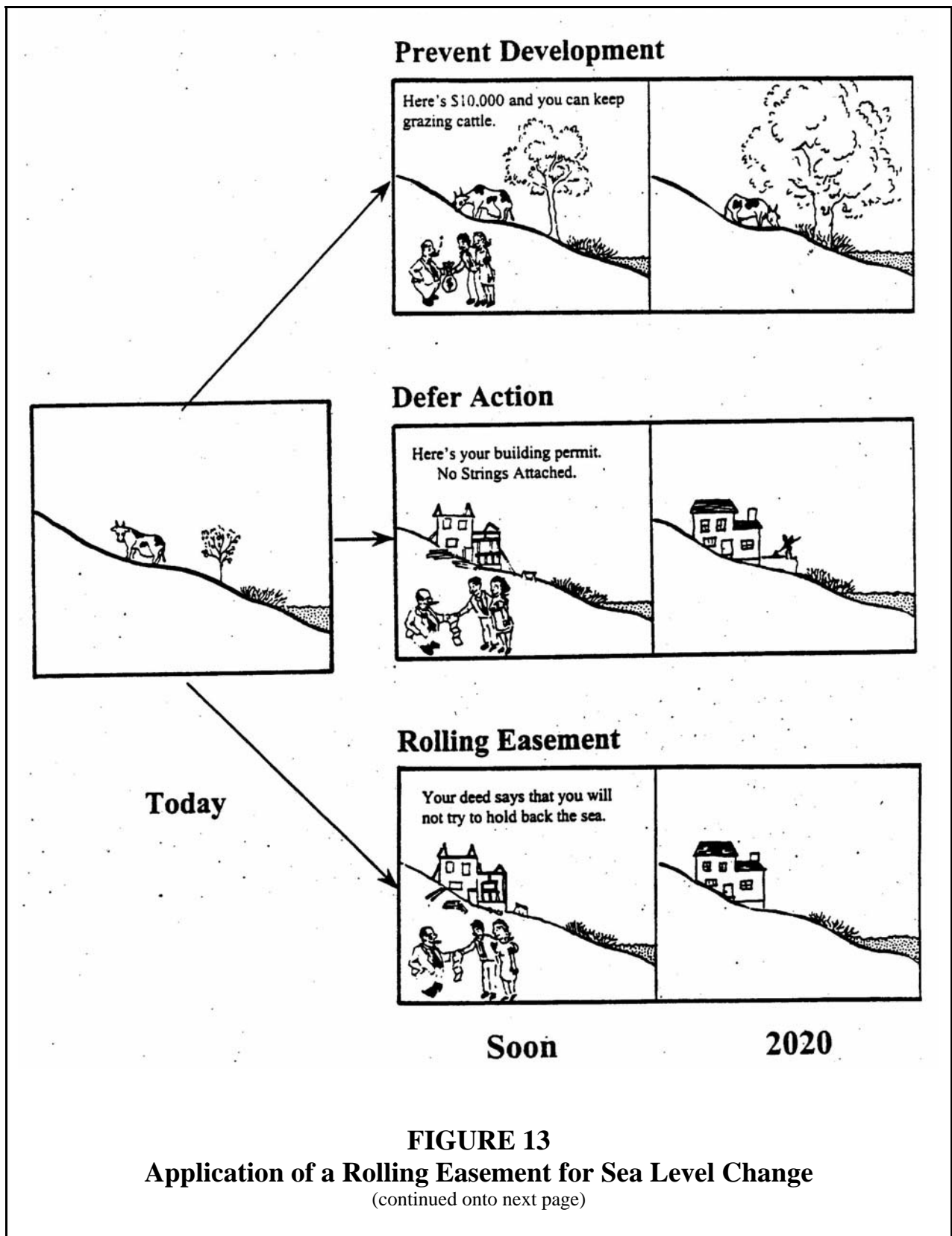


FIGURE 13
Application of a Rolling Easement for Sea Level Change
(continued onto next page)

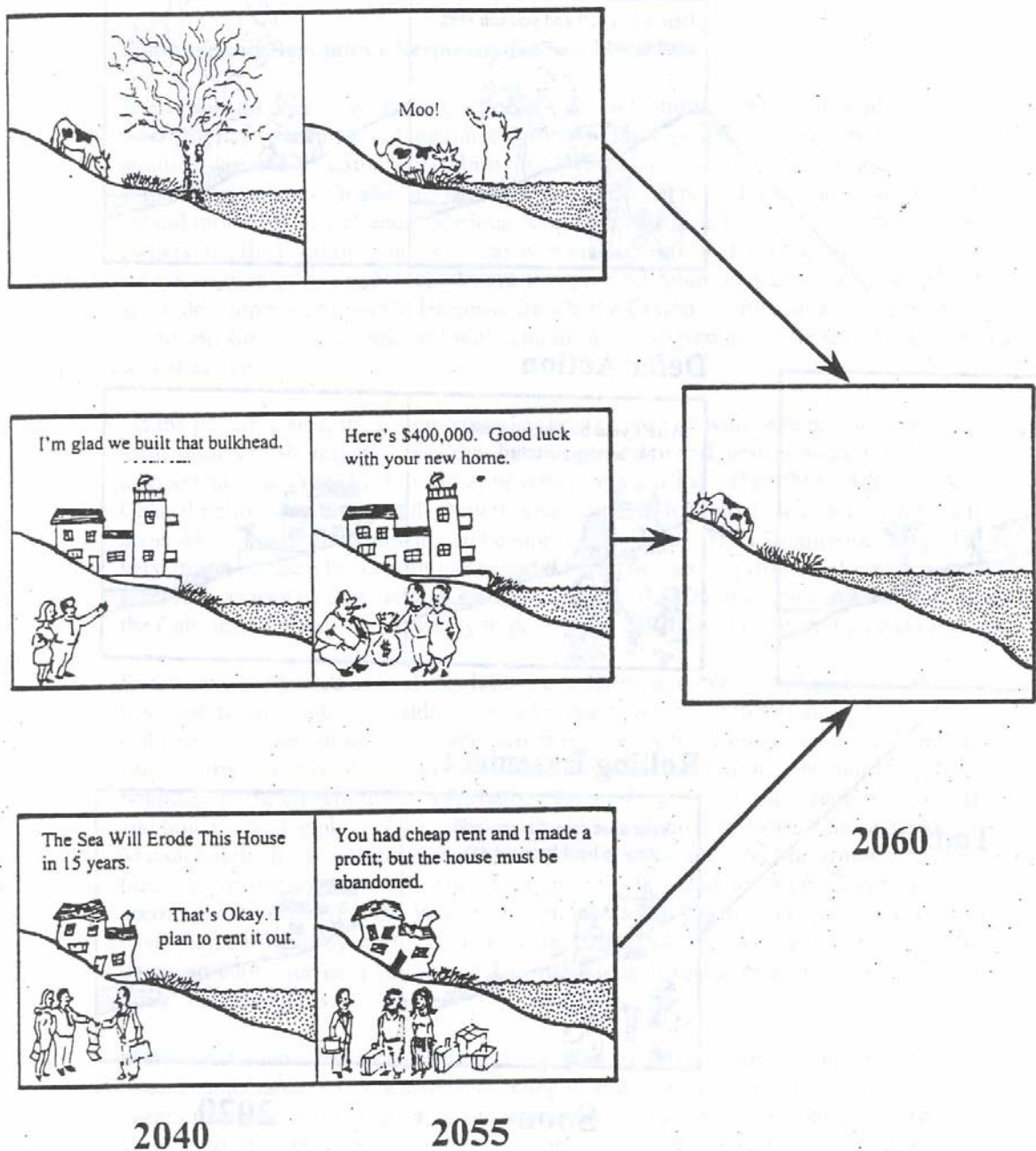


FIGURE 13 (Continued from Previous Page)
Application of Rolling Easement for Sea Level Change

Source: Titus, 1998

Conclusions

Global sea level has been rising since the end of the last ice age. The rate of rise has varied and for short periods of time, such as the Little Ice Age, sea level has even dropped. However, based on current climate models and projections of green house gas emissions, it is expected that future sea level will rise at a greater rate than it has over the past hundred years.

The continued rise in sea level will increase inundation of low coastal areas. Nearshore wave heights and wave energy will increase, increasing the potential for storm damage, beach erosion and bluff retreat. Ports and harbors will have reduced cargo transfer capability as ships ride higher along the dock. Wetlands may be inundated if they are not able to migrate either upward or landward. Almost all coastal systems will be affected; even groundwater aquifers will be a greater risk from saltwater intrusion.

Sea level rise is not a new phenomenon; it has been a major component of coastal change throughout time. While there are a number of possible responses to future changes in sea level, in many situations response flexibility will be important. Reliance on a single response for a certain water level may be useful while that water level occurs. But, as either the water level continues to rise or the coastal land subsides, the fixed response will become less efficient and be less appropriate to the new conditions.

In California, it is likely that a combination of hard engineering, soft engineering, accommodation/adaptation and retreat responses will be considered to address sea level rise. There are situations where each response may be appropriate and well suited. In all coastal projects, it is important to recognize and accept that there will be changes in sea level and in other coastal processes over time. Careful review, siting and permitting of new projects on the coast can increase the likelihood that these projects will be able to adapt and change to accommodate future coastal hazards. It will be important that the Commission continues to be involved in studies of the California coast, coastal hazards and changes in coastal processes. Public education programs and efforts to alert coastal property owners to the dynamic and changing natural of the coast will be important.

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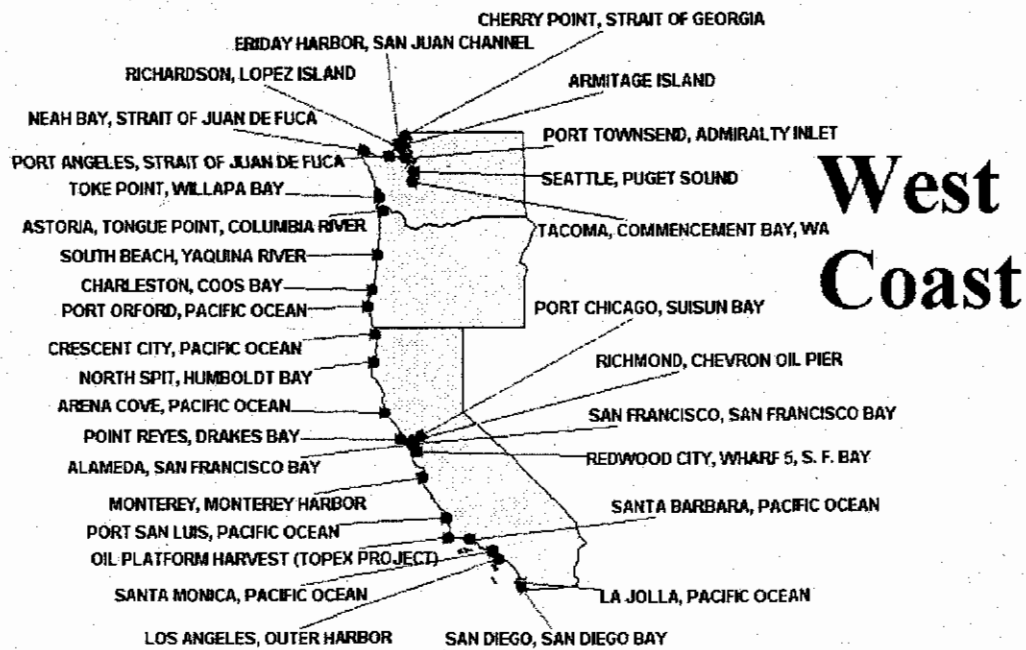
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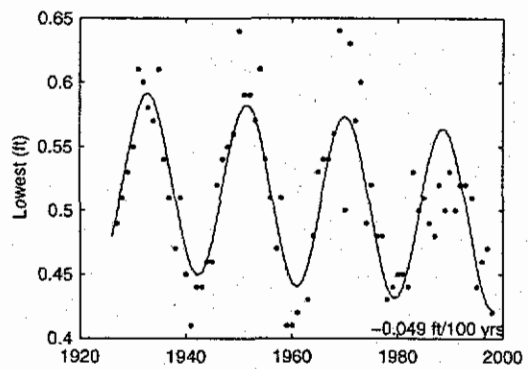
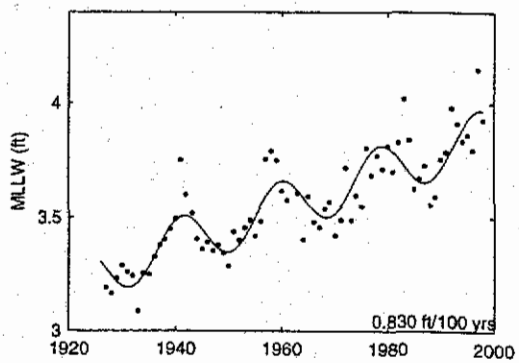
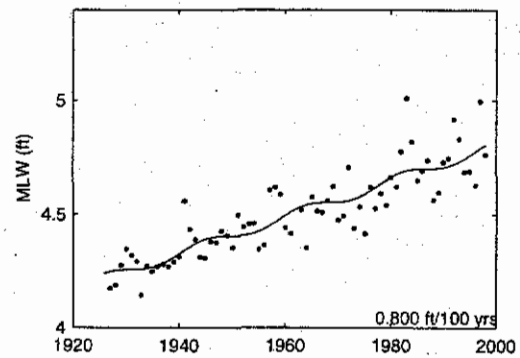
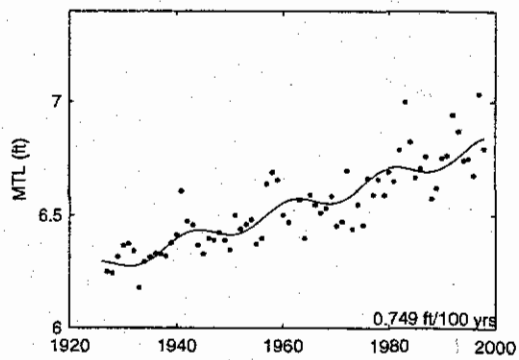
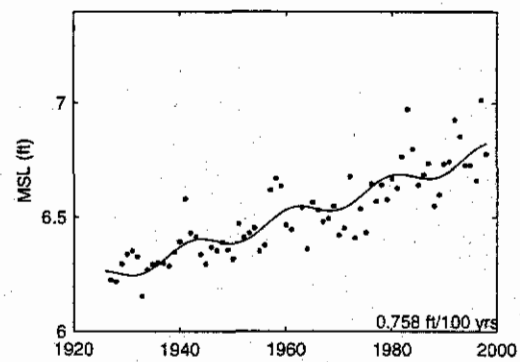
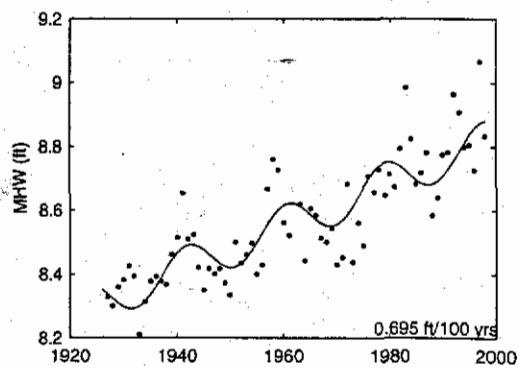
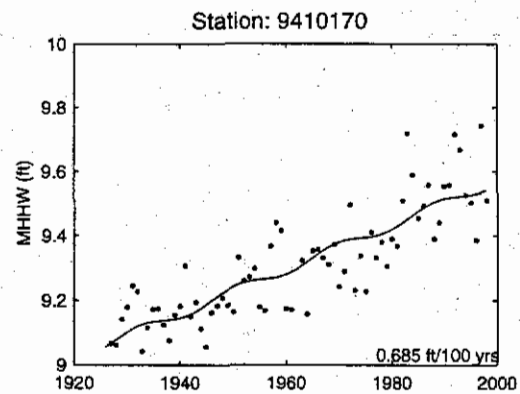
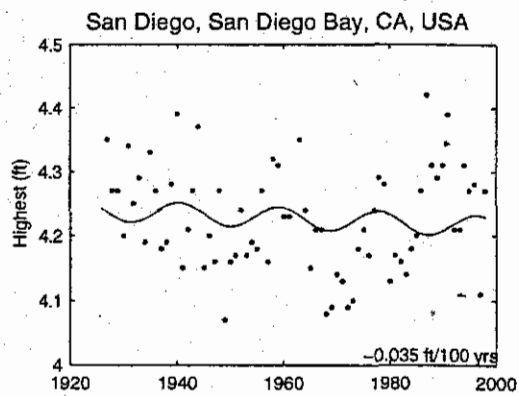
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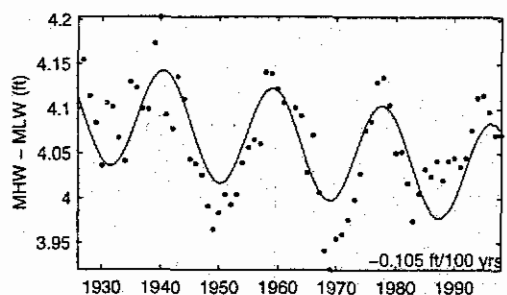
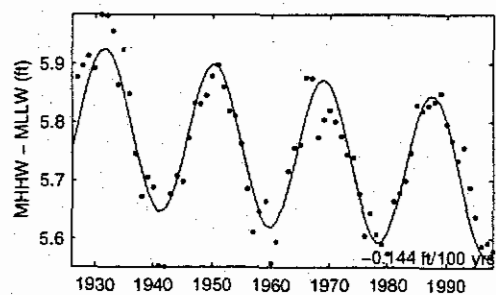
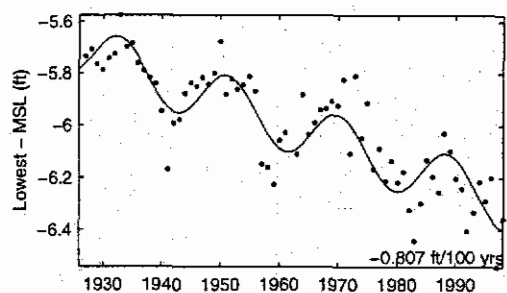
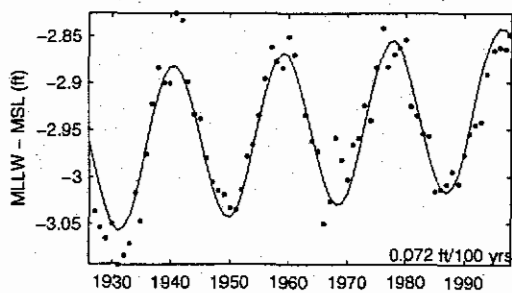
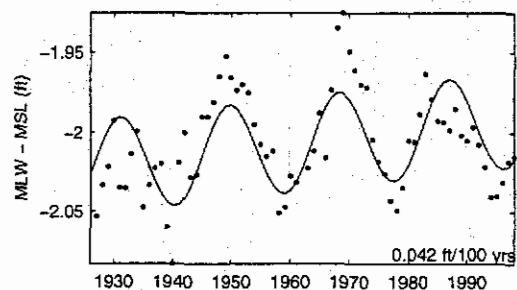
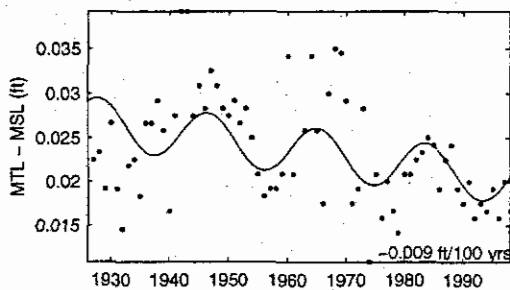
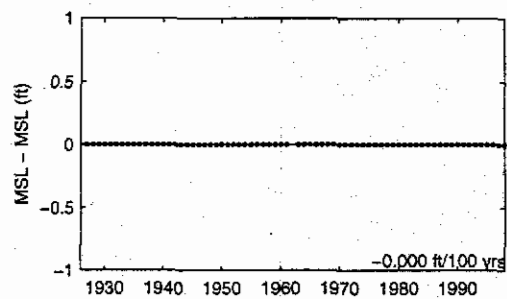
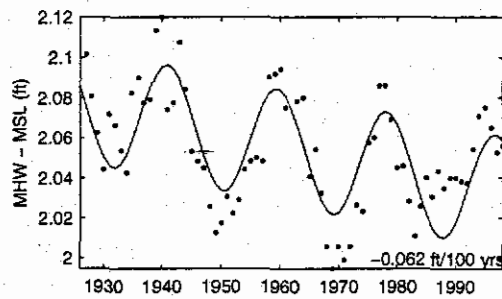
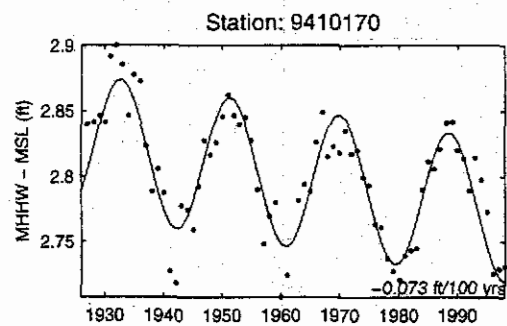
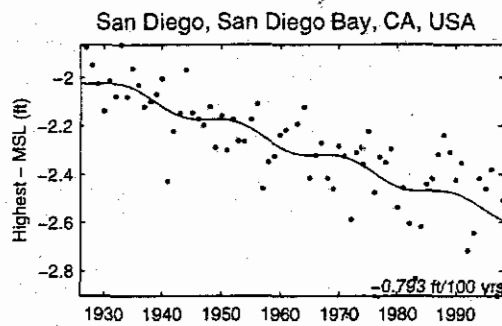
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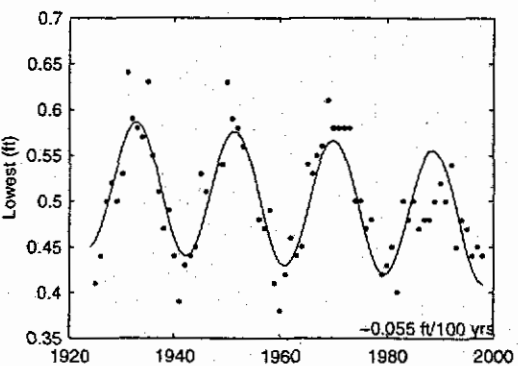
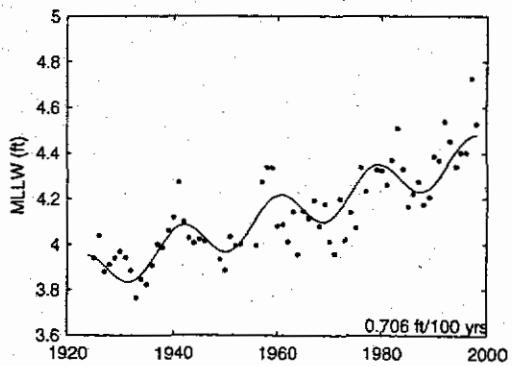
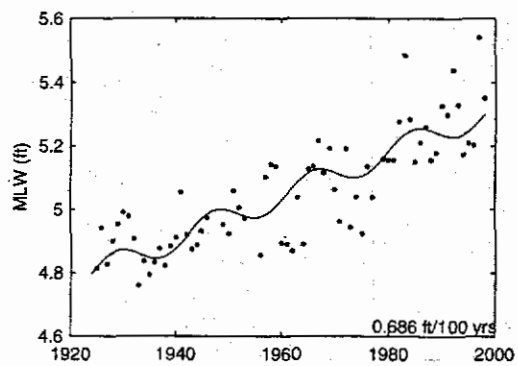
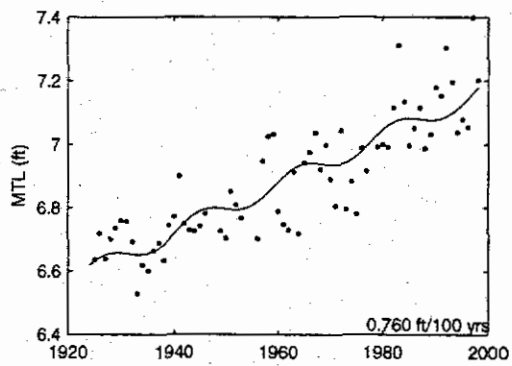
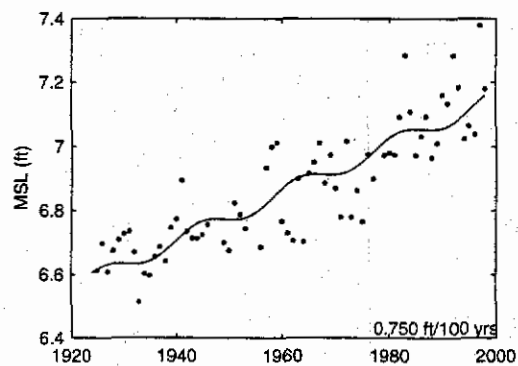
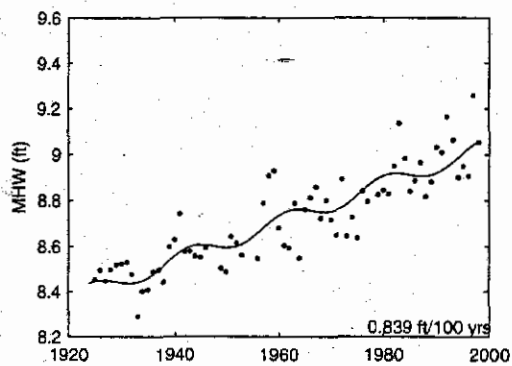
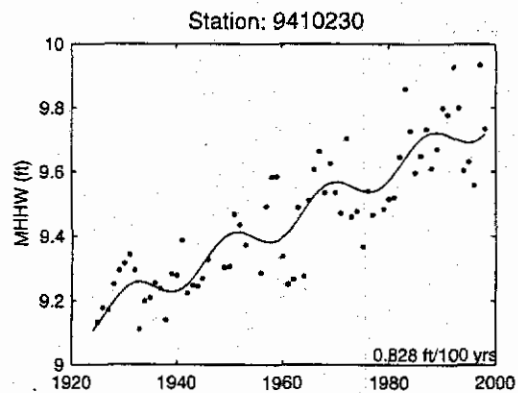
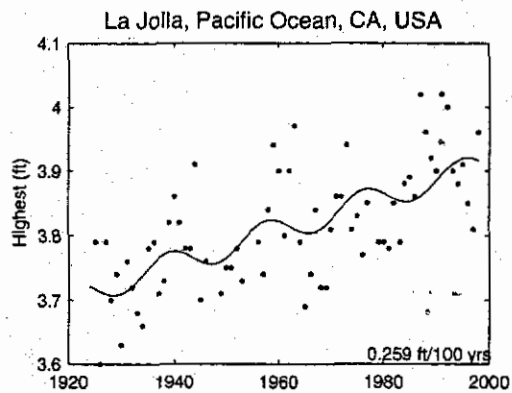
APPENDIX A TRENDS IN CALIFORNIA TIDAL DAUM STATISTICS AND TIDE RANGE



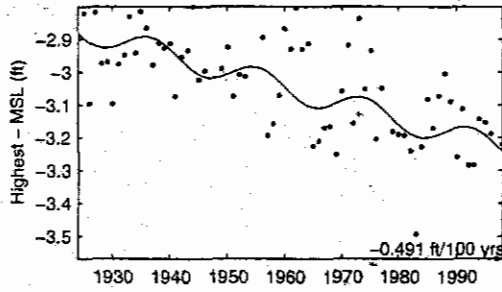
Source: Flick, Murray and Ewing, 1999



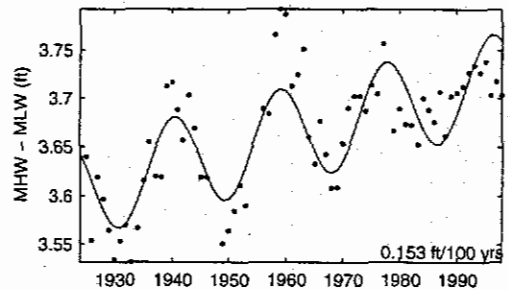
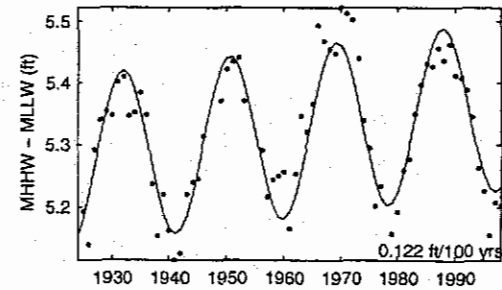
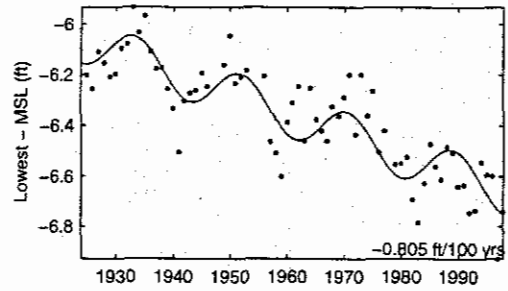
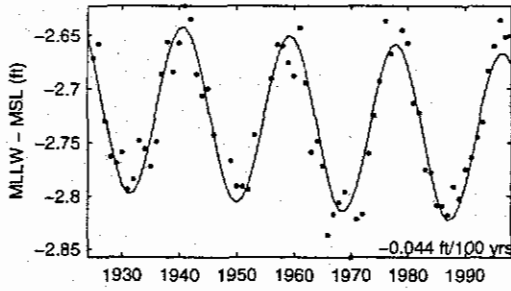
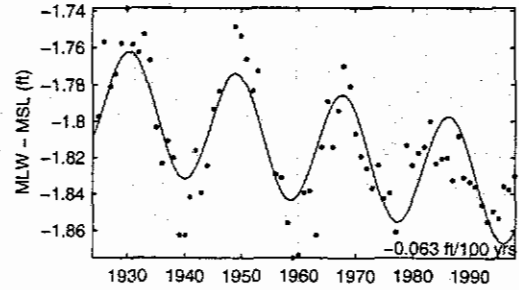
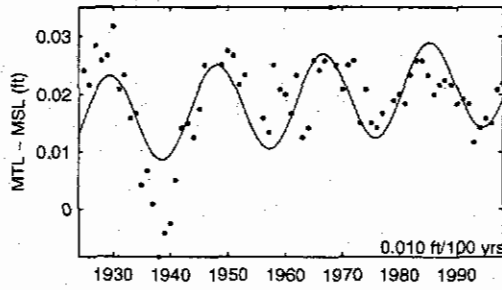
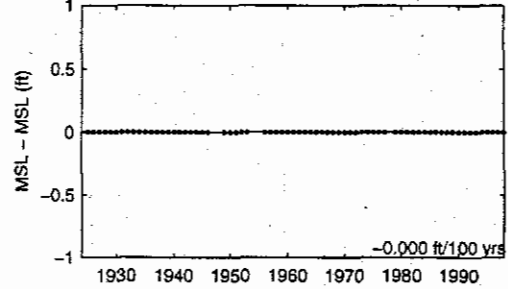
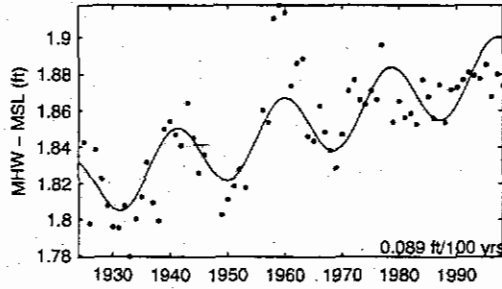
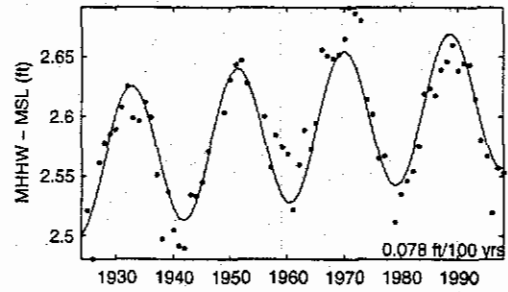


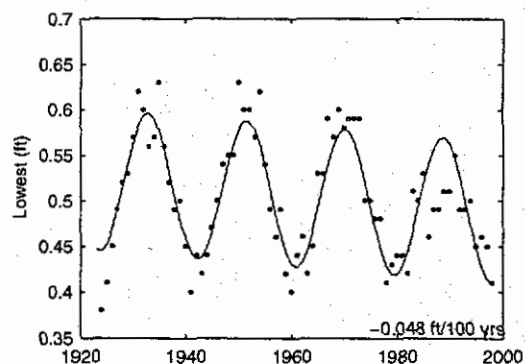
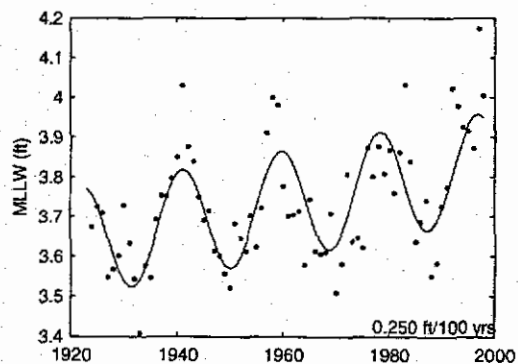
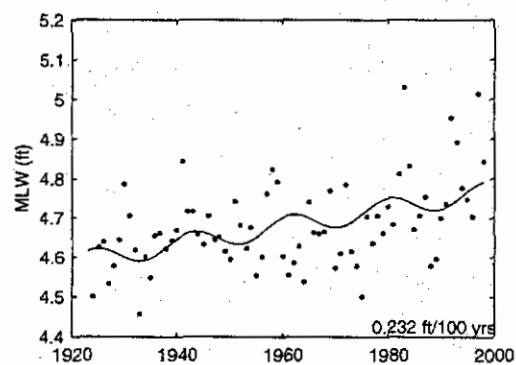
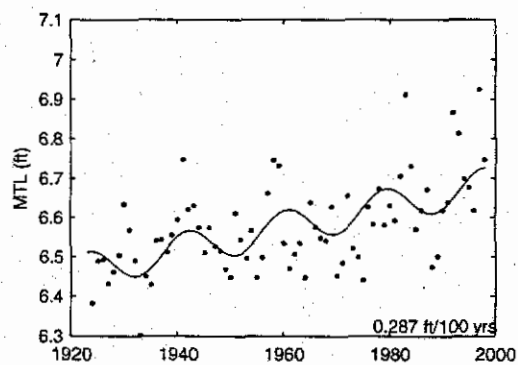
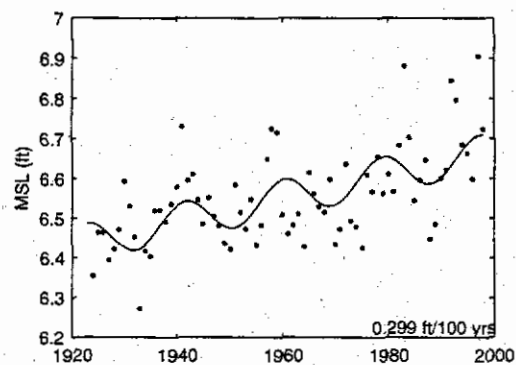
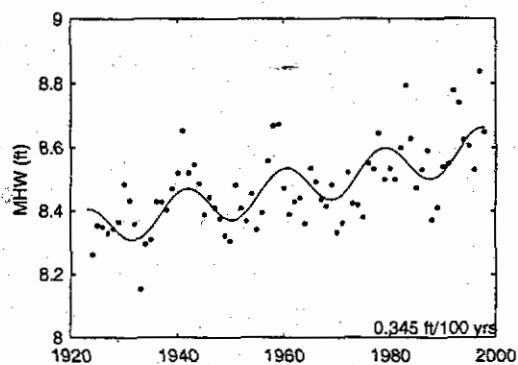
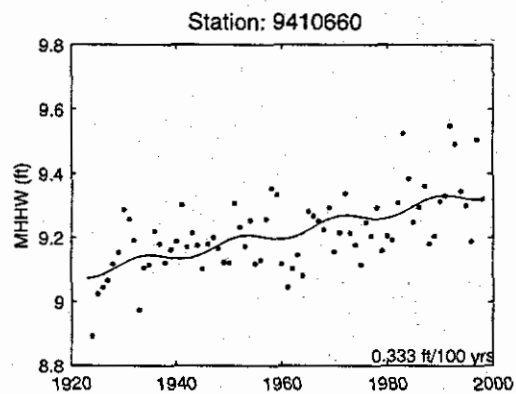
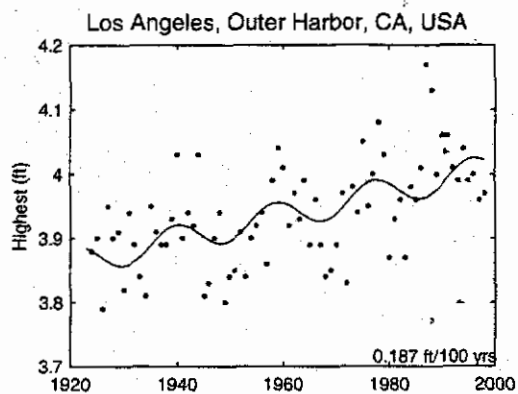


La Jolla, Pacific Ocean, CA, USA

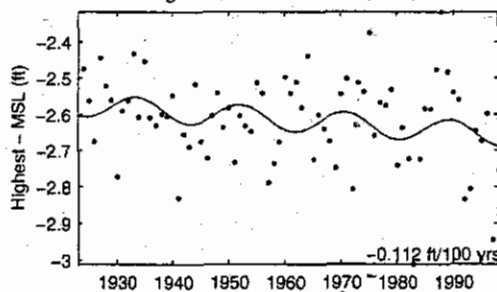


Station: 9410230

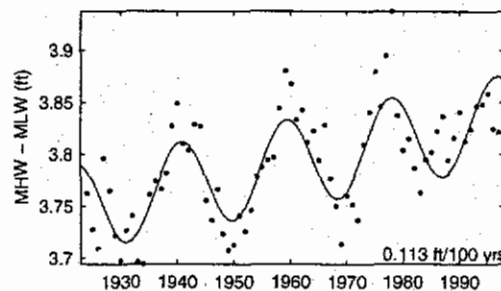
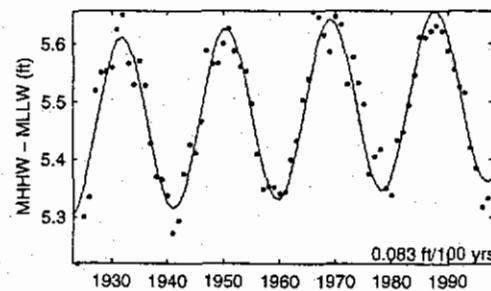
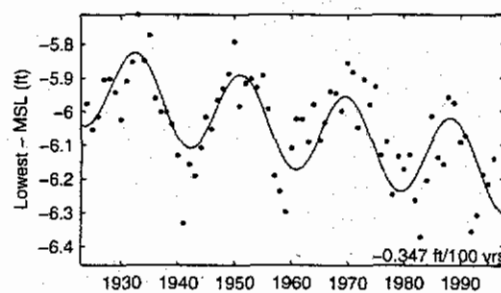
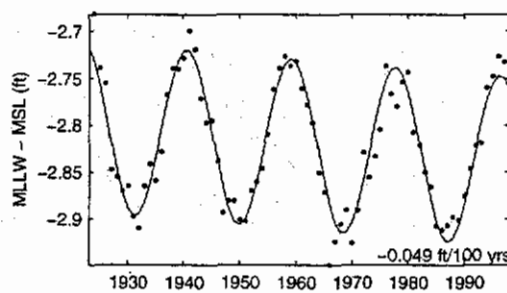
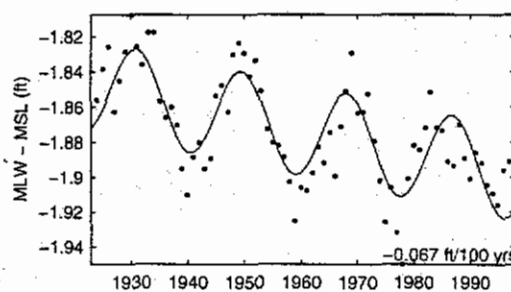
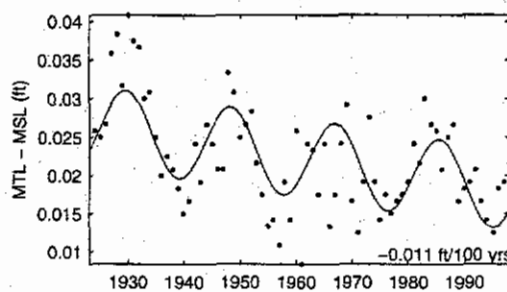
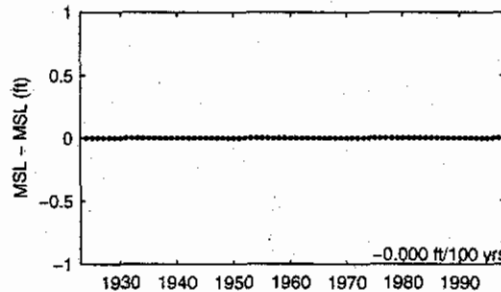
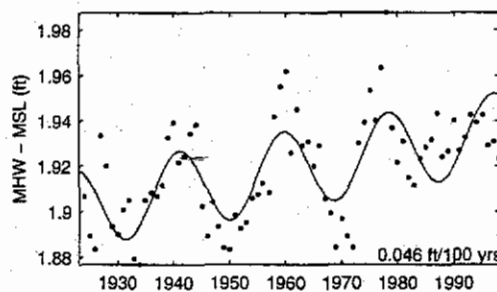
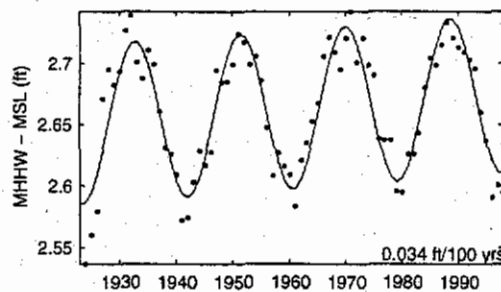


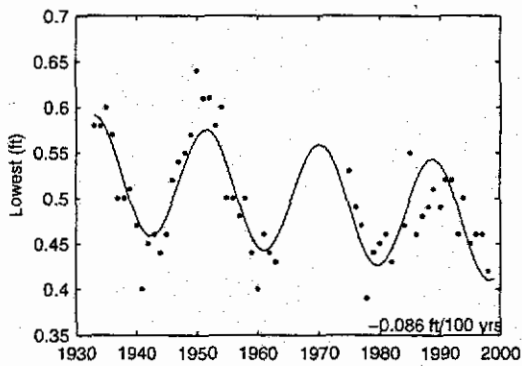
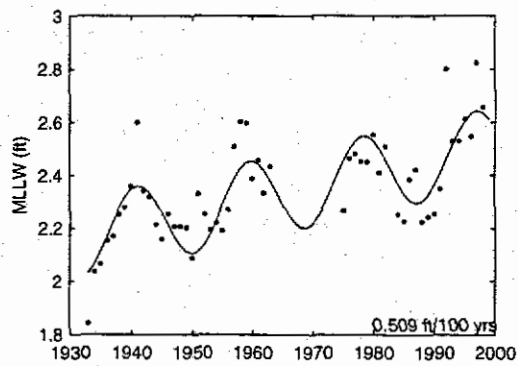
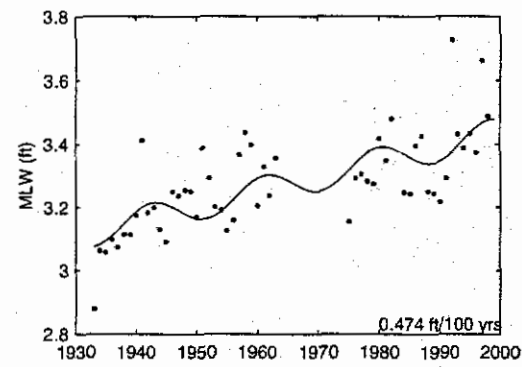
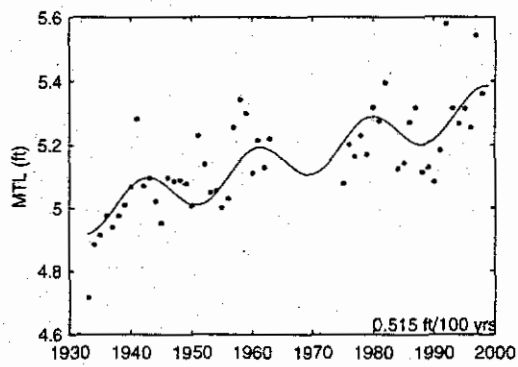
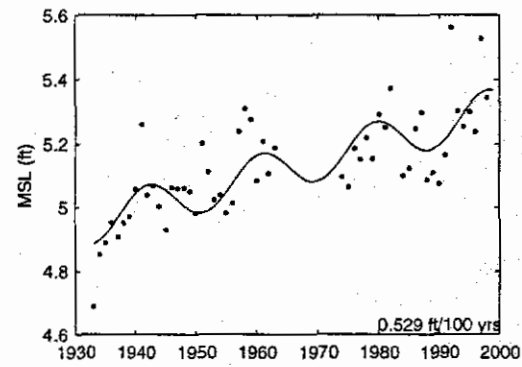
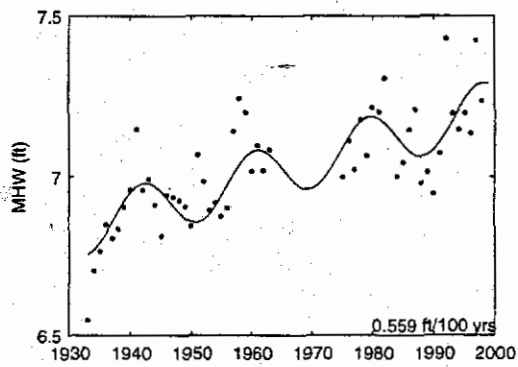
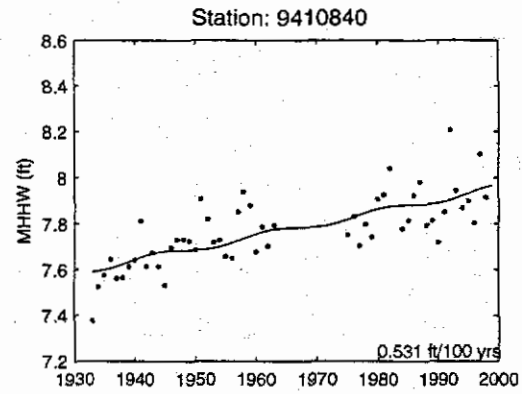
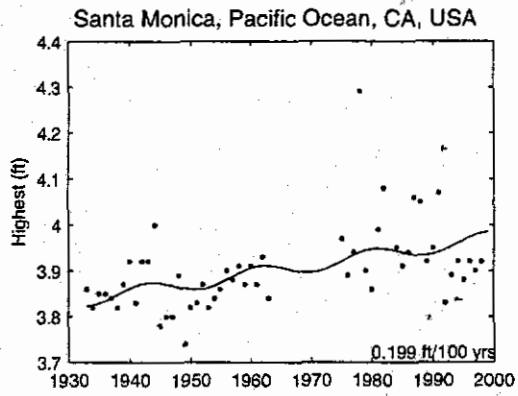


Los Angeles, Outer Harbor, CA, USA

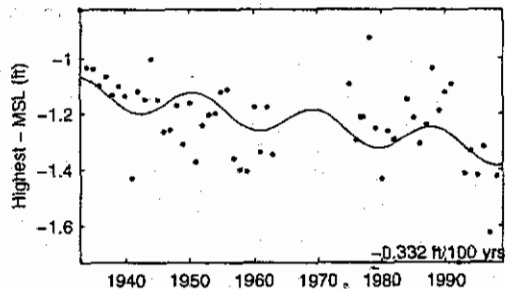


Station: 9410660

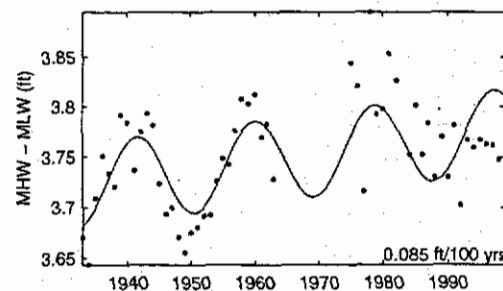
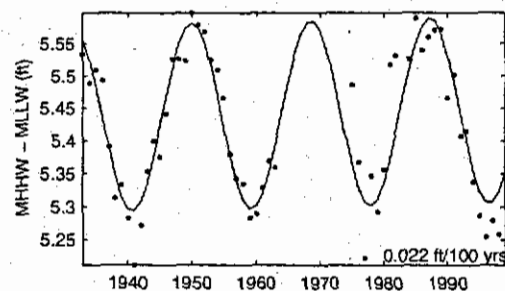
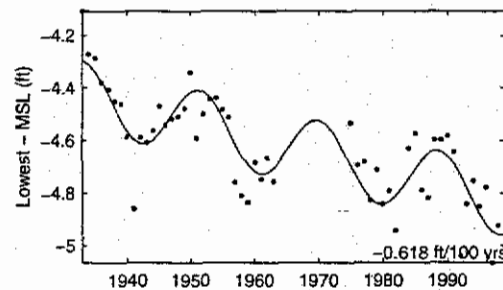
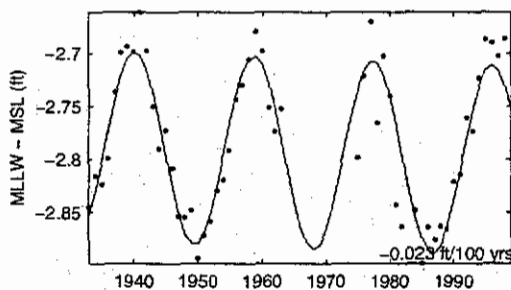
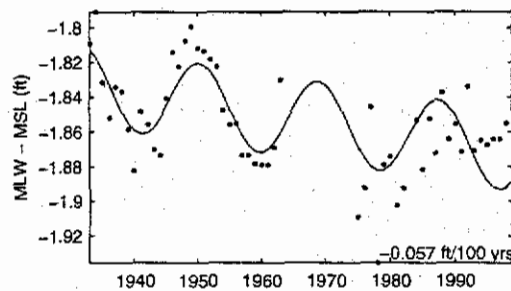
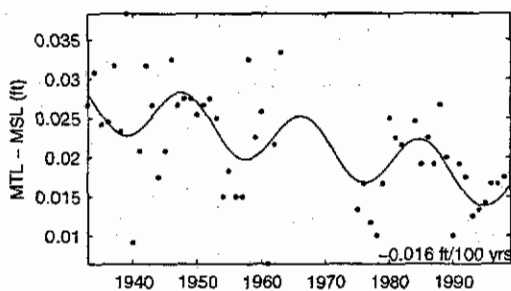
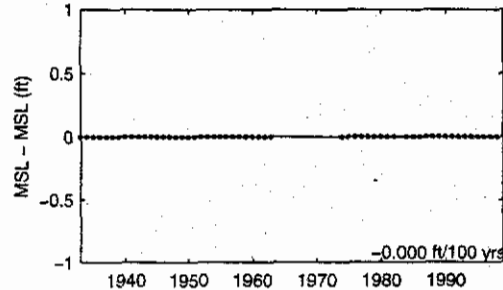
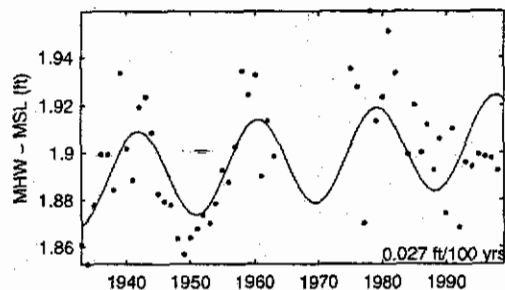
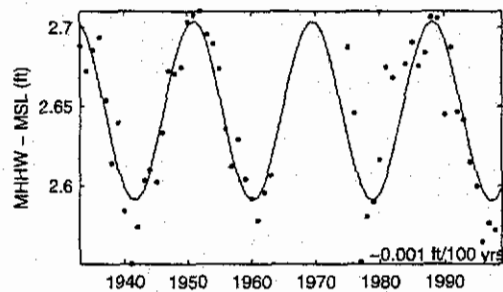


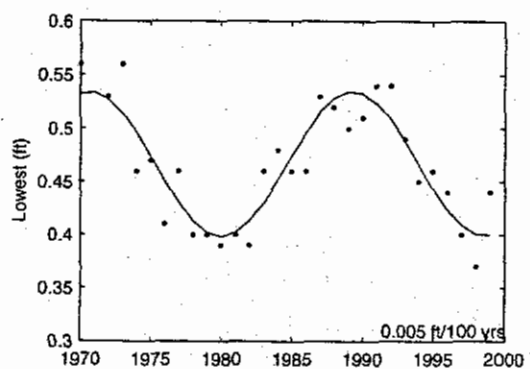
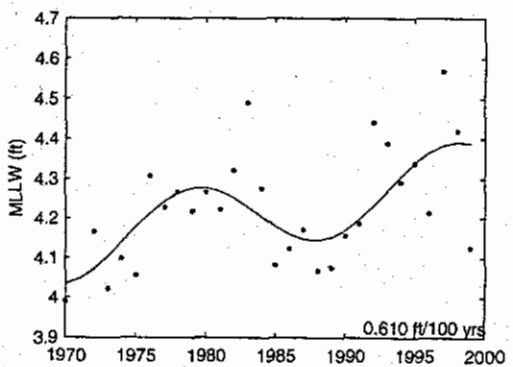
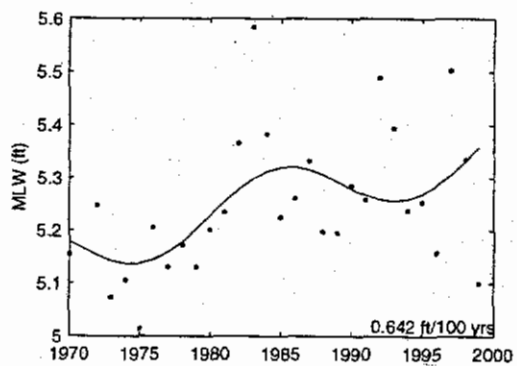
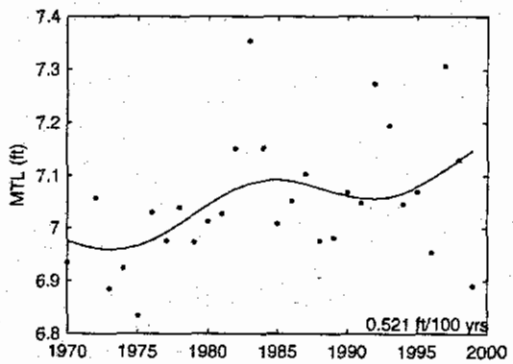
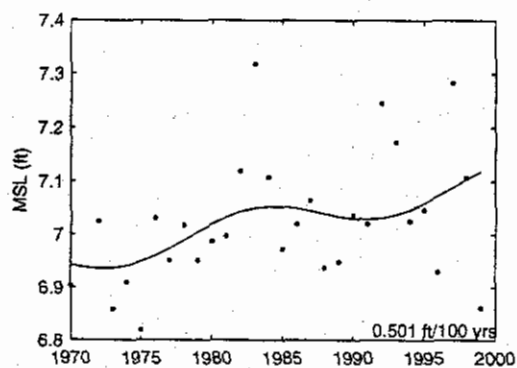
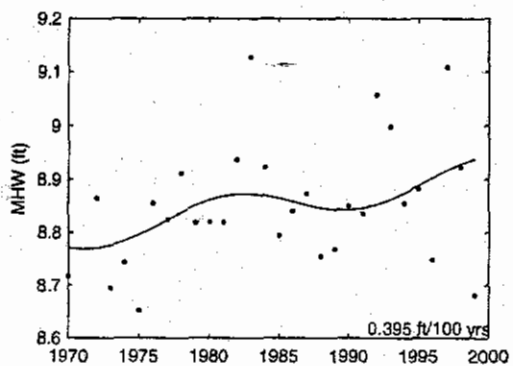
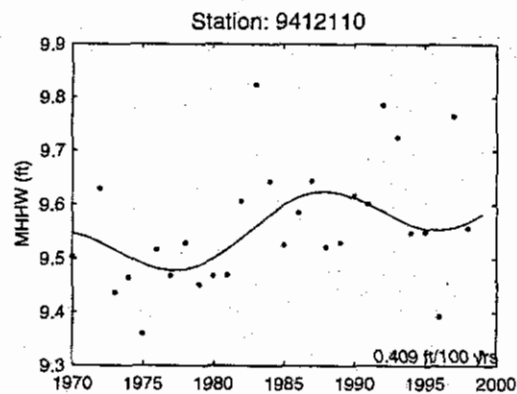
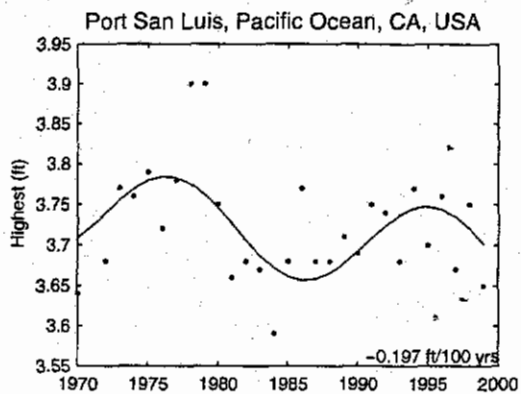


Santa Monica, Pacific Ocean, CA, USA

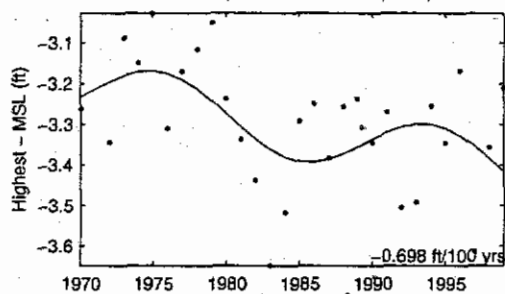


Station: 9410840

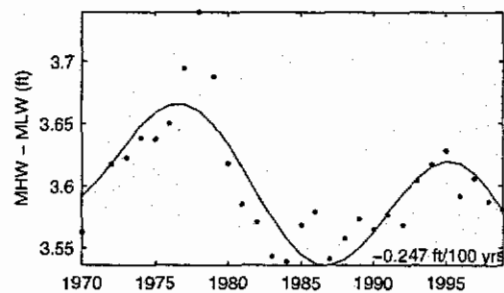
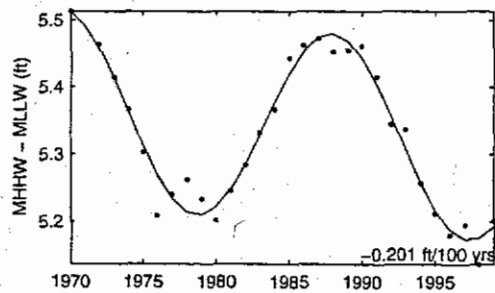
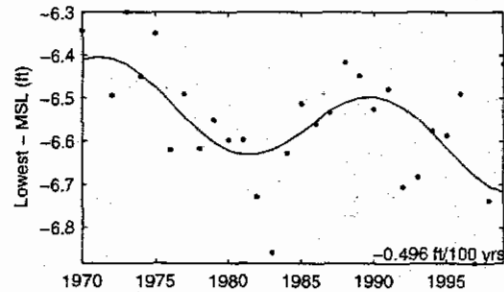
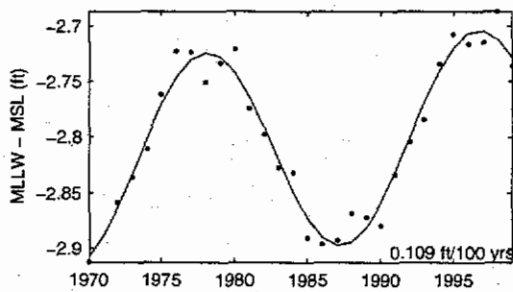
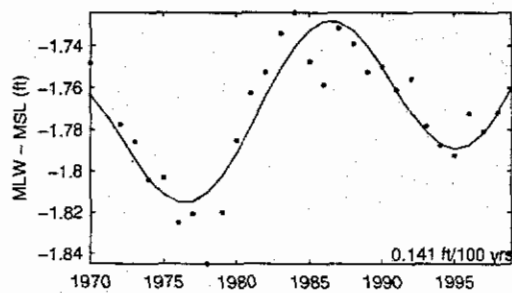
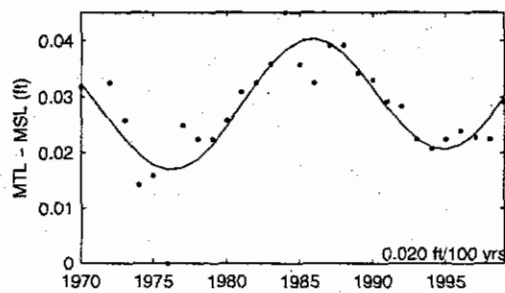
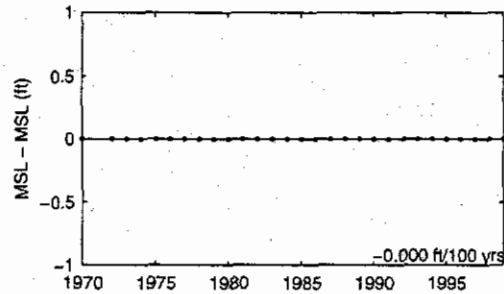
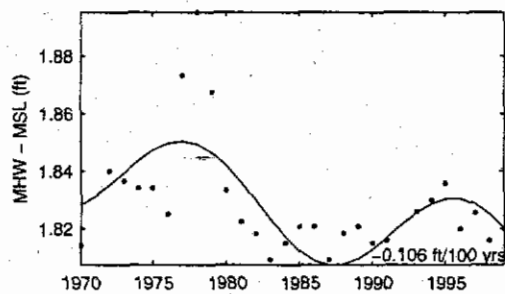
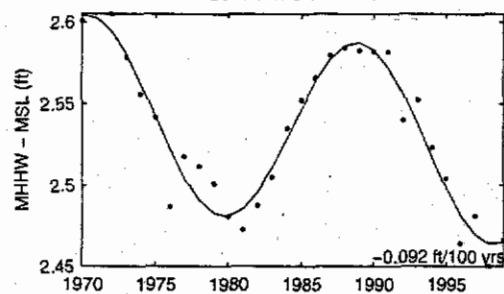


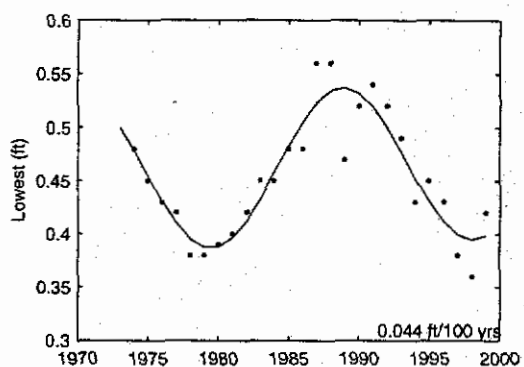
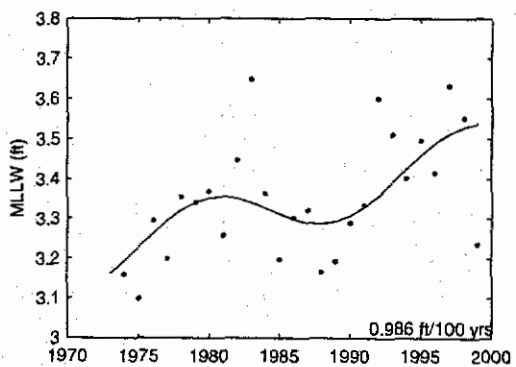
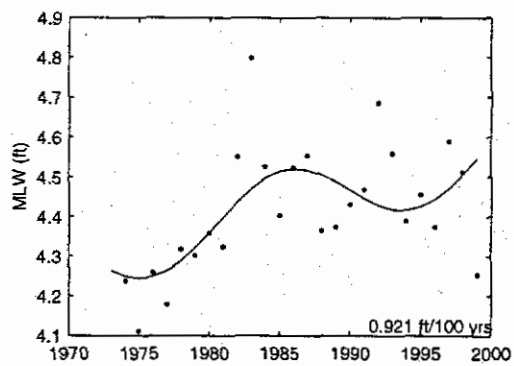
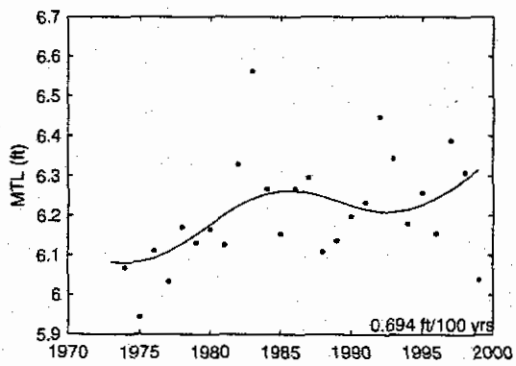
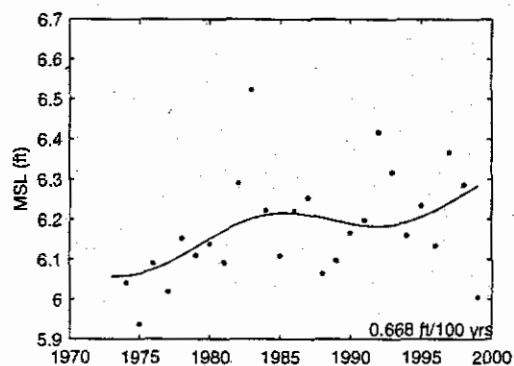
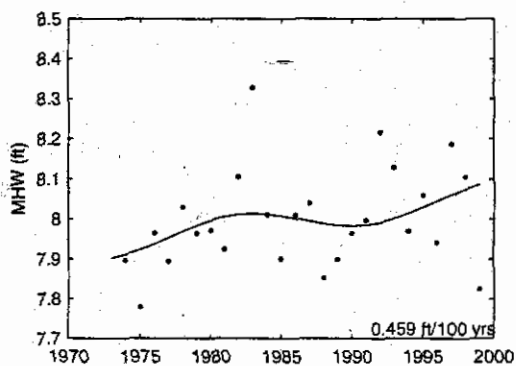
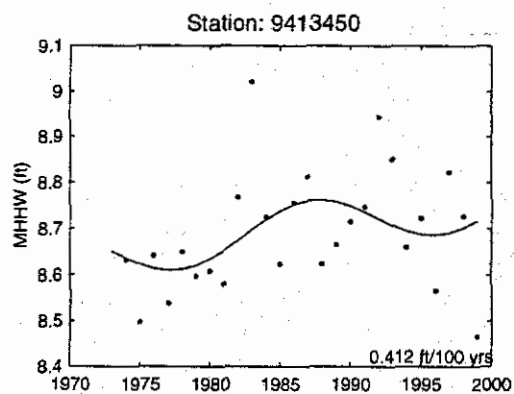
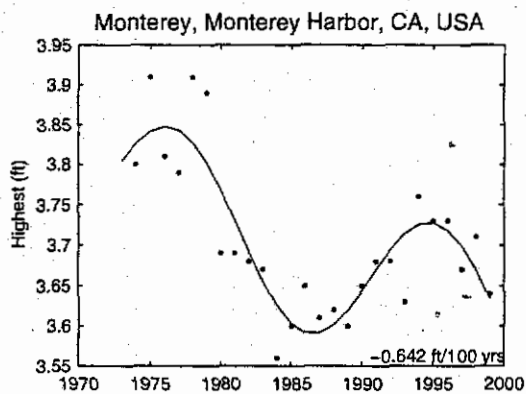


Port San Luis, Pacific Ocean, CA, USA

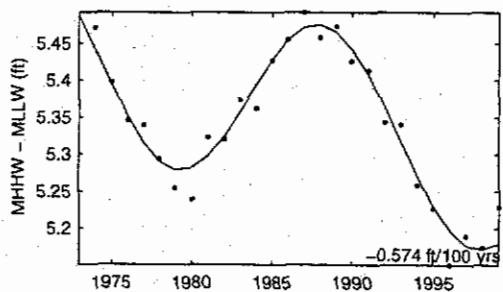
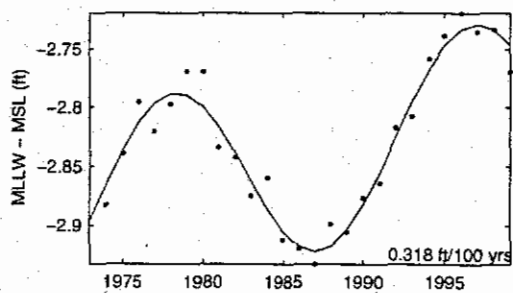
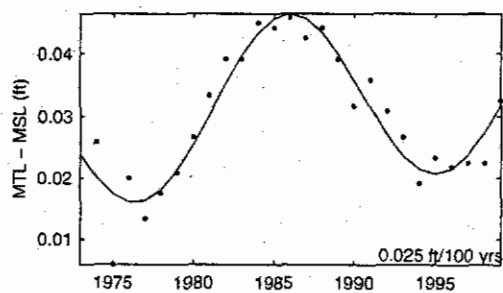
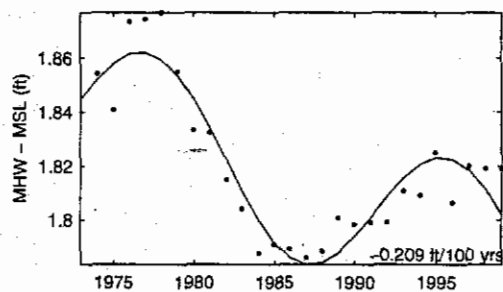
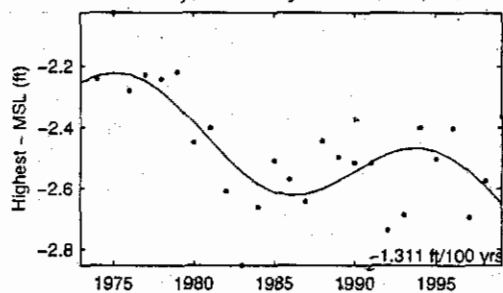


Station: 9412110

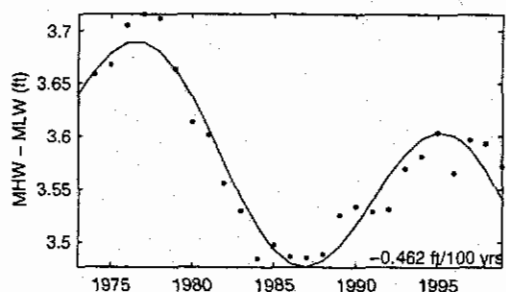
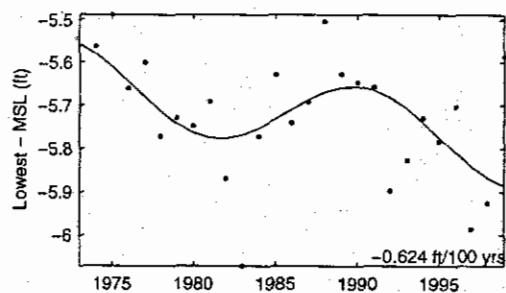
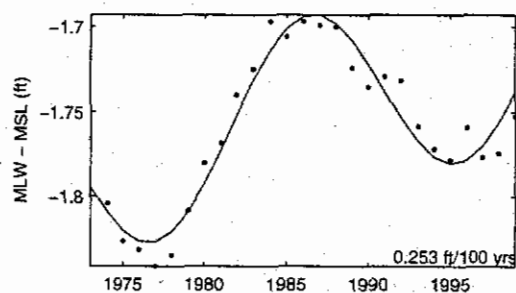
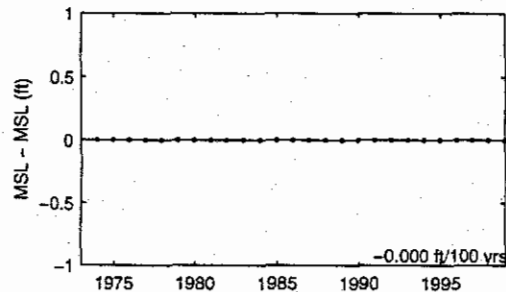
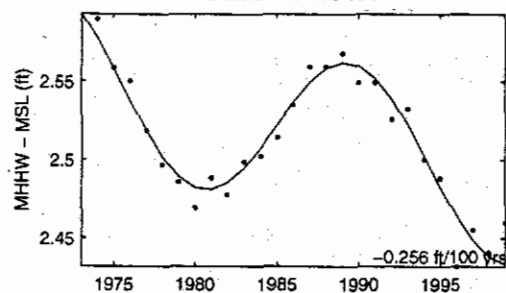


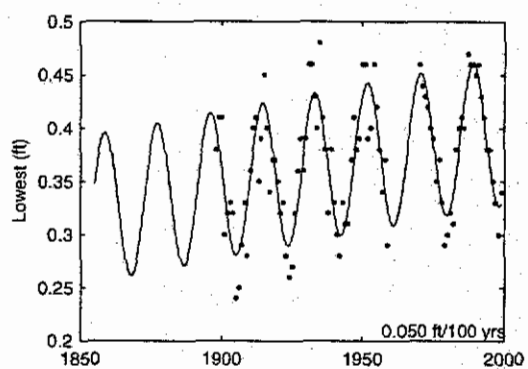
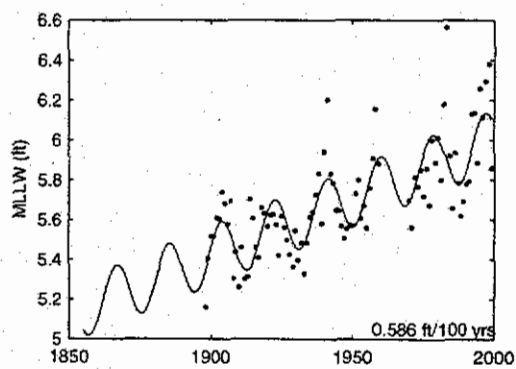
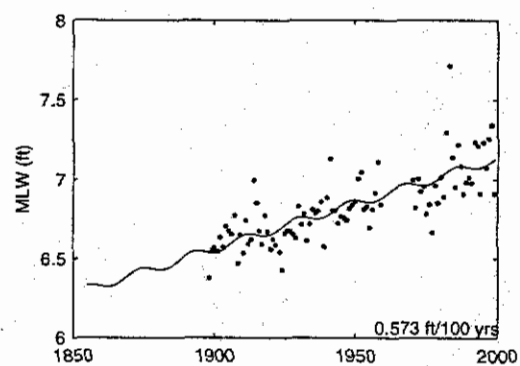
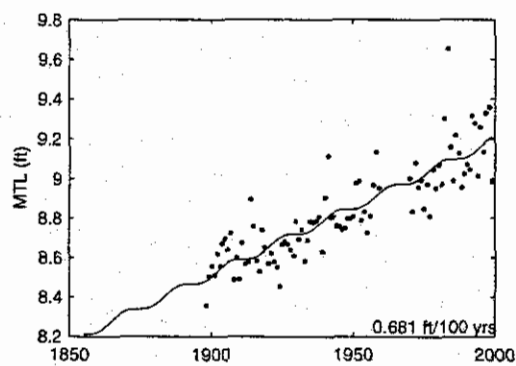
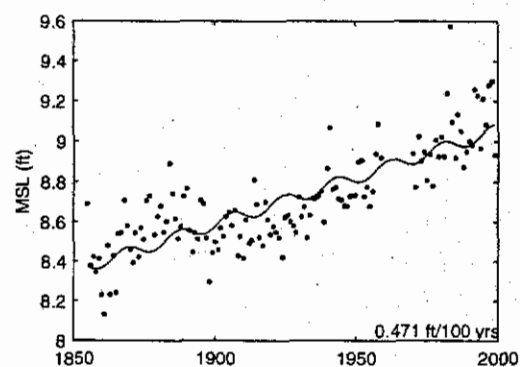
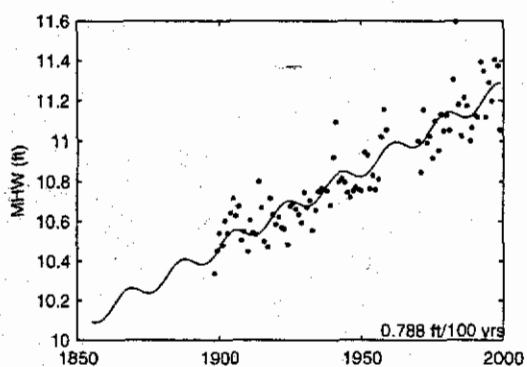
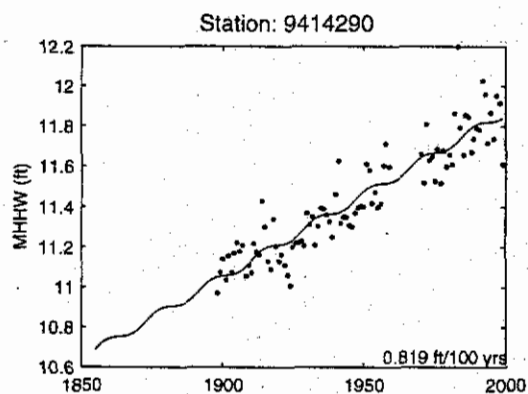
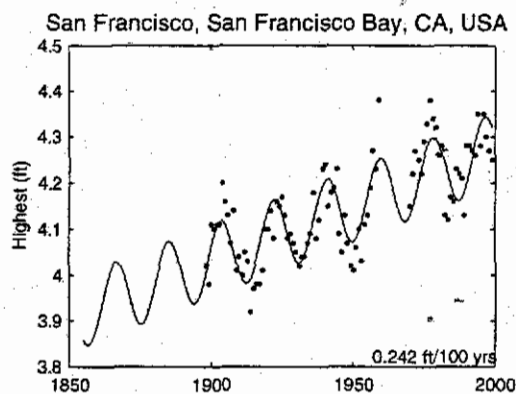


Monterey, Monterey Harbor, CA, USA



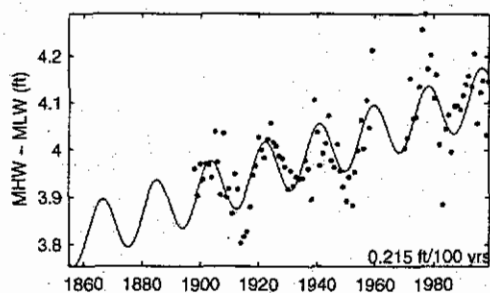
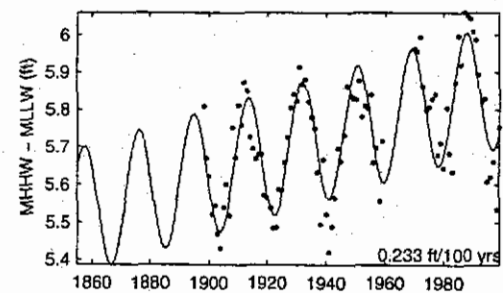
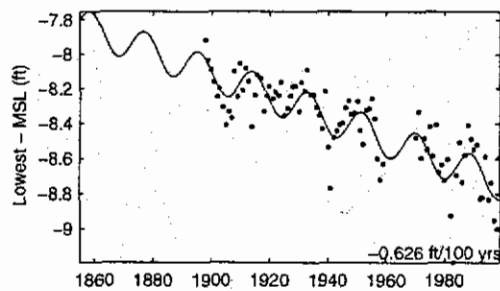
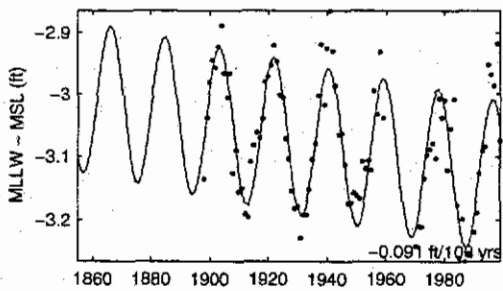
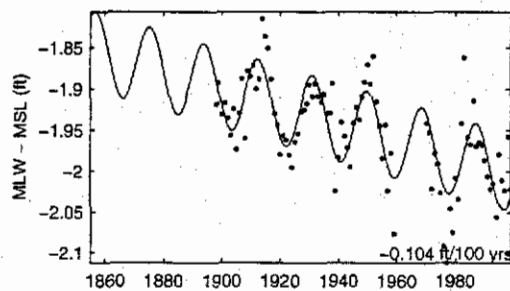
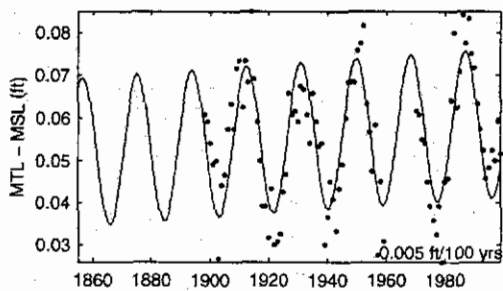
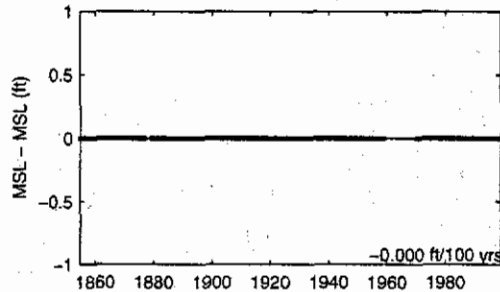
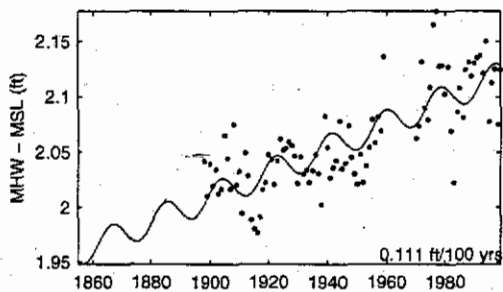
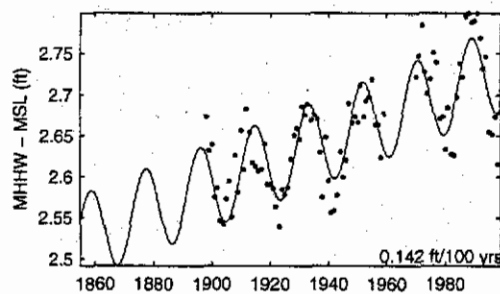
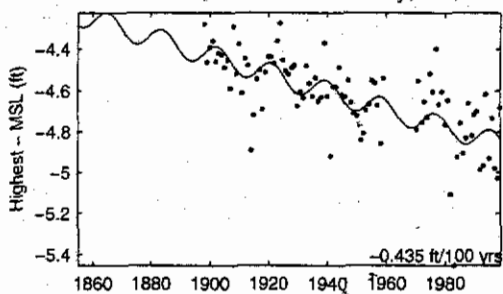
Station: 9413450

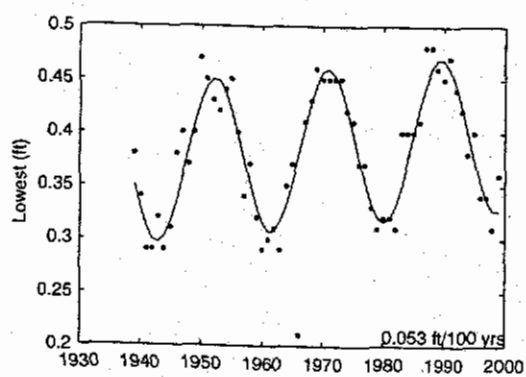
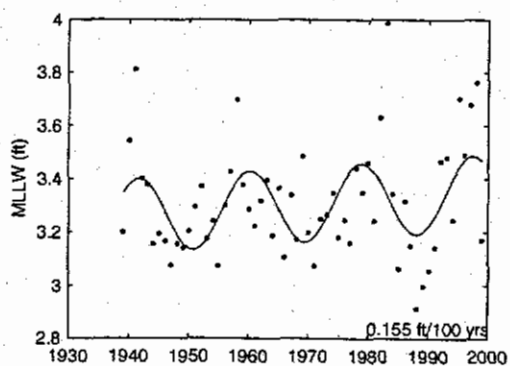
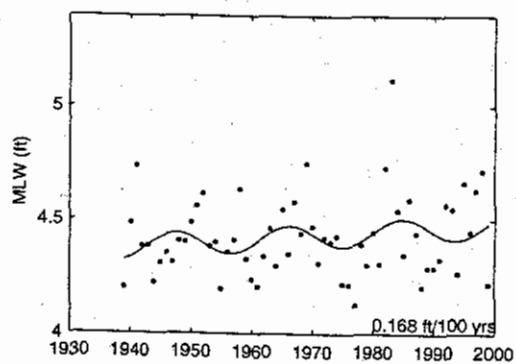
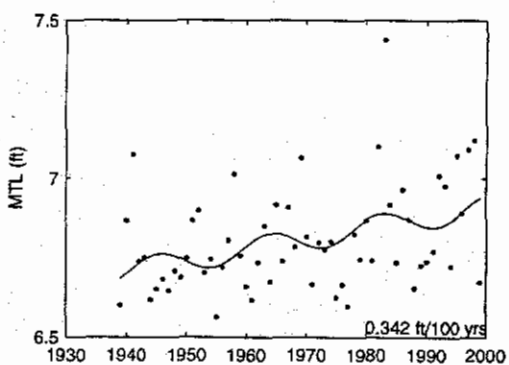
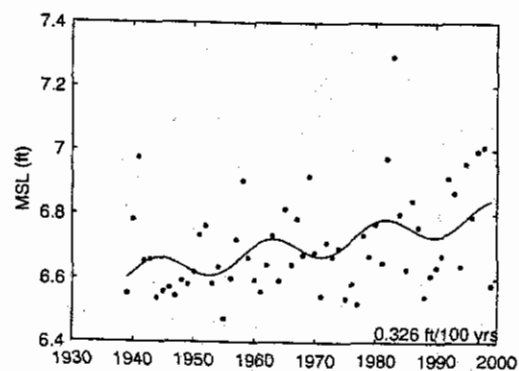
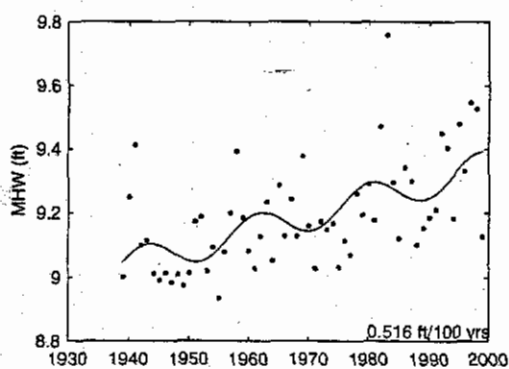
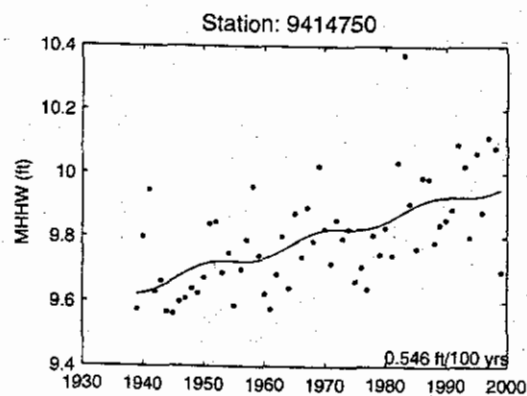
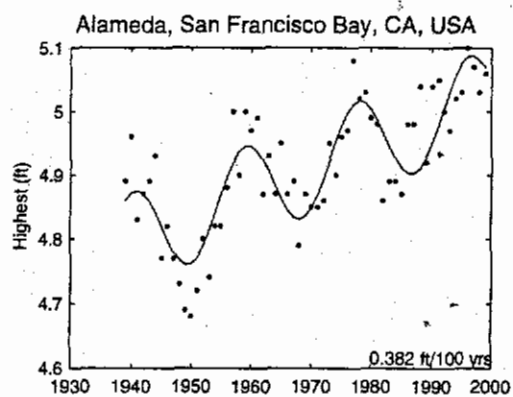




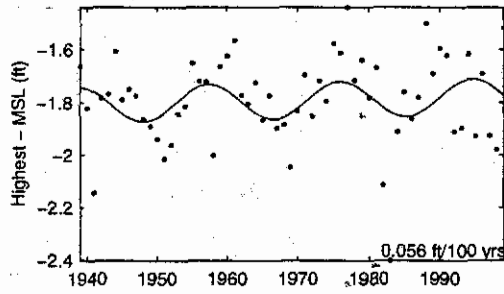
San Francisco, San Francisco Bay, CA, USA

Station: 9414290

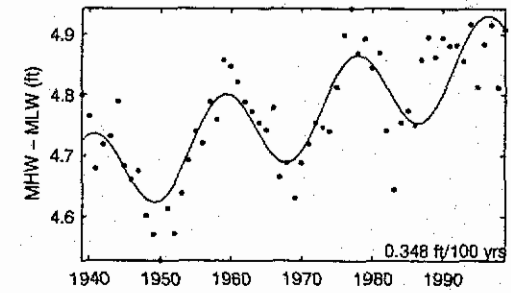
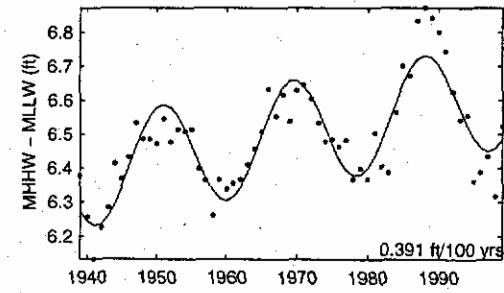
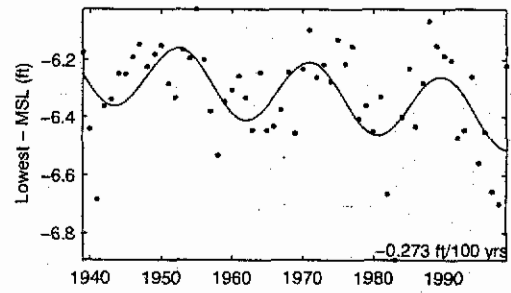
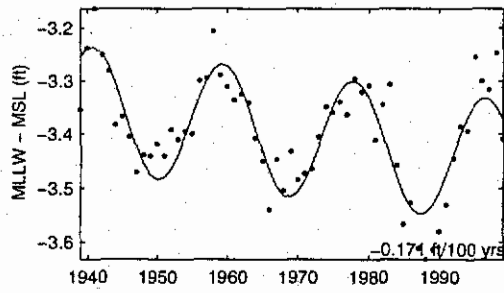
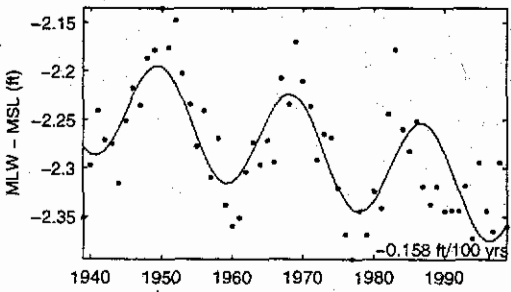
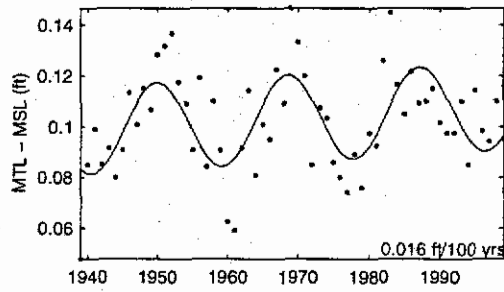
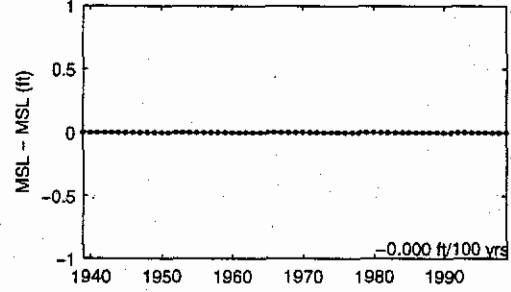
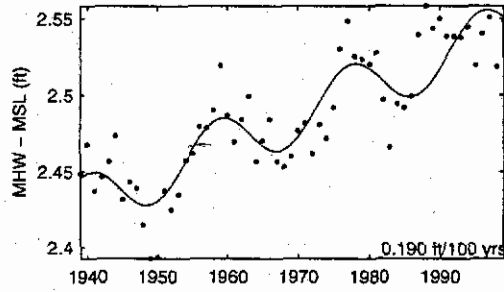
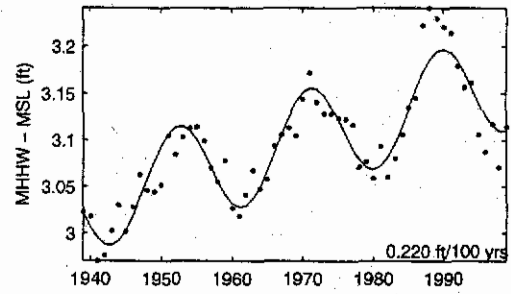


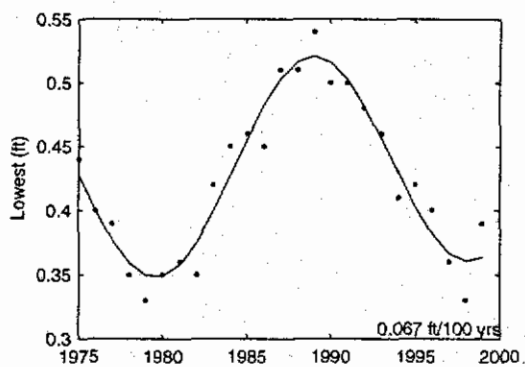
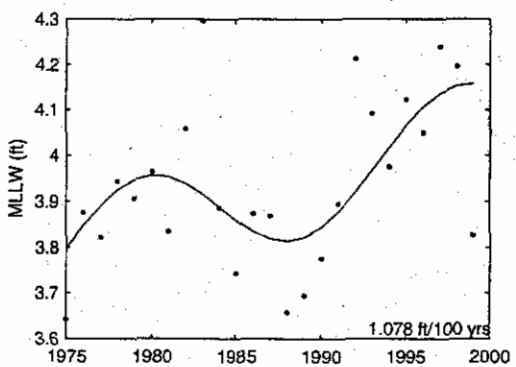
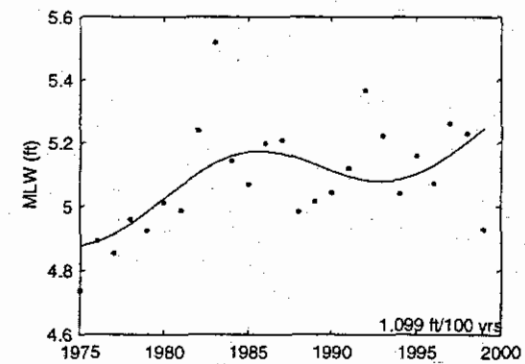
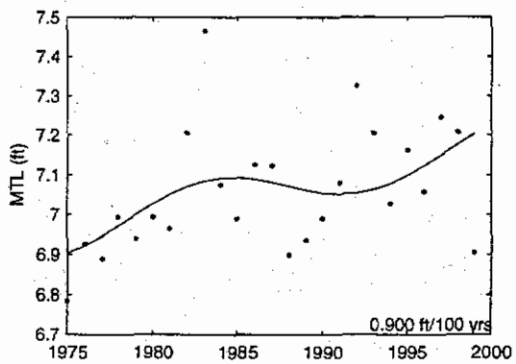
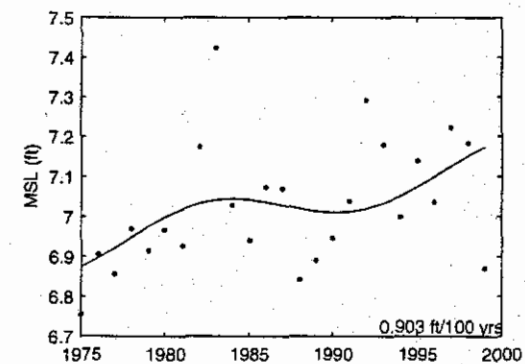
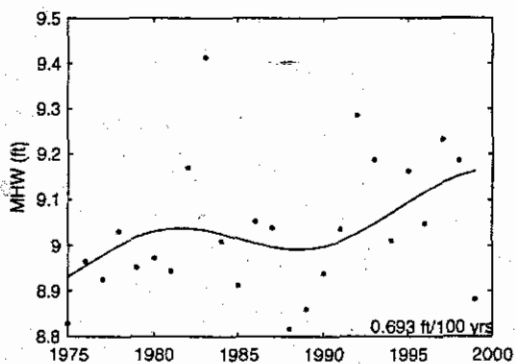
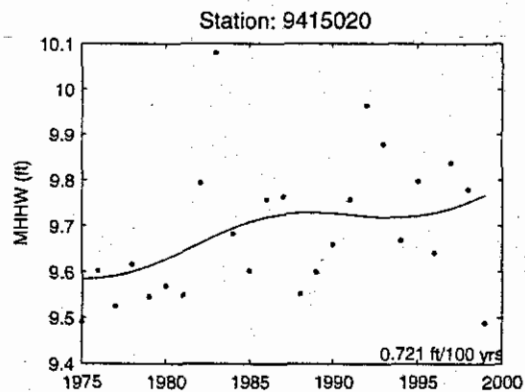
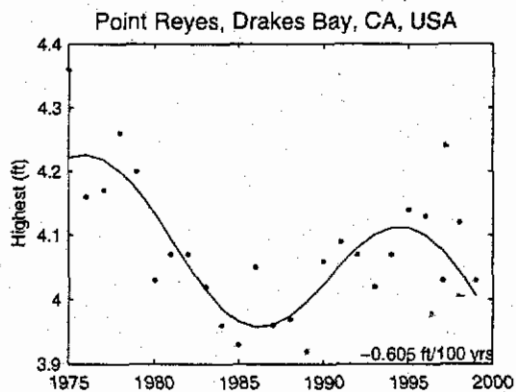


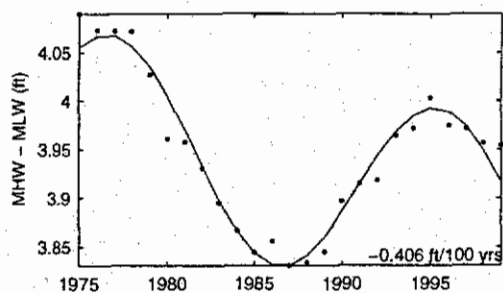
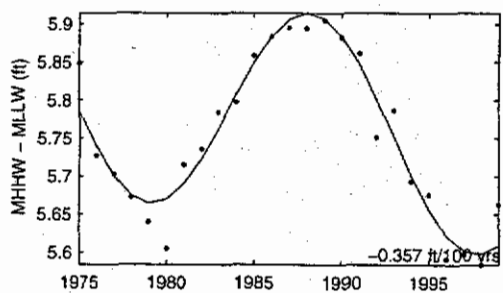
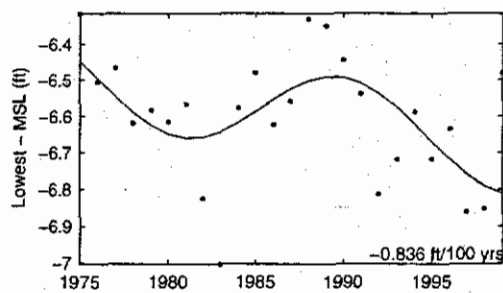
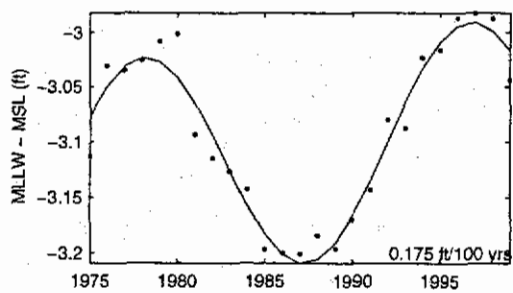
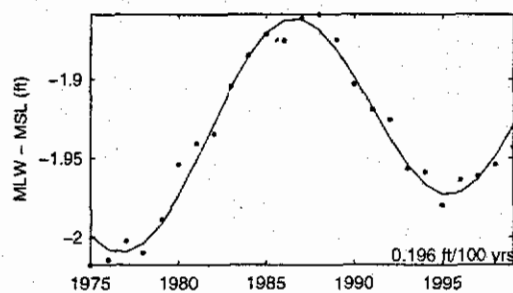
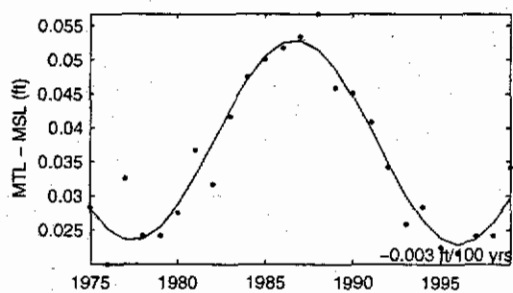
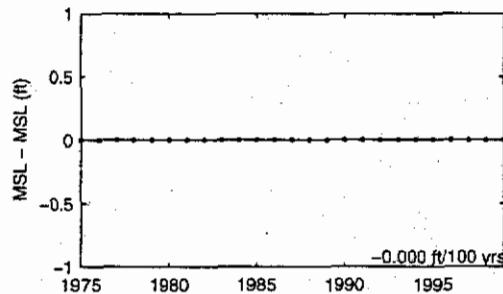
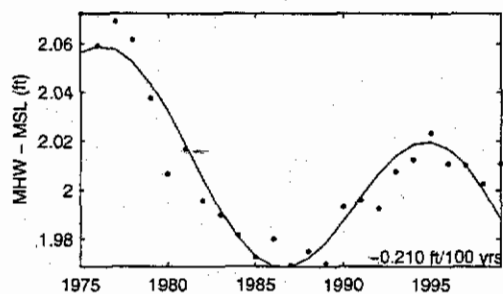
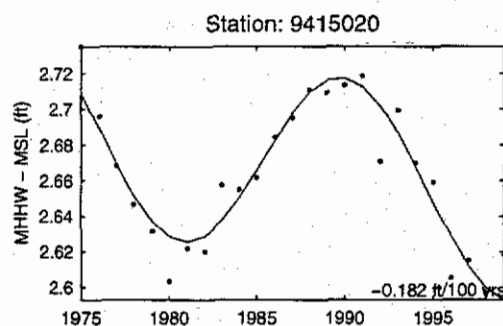
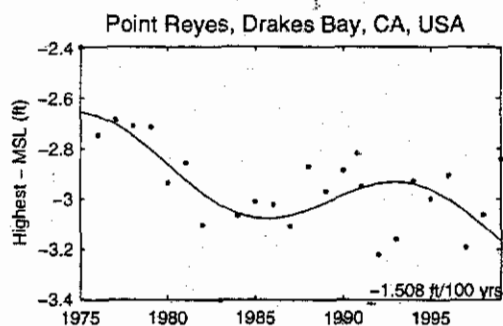
Alameda, San Francisco Bay, CA, USA

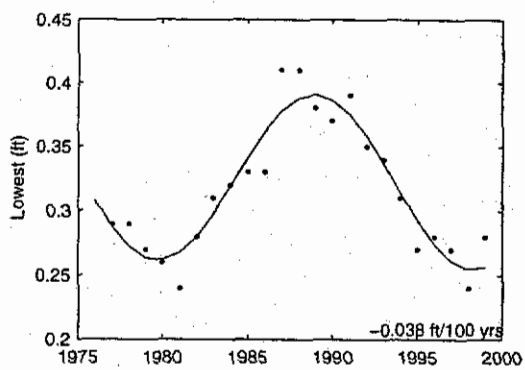
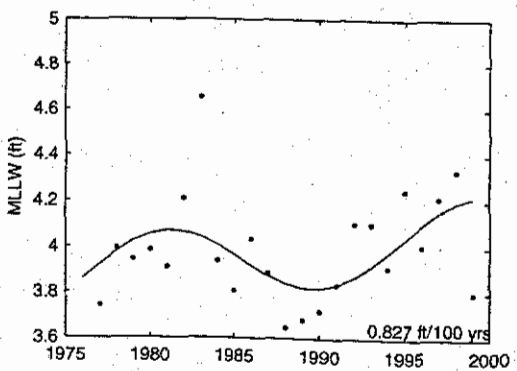
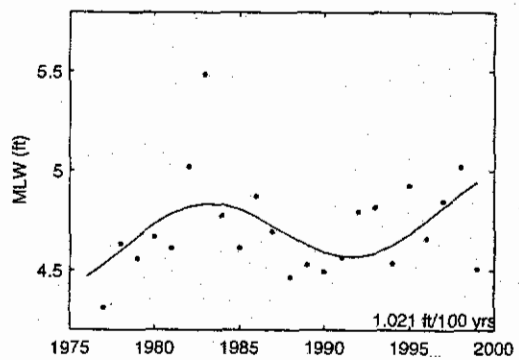
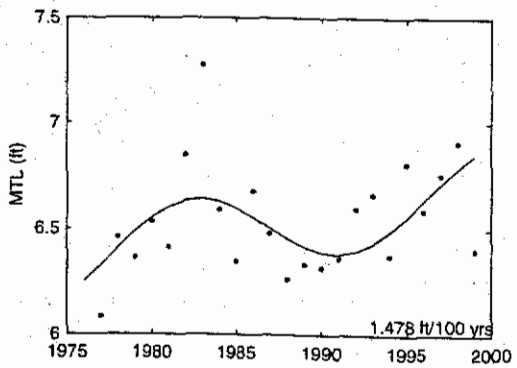
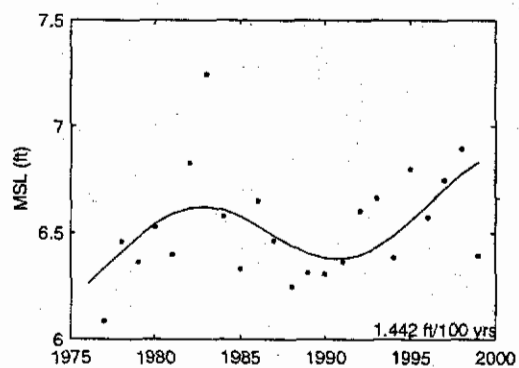
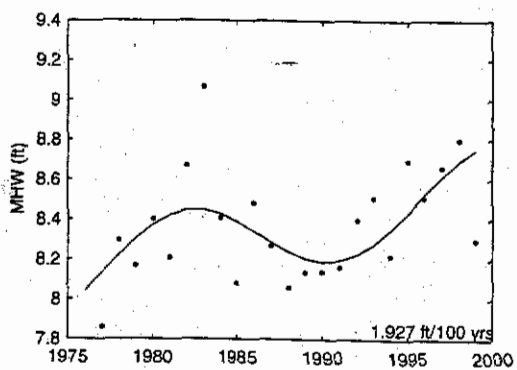
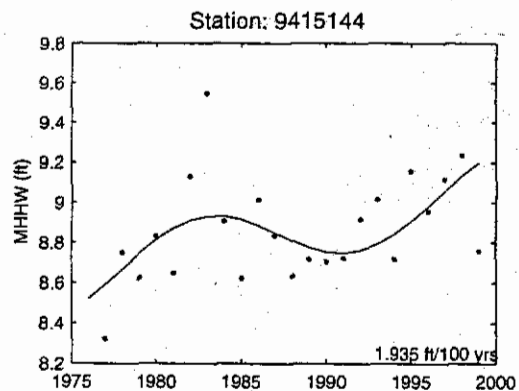
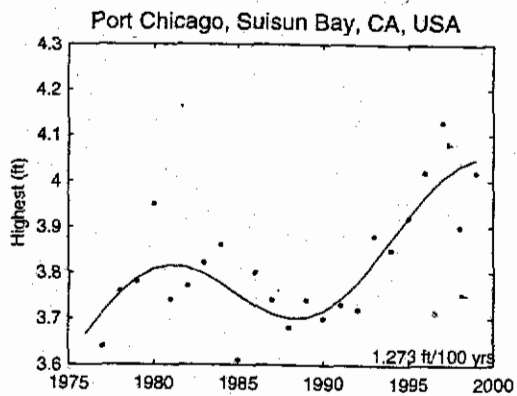


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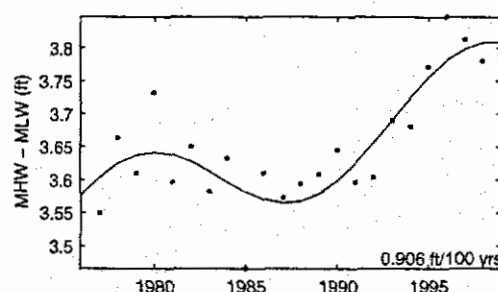
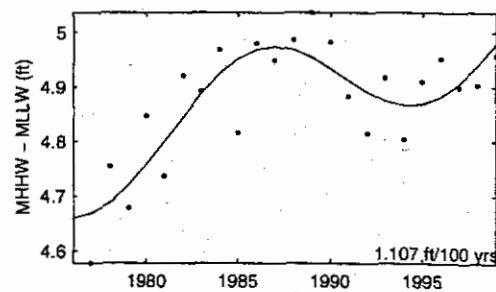
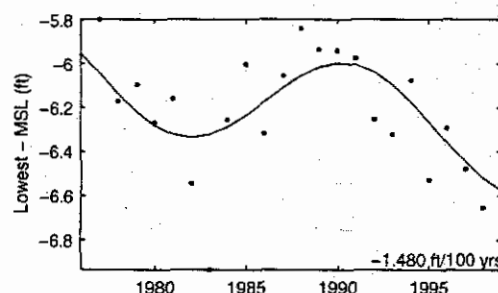
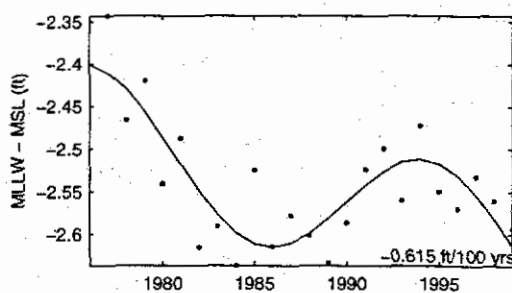
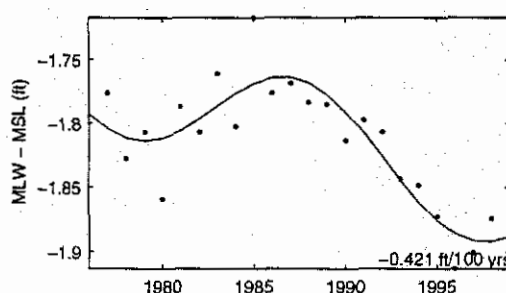
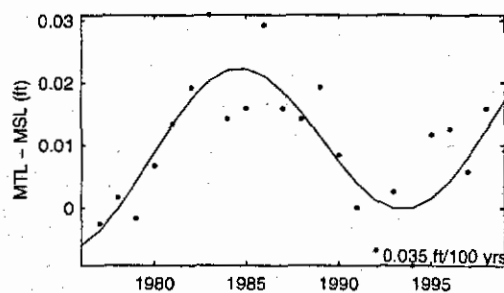
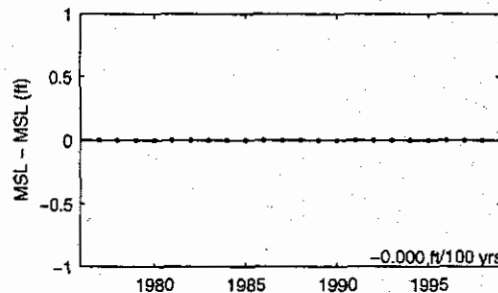
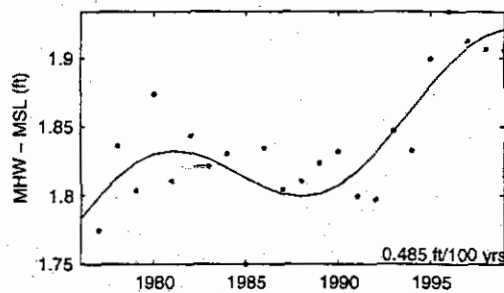
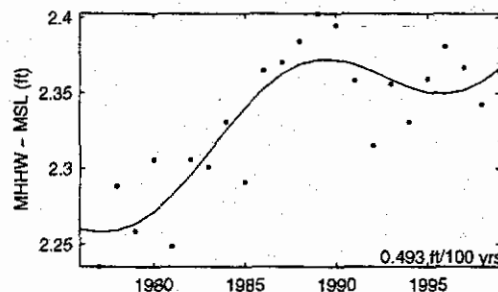
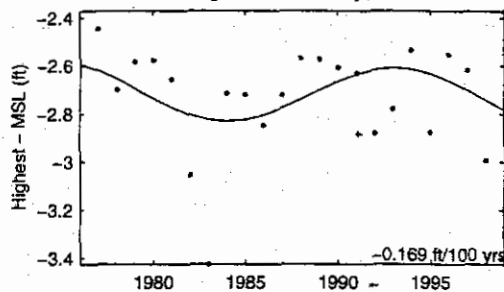


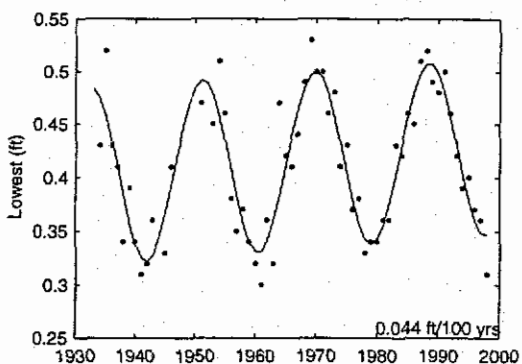
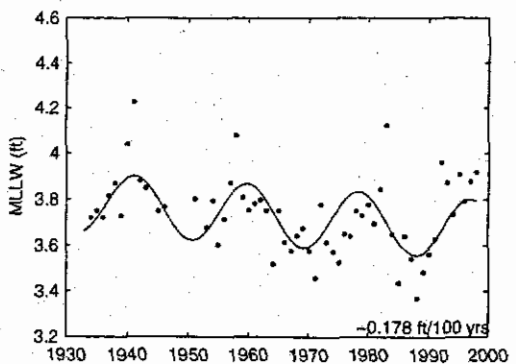
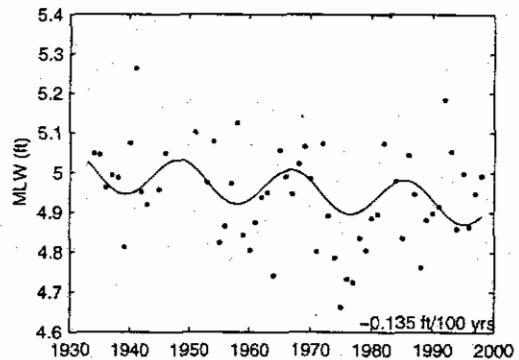
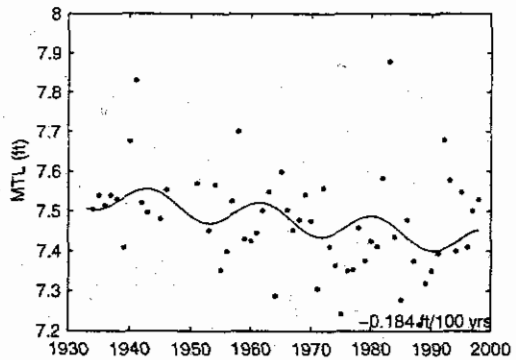
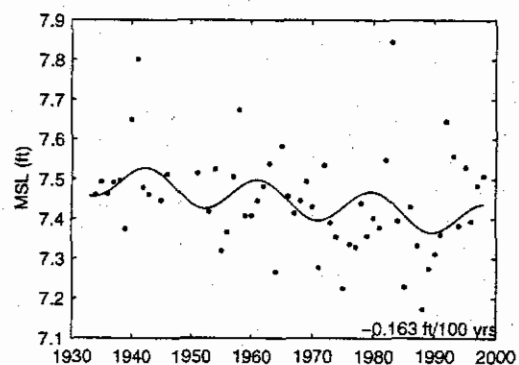
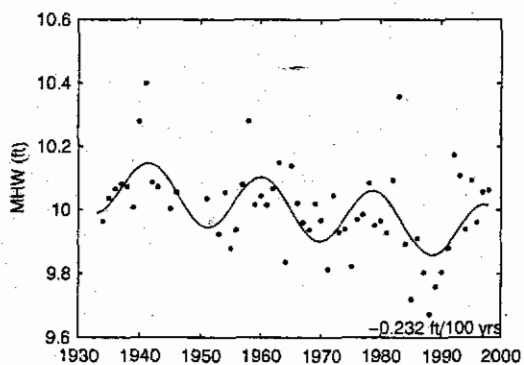
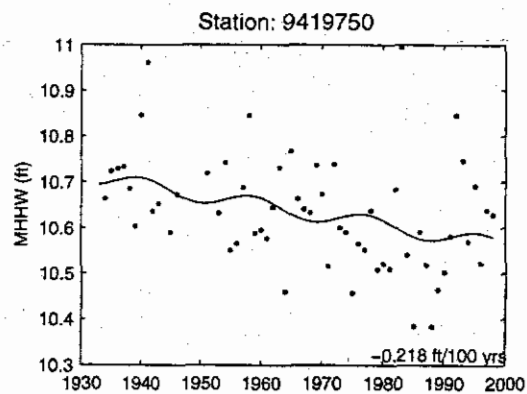
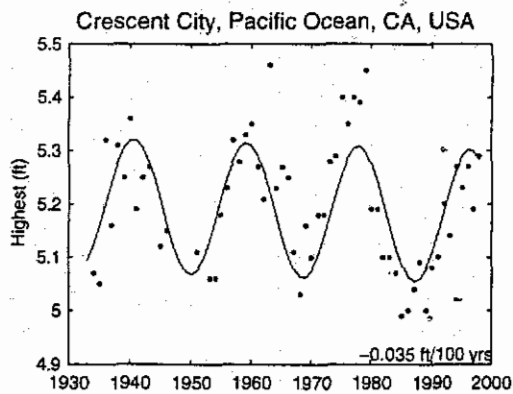




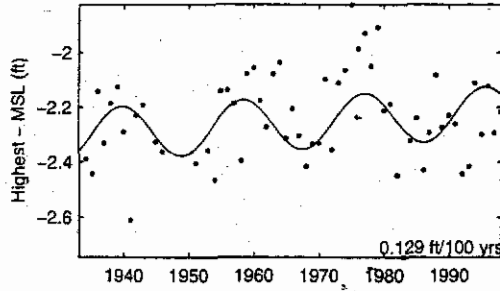
Port Chicago, Suisun Bay, CA, USA

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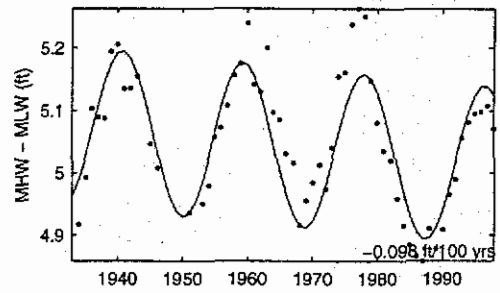
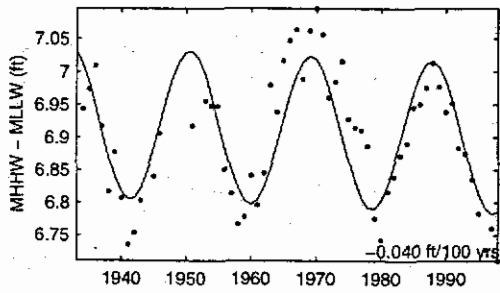
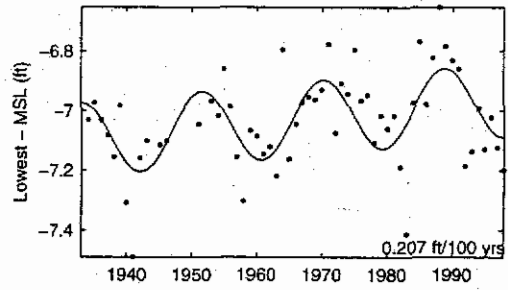
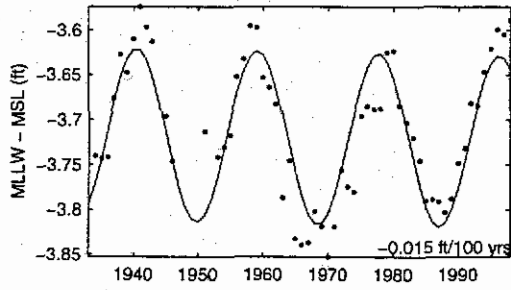
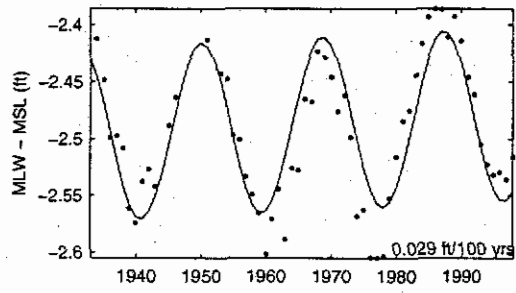
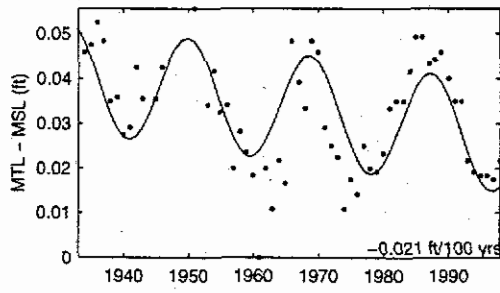
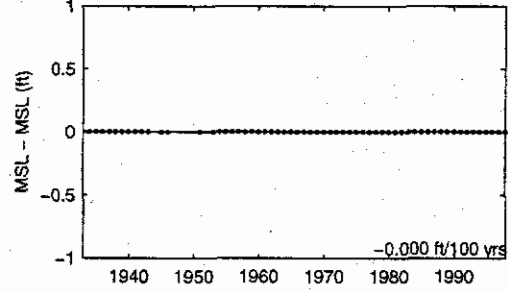
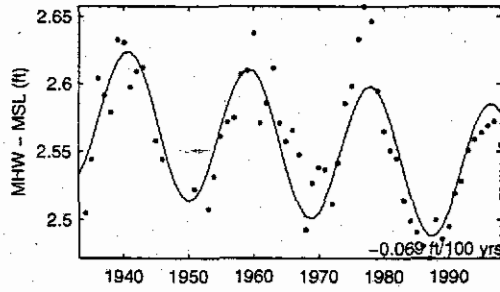
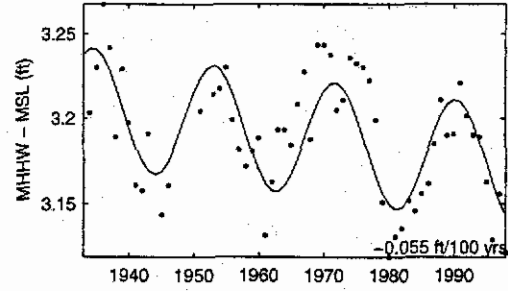




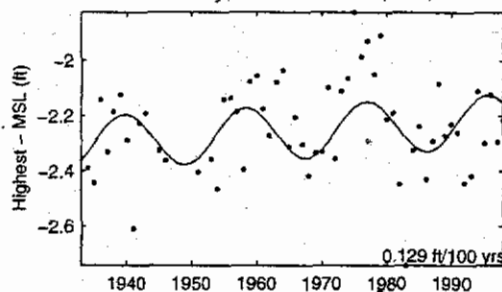
Crescent City, Pacific Ocean, CA, USA



Station: 9419750



Crescent City, Pacific Ocean, CA, USA



Station: 9419750

