NOAA Technical Report NOS CO-OPS 36

SEA LEVEL VARIATIONS OF THE UNITED STATES 1854-1999

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Silver Spring, Maryland
July, 2001

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services
Products and Services Division

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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July, 2001

noaa **National Oceanic and Atmospheric Administration**

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List of Acronyms

CO-OPS	Center for Operational Oceanographic Products and Services
ENSO	El Nino/Southern Oscillation
MSL	Mean Sea Level
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network

EXECUTIVE SUMMARY

In this report, monthly mean sea level (MSL) variations are analyzed for 117 stations of the National Ocean Service's (NOS) National Water Level Observation Network (NWLON) having between 25 and 146 years of data. Monthly MSL data up to the end of 1999 are used to calculate linear trends, and to obtain the average seasonal cycle, the residual time series, and the autoregressive coefficient of the residual with accurate estimates of standard errors. Months with extreme high or low residuals are defined and periods of broad regional correlations between station anomalies are observed.

Since the derived trends include the local vertical land motion, they are spatially variable. Calculated MSL trends range from 9.85 mm/yr for Grand Isle, LA to -16.68 mm/yr for Skagway, AK and are consistent with previous station trends published by NOS. The appendices of this report include time series plots for each station of the monthly MSL with the seasonal cycle removed, the seasonal cycle, and the MSL residual after both the seasonal cycle and the trend are removed. The location and timing of any major earthquakes near stations in tectonically-active areas are noted, since an associated vertical offset or a change in MSL trend is possible.

An inverse power relationship is derived empirically, relating the standard error for linear trends to the year range of MSL data. An estimated 50 to 60 years of data are required for obtaining linear MSL trends having a 1 mm/yr precision with a 95% statistical confidence interval. For a given length of data, the standard errors for trends at Pacific Ocean and western Gulf of Mexico stations tend to be greater than standard errors for trends at Atlantic coastal stations.

MSL trends for the most recent 50-year period of 1950-1999 are compared with trends obtained from each station's entire data set. The trend for the past 50 years is significantly lower at only three out of sixty stations (Eastport, Portland, and Boston). At no station is the 1950-1999 trend significantly higher than the trend obtained from the station's entire data set.

In an examination of 50-year MSL trends at sixteen of the longest term stations, it was found that for six Atlantic stations, the periods centered on years from 1930 to 1955 tend to have significantly higher trends than periods centered on years from 1965 to 1975. For San Francisco, trends for all 50-year periods centered from 1890 to 1915 are significantly lower than the overall trend and the trend since the 1906 San Francisco earthquake.

I. INTRODUCTION

The National Water Level Observation Network (NWLON) is operated by the Center for Operational Oceanographic Products and Services (CO-OPS), a component of the National Ocean Service (NOS). The NWLON is composed of approximately 175 long term, continuously-operating stations located along the United States coast, including the Great Lakes and islands in the Atlantic and Pacific Oceans. The NWLON provides the basis for establishing U.S. tidal datums for marine and coastal boundaries and the NOS navigational chart datum for hydrographic surveys. In addition, NWLON data are used for scientific studies of wetlands, coastal processes, tectonics, tsunamis, storm surges, and climate change.

Most of the NWLON stations have been recording water levels for several decades, with two stations (New York and San Francisco) having accurate records beginning in the 1850s. Water levels have been recorded by a variety of instruments over the years with continuing improvements in instrument accuracy (Bilham, 1991) and with occasional small shifts in instrument location. The earliest water levels were observed with a tide staff and recorded by the U.S. Coast and Geodetic Survey, a predecessor of the NOS. As a result of technological innovations, water levels have subsequently been recorded automatically by float-driven analog gauges, gas-purged pressure or bubbler recorders, analog-to-digital recording gauges, pressure sensors, and air acoustic ranging sensors.

The data recorded by water level instruments over the years can be combined into a single time series for a location only if the vertical datum (or datum of tabulation) has been carefully maintained. This is accomplished through frequent leveling to fixed benchmarks maintained in the vicinity of the station (Smith, 1980; Gill and Schultz, 2001).

The data to be examined in this report consist of monthly mean sea levels (MSL) for all NWLON stations in operation for a span of at least 25 years. The monthly means are an average of hourly water level heights for a complete month of data. The sea level variations to be determined in this report are the linear secular trend, the average seasonal cycle, and the residual variability at each station. Recorded water levels are a combination of changes in the sea level and the vertical land motion at the location of the gauge. Therefore, the trends derived are relative MSL trends and can be considered valid only for a region near the gauge with uniform vertical land motion. Calculation of absolute MSL trends requires the accurate determination of vertical land motion at the gauges and is beyond the scope of this report.

The monthly MSLs used in this report are relative to the NOS-established MSL datum, which is the arithmetic mean of hourly heights observed during the National Tidal Datum Epoch (NTDE), a standard 19-year period presently defined by NOS as 1960-1978. The NTDE will be updated to the 1980-1998 period in the near future due to the effect of the linear secular trends at each station since 1978. At a limited number of stations, where the linear secular trends have been large, MSL datums were very recently updated using a shorter 5-year period in the 1990s in an effort to keep the datum current.

The NOS has previously determined and published listings of linear secular trends at NWLON stations derived from annual MSLs (an average of all the monthly MSLs for a complete year). Hicks and Shofnos (1965) determined MSL trends up to the year 1962 at 44 stations. Hicks and Crosby (1974) redetermined the MSL trends up to the year 1972 at 50 locations. Hicks et al. (1983) recalculated MSL trends up to the year 1980 at 67 stations and included a determination of the average seasonal MSL cycles. Lyles et al. (1988) updated the MSL trends and the seasonal cycles up to the year 1986 at 78 stations.

Smith and Leffler (1980) published an analysis of long term sea level trends at NWLON stations along the California coast. Mitchell et al. (2000) calculated sea level trends up to 1999 for Australia and the Pacific Ocean including trends for twelve NWLON stations. An up-to-date compilation of MSL secular trends at most long term water level stations around the world is produced by the Permanent Service for Mean Sea Level (available at http://www.nbi.ac.uk/psmsl/datainfo/rlr.trends).

There have been a number of studies (Parker, 1992) in which MSL trends from stations around the world are combined in order to determine the global MSL trend due to the thermal expansion of seawater caused by global temperature changes and glacial melting. Although most coastal regions of the world indicate a MSL rise, some coastlines show rapidly falling MSLs. This is a consequence of water level gauges measuring relative MSL change which combines the effects of absolute MSL change and any vertical land movement. Various averaging schemes and/or corrections for vertical land motions have been devised, resulting in estimates of global MSL rise ranging from 1.0 to 2.4 mm/yr (Douglas et al., 2001).

Continuing isostatic rebound of the lithosphere in response to melting of the ice sheets is the cause of the largest vertical land motion at many northern hemisphere stations (Hicks, 1965). Viscoelastic models of the earth have been developed based on radiocarbon dating of shoreline levels over the past 18,000 years. The glacial isostatic adjustment effect is expected to be essentially linear for the period of instrumentally-recorded water levels. The vertical trends derived from these models have been used to correct individual sea level trends for the glacial isostatic rebound and to derive a globally-averaged MSL trend (Peltier and Tushingham, 1989; Mitrovica and Davis, 1995; Davis and Mitrovica, 1996). An additional significant cause of rapid vertical land motion is the tectonic processes at plate boundaries. Douglas (1991) produced an estimated global MSL trend by excluding all water level stations at convergent plate boundaries.

Another use of MSL data is to estimate the acceleration of global MSL in order to identify possible changes in the rate of sea level rise due to man-made contributions to global warming. Using data up to the mid to late 1980s from long term stations, no consistent, statistically-significant nonlinear parameters have been found (Woodworth, 1990; Douglas, 1992).

For scientific research in the fields of tectonics, sedimentary basin subsidence, seismology, and volcanology, vertical land motion is the desired signal in the MSL record while absolute changes in oceanic water levels are considered as noise to be removed (Vanicek, 1978; Chelton and Enfield, 1980). At plate boundary faults, strain is continuously accumulated and periodically released as earthquakes, aseismic fault creep, and/or viscoelastic readjustment, resulting in time-dependent horizontal and vertical deformation. The earthquake cycle at major plate boundaries can be divided into four time periods: interseismic (strain accumulation), preseismic (incipient strain release), coseismic (elastic rebound), and postseismic (transient strain release) (Mavko, 1981). Vertical land movement at different rates may be expected during each period and consequently can cause variations in relative MSL trends.

Water level records in Japan show offsets and clear changes in MSL rates after major earthquakes (Kato, 1983). These records have been used to model the fault mechanics and the viscoelastic structure of subduction zones (Savage and Thatcher, 1992; Savage, 1995). The NWLON stations in California, Oregon, Washington, and Alaska are also in tectonically active regions close to plate boundaries with the potential for large magnitude earthquakes.

Water level records along the south coast of Alaska have been used in studies of transient postseismic deformation following the March 1964 Prince William Sound earthquake, one of the strongest recorded seismic events (Hicks, 1972; Savage and Plafker, 1991; Cohen et al., 1995; Cohen, 1996; Cohen and Freymueller, 1997). Water level records for the Cascadia subduction zone along the coast of California, Oregon, and Washington have been examined in an effort to measure tectonic strain accumulation and the potential for major earthquakes (Savage et al., 1991; Dragert et al., 1994; Mitchell et al., 1994).

The occurrence of a major earthquake near a water level station should be noted in evaluating MSL trends, even if there is no obvious coseismic offset in the record. A change in MSL trend may not become evident until several decades after an earthquake (Cohen and Freymueller, 2001).

II. WATER LEVEL STATIONS

NOS has collected water level data for a span of more than 25 years at 117 locations. These stations are listed in Appendix I. Although there may be long data gaps at some of the locations, the existing data can provide good estimates of linear MSL trends since the vertical datums have been carefully maintained through periodic leveling to stable benchmarks with respect to the adjacent landmass. Appendix I gives the NWLON station number, latitude, longitude, first year of data, last year of data, range of years, and the station name and state or territory.

At a few stations, a new NWLON station number was given when the gauge was moved to a nearby location. A single time series can represent these locations, since the vertical station datums have been leveled to some of the same benchmarks. These locations are Bermuda, Philadelphia, Cambridge, Springmaid Pier, Grand Isle, Sabine Pass, and Kodiak Island.

Data collection at some stations has been discontinued, but a long enough span of data exists to produce accurate linear MSL trends. These stations and their termination years are Chuuk (1995), Seavey Island (1986), Port Jefferson (1992), New Rochelle (1981), Portsmouth (1987), Miami Beach (1981), Eugene Island (1974), Padre Island (1994), Newport Beach (1993), Rincon Island (1990), and Guantanamo Bay (1971).

The locations of the stations in Appendix I are shown in Figures 1 to 7, with the size of the station symbols indicating the year range of water level data. Also shown are the locations of major earthquakes with magnitudes greater than 7.5. The dates and epicenter locations of these earthquakes are listed in Table 1. All the earthquakes are in Alaska, except for one each in California, Hawaii, and Guam. These earthquakes can result in slip along several hundred kilometers of a tectonic plate boundary, immediately affecting the water levels at nearby NWLON stations with an offset and/or a change in the MSL trend.

Table 1. Major earthquakes near NWLON stations

Date	State or Territory	Longitude	Latitude	Magnitude
04/18/1906	California	122 28.8 W	37 40.2 N	7.7
03/09/1957	SW Alaska	175 37.8 W	51 17.4 N	8.8
07/10/1958	SE Alaska	136 31.2 W	58 20.4 N	8.3
03/28/1964	South Alaska	147 43.8 W	61 2.4 N	9.2
02/04/1965	SW Alaska	178 33.0 W	51 17.4 N	8.7
07/30/1972	SE Alaska	135 41.4 W	56 49.2 N	7.6
11/29/1975	Hawaii	155 0.0 W	19 20.4 N	7.5
02/28/1979	South Alaska	141 36.0 W	60 38.4 N	7.6

Table 1. Major earthquakes near NWLON stations				
Date	**State or Territory**	**Longitude**	**Latitude**	**Magnitude**
05/07/1986	SW Alaska	174 45.0 W	51 19.8 N	8.0
11/30/1987	SE Alaska	142 47.4 W	58 40.8 N	7.9
03/06/1988	SE Alaska	143 1.8 W	56 57.0 N	7.7
08/08/1993	Guam	144 48.1 E	12 58.9 N	8.0
06/10/1996	SW Alaska	177 37.8 W	51 33.6 N	7.9

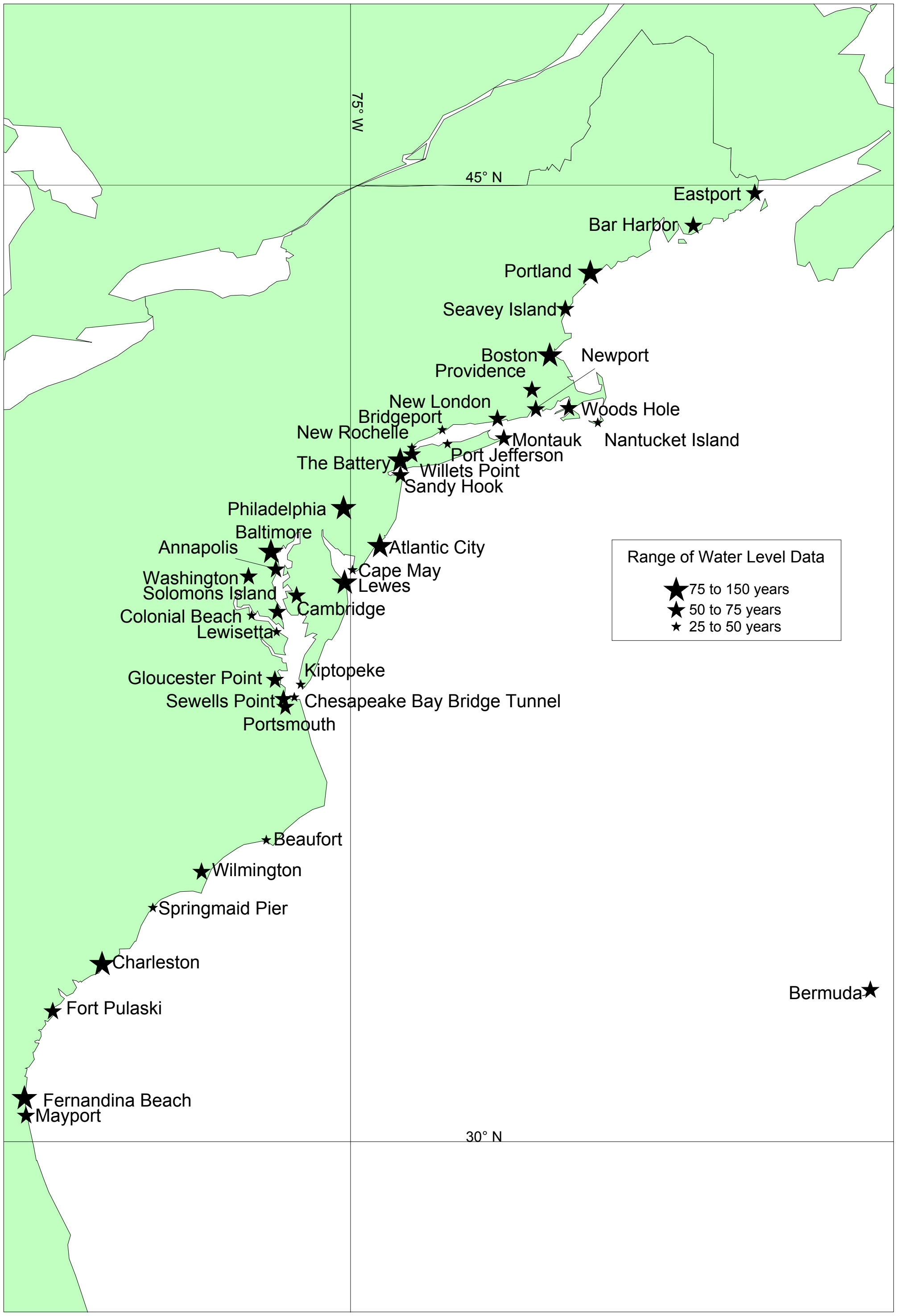

Figure 1. NWLON stations on the U.S. east coast.

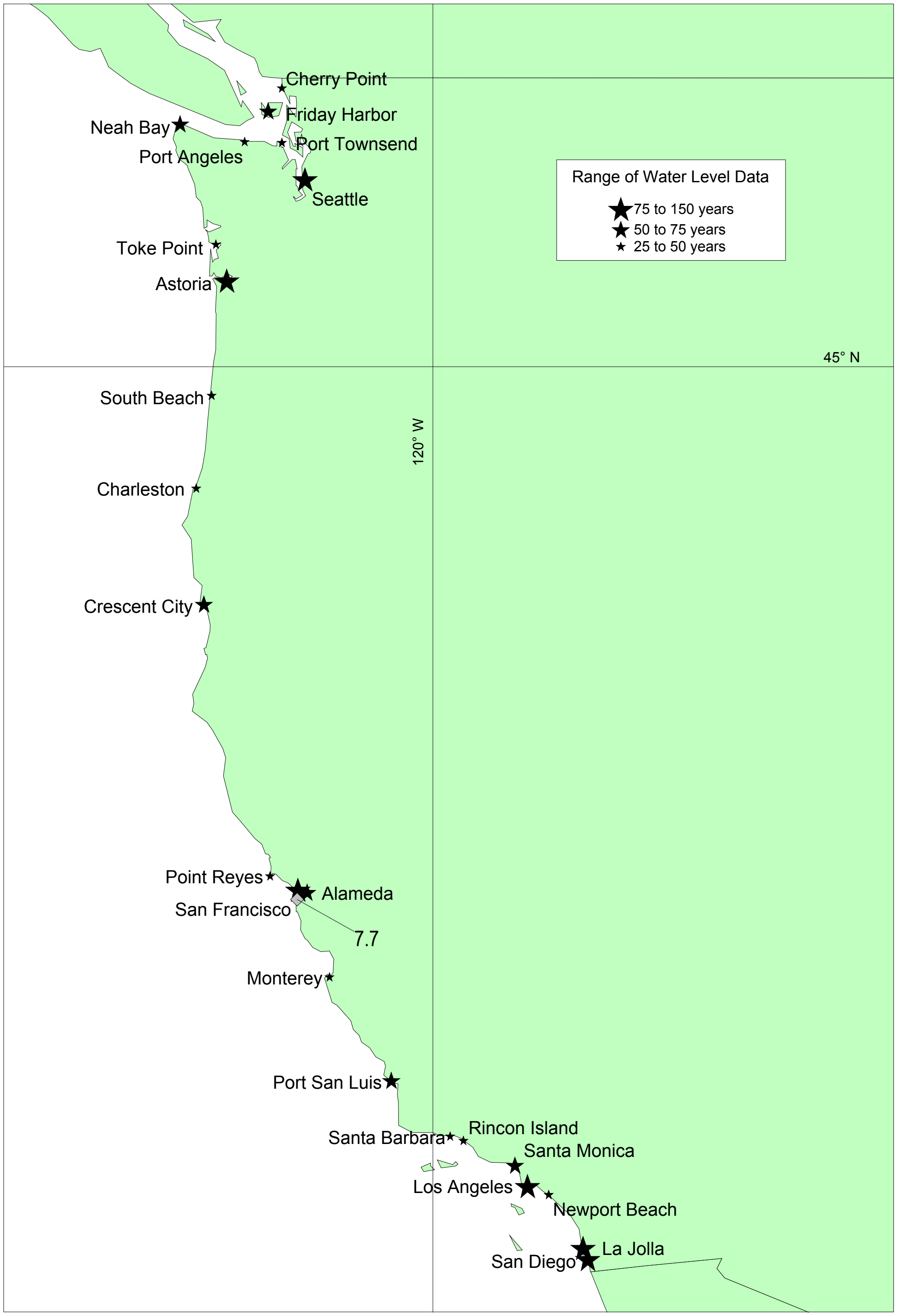

Figure 2. NWLON stations on the U.S. west coast with major earthquake indicated by diamond.

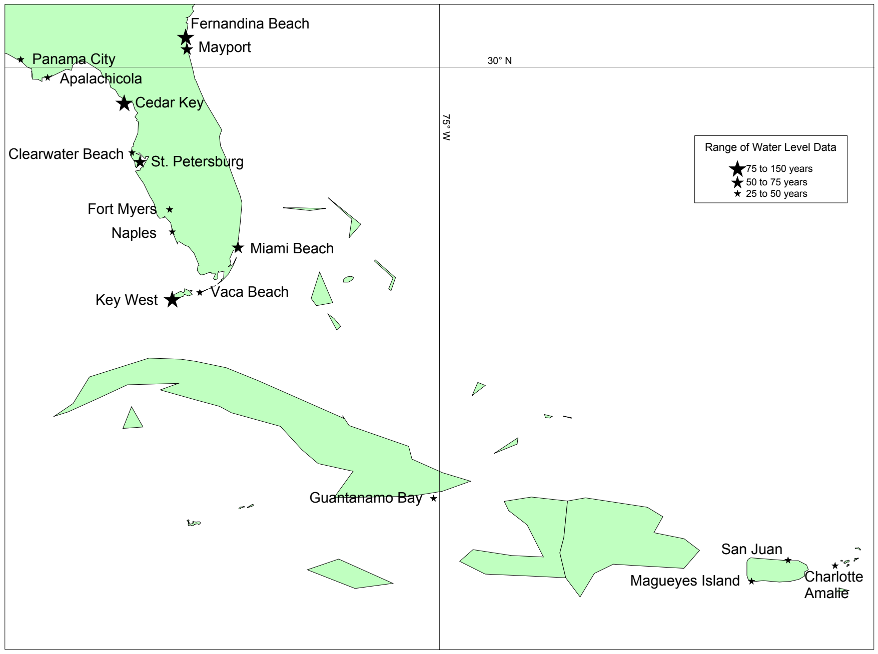

Figure 3. NWLON stations in the eastern Gulf of Mexico and Caribbean.

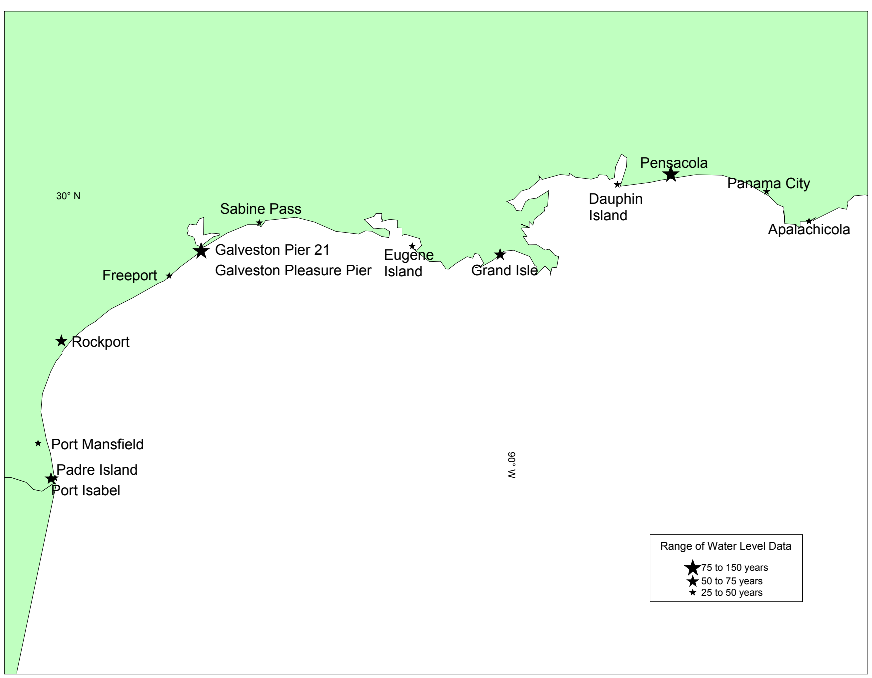

Figure 4. NWLON stations in the western Gulf of Mexico.

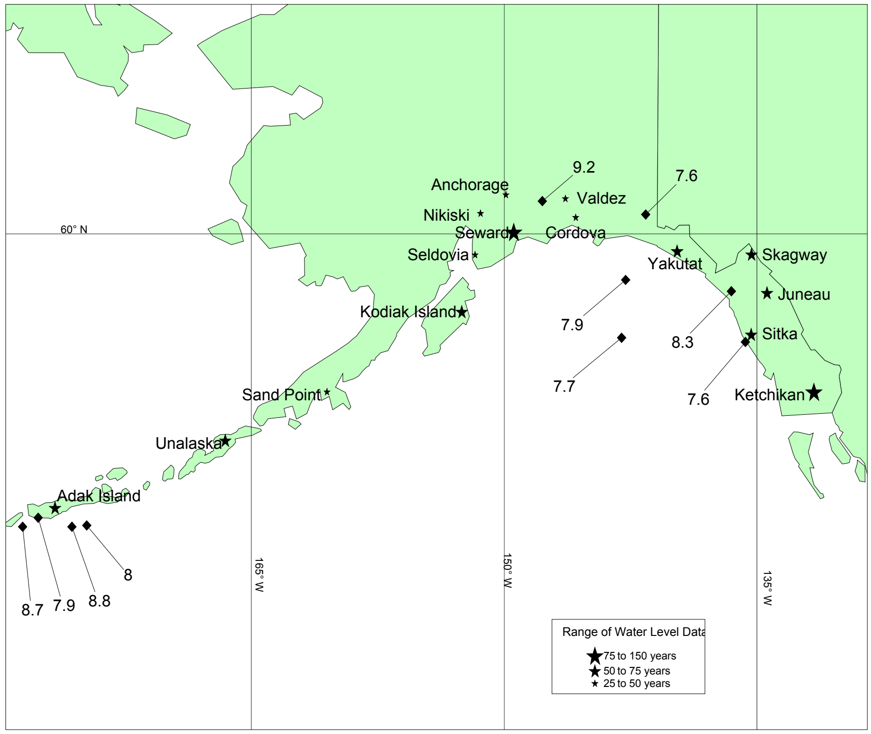

Figure 5. NWLON stations in Alaska with major earthquakes indicated by diamonds.

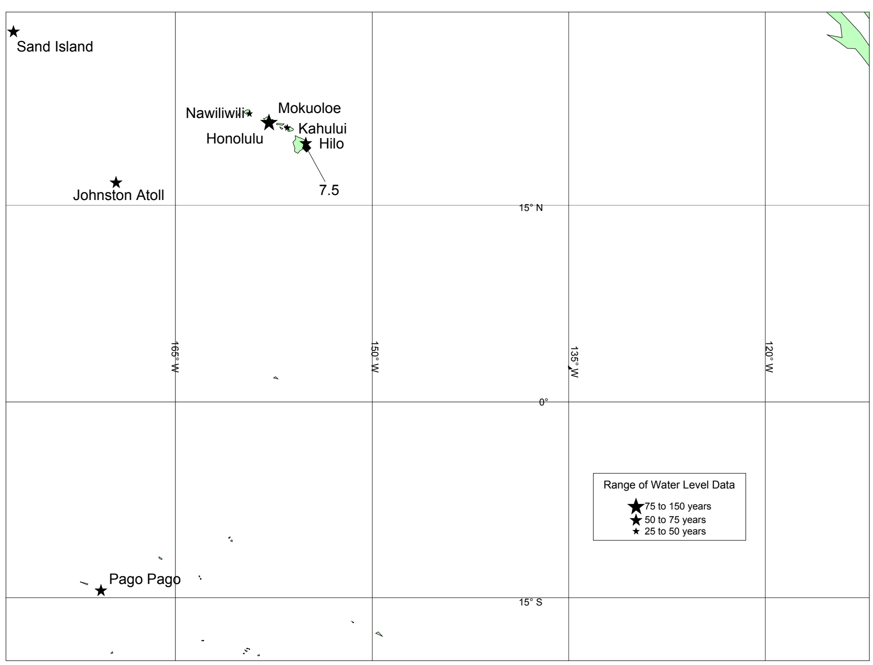

Figure 6. NWLON stations in the eastern Pacific Ocean with major earthquake indicated by diamond.

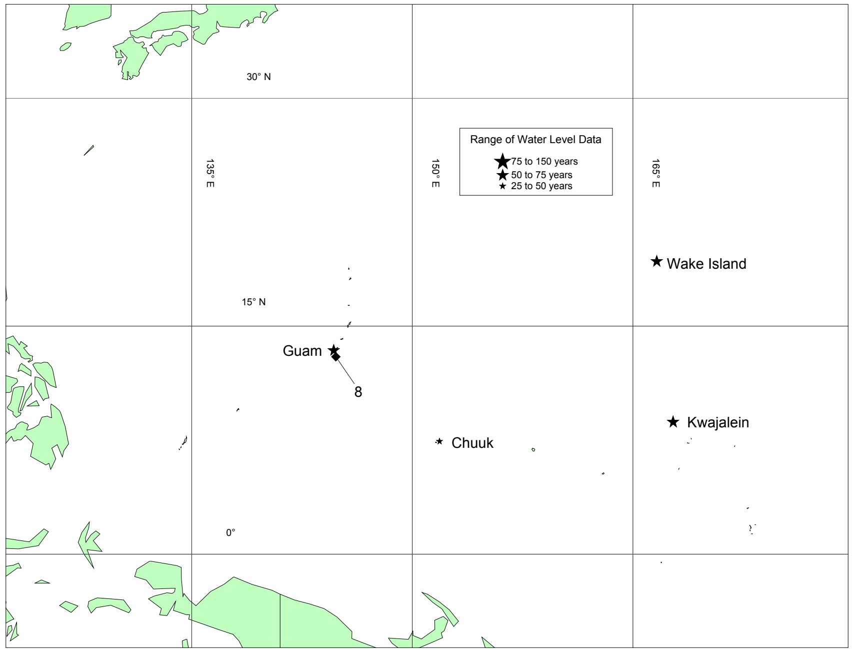

Figure 7. NWLON stations in the western Pacific Ocean with major earthquake indicated by diamond.

III. DERIVATION OF MEAN SEA LEVEL TRENDS

Linear secular trends in annual MSL data are usually computed as the least squares linear regression to a bivariate distribution of the data value versus year. If x_i and y_i represent the year and the corresponding annual MSL after the subtraction of their respective means, the slope of the least squares best-fit line is

$$b = \frac{\sum_i x_i y_i}{\sum_i x_i^2} \qquad \textbf{(1)}$$

The standard error of the slope is

$$s_b = \frac{s_{xy}}{\sqrt{\sum_i x_i^2}} \qquad \textbf{(2)}$$

where

$$s_{xy} = \sqrt{\frac{\sum_i y_i^2 - b\left(\sum_i x_i y_i\right)}{n-2}} \qquad \textbf{(3)}$$

is the standard deviation of the MSL residual y_i - bx_i and n is the number of annual MSL values. This method does not take into account the fact that the data are a consecutive time series rather than being composed of independent data points.

The estimated error of the slope s_b is valid only if the residual values are serially uncorrelated (Box and Jenkins, 1976; Box et al, 1978). The residual MSL for each year should be independent of the residual MSL for any previous year or any following year (i.e. the residual series must be a random stationary process). This condition is often untrue in time series analysis and, in particular, is usually untrue for sea level time series. The predominant residual signal is characterized by periods of 3-5 years and is driven by the propagation of ENSO (El Nino/Southern Oscillation) conditions in the tropical Pacific throughout the global oceans and atmosphere (Chelton and Enfield, 1986; Douglas et al., 2001).

In fact, the sea level residual variability can be characterized, to first order, as an autoregressive time series of order 1. For an autoregressive process of order 1, the best estimate of the next data value is not zero, but a fraction of the present value. For a residual water level y_i - bx_i,

$$y_i - bx_i = \phi_1\left(y_{i-1} - bx_{i-1}\right) + \varepsilon_i \qquad \textbf{(4)}$$

where i-1 indicates the previous data value, ϕ_1 is the autoregressive parameter of order 1, and ϵ_i is a stationary random time series representing the model's error. ϵ_i is essentially the unpredictable part of the residual MSL.

Both the slope b of the least squares fitted line and the autoregressive parameter ϕ_1 must be determined from the available MSL data. Although the slope b will be nearly identical to the slope obtained from a simple linear regression, the standard error s_b will be greater, due to the necessity of also determining ϕ_1 from the same set of data. The main consequence of not considering the autocorrelation of the residual is that the uncertainty in MSL trends is underestimated. Observation of significant differences in MSL trends over time or between locations can require a longer data series, if they are correctly modeled as linear trends with autoregressive residuals instead of as simple linear trends.

MSL trends can be determined with higher precision from monthly MSL data even if twelve additional parameters are introduced to describe the average seasonal cycle by month. The equation to be solved for linear regression with autoregressive residuals of order 1 from monthly MSL data is

$$y_i - bx_i - m_j = \phi_1\left(y_{i-1} - bx_{i-1} - m_{j-1}\right) + \varepsilon_i \qquad \textbf{(5)}$$

where y_i is now the monthly MSL, x_i is the year plus a fractional year corresponding to the month of y_i, and m_j is a mean offset corresponding with the month of y_i and is one of the twelve parameters representing the average seasonal MSL cycle. The autoregressive coefficient ϕ_1 for each station indicates the predictable part of the residual MSL. ϵ_i is a stationary random time series representing the model's error which is the unpredictable part of the residual MSL.

When MSL trends were calculated for all 117 stations described in Section II, the average of all the trend standard errors are shown in Table 2 for four different methods of calculation. The results discussed in the following sections of this report will be those obtained by linear regression of monthly MSL data with autoregressive residuals of order 1. In addition to producing the correct standard error for the trend, the average seasonal MSL cycle and the autoregression coefficient are also produced.

Table 2. Average standard error of mean sea level trends

Method of Calculation	Annual MSL Data	Monthly MSL Data
Linear Regression	0.57 mm/yr	0.27 mm/yr
Linear Regression with Autoregressive Residuals of Order 1	0.75 mm/yr	0.47 mm/yr

IV. LINEAR MEAN SEA LEVEL TRENDS

Following the method outlined in Section III, linear MSL trends were calculated for the NWLON water level stations listed in Appendix I using all available monthly data. Table 3 lists the slope of the trend, the intercept at the year 2000, and the autoregressive coefficient along with the standard errors of each value. The 95% confidence interval for each value is 1.96 times the standard error above and below the calculated value (Box et al., 1978). Also shown in the last column of Table 3 is the standard error of the linear regression with autoregressive residual model. Values for the average seasonal MSL cycles were obtained simultaneously and will be discussed in Section V of this report.

The 95% confidence intervals of the MSL trends for all water level stations are displayed in Figures 8 to 10. The range of the confidence intervals are inversely proportional to the length of the data series. The data time periods vary from a minimum of 25 years up to 146 years. The widest confidence intervals are for the stations with the shortest time periods of data.

Since most of the U.S. east coast stations (Figure 8) have been in operation for many years, the trends are well determined showing narrow confidence intervals. The stations south of The Battery generally have a greater MSL trend than stations north of The Battery. New Rochelle appears to have an anomalously low trend (0.54 mm/yr) based on 25 years of data (1957-1981) while Chesapeake Bay Bridge Tunnel appears to have an anomalously high trend (7.01 mm/yr) based on 25 years of data (1975-1999). However, comparable trends were found at nearby stations over the same 25-year periods. This indicates the danger in relying on only 25 years of data to determine a long term MSL trend without considering the confidence interval.

The U.S. west coast and Alaskan NOS stations (Figure 9) have a greater variability of trends due to the variety of tectonic activity affecting vertical land motions. Often nearby stations can have significantly different trends. Some of the newer west coast and Alaskan stations have wide confidence intervals due to shorter data sets. The most negative trend for all the stations is at Skagway where rapid vertical uplift due to local glacial rebound is occurring. Four stations (San Francisco, Seward, Adak Island, and Unalaska) have separate trends determined for pre- and post-earthquake time periods. Although pre-earthquake trends for Adak Island and Unalaska are based on only 14 and 23 years of data, respectively, they are included for comparison with post-earthquake trends.

There is somewhat less variability in the trends for the tropical Pacific, Bermuda, Gulf of Mexico, and Caribbean stations (Figure 10), except for a group of stations in Louisiana and part of Texas which show large positive trends. The stations in Louisiana and Texas are undergoing rapid land subsidence due to sediment loading and compaction of the Mississippi River delta and/or oil and gas extraction. In the Hawaiian Islands, the station at Hilo has a larger MSL trend than the other Hawaiian stations. Hilo is on the volcanically active island of Hawaii, which is in the process of loading the Pacific lithospheric plate. The MSL trend initially derived for Freeport was 10.83 mm/yr. However, a comparison of the data at Freeport with nearby stations showed an unexplained offset from December 1971 to January 1972. Therefore, a parameter was introduced to account for this offset, and the corrected MSL trend is 5.87 mm/yr with an offset of 0.160 m +/- 0.039.

Figure 11 shows an example of how well the MSL trend and its 95% confidence interval fit the monthly MSL data for Honolulu after the removal of the average seasonal cycle. The plot also shows a smoother 5-month running average. There are similar plots for all NWLON stations in Appendix II. The value of the intercept at which the trend crosses the year 2000 axis (given in Table 3) indicates how far the MSL has changed since the last establishment of the MSL datum. For most stations, the last MSL datum was established with data for the epoch 1960-1978, centered on the year 1969. For most stations with significant trends, the trendline can be seen to cross zero close to the year 1969 (Figure 11 and 12). Therefore, 31 years have elapsed by the year 2000 with corresponding changes in MSL caused by the individual station trends. The MSL datums of the stations with the most rapid trends have been recently revised, and their year 2000 MSL values are now closer to zero. Sabine Pass, Galveston Pier 21, and Galveston Pleasure Pier MSL datums were updated with 5 years of data from 1990-1994. Juneau, Skagway, Seldovia, Nikiski, Anchorage, Kodiak Island, and Unalaska datums were updated with 5 years of data from 1994-1998. The rest of the station datums are due for updating with data from the NOS-defined epoch 1980-1998.

In the plots in Appendix II, the times of major earthquakes occuring near NWLON stations (as listed in Table 1) are shown as solid vertical lines. Several stations show clear offsets due to vertical land motion caused by a major earthquake, sometimes accompanied by a change in the MSL trend after the earthquake. At four stations, separate MSL trends were calculated for periods before and after the event. Unalaska (Figure 13) and Adak Island show small offsets at the time of the March 9, 1957 Andreanof Islands earthquake. Seward had a substantial offset of about 1 m at the time of the March 28, 1964 Prince William Sound earthquake. Although there are no clear offsets associated with the other earthquakes in Table 1, there may have been a change in MSL trend at San Francisco after the April 18, 1906 earthquake. The San Francisco station is only 6 km away from the San Andreas fault which slipped horizontally by over 3 m at some locations. Therefore, three MSL trends were determined for San Francisco using 1) the total data set, 2) the data before the event, and 3) the data after the event (Table 3 and Appendix II).

The 95% confidence intervals of the autoregressive coefficients of order 1 (Table 3) are plotted in Figures 14, 16, and 18. A high coefficient indicates a high autocorrelation (or predictability) from one monthly residual MSL to the next. For the U.S. east coast stations (Figure 14) and Alaskan stations (Figure 16), the autoregressive coefficients cluster about 0.4. For the California stations south of Point Reyes, autocorrelations are higher, with the autoregressive coefficients grouped about 0.7. Further north, the autoregressive coefficients drop to 0.4-0.5. The sparseness of the data at Nikiski gives a poorly resolved autoregressive coefficient. The coefficients for the Gulf of Mexico, Bermuda, Johnston Atoll, Sand Island, and Wake Island cluster about 0.5 (Figure 18). Higher values around 0.7 are found for the Hawaiian and Caribbean stations. The highest values are above 0.8 and occur at the four western Pacific stations at Guam, Pago Pago, Kwajalein, and Chuuk.

The standard errors (in mm) listed in the last column of Table 3 are plotted in Figures 15, 17, and 19. They comprise the part of the time series not fitted by the linear regression with autoregressive residuals method. The standard errors indicate the level of the remaining variability which is the unpredictable portion of the month-to month change in mean sea level.

For the U.S. east coast (Figure 15), the standard errors rise gradually from a low of 40 mm in the north to a high of 70 mm in the south with two exceptions at Philadelphia and Washington, DC. These two river stations have high standard errors above 70 mm. Figure 12 shows the high month-to-month variability for Washington, DC which is greatly smoothed out by the 5-month running average.

In contrast to the east coast, standard errors of the U.S. west coast and Alaska stations (Figure 17) increase from south to north. The standard errors rise from 30 mm for southern California to over 90 mm in southwest Alaska. Standard errors rise to levels above 80 mm at Astoria and Toke Point and fall to about 60 mm for stations in Puget Sound.

The Hawaiian stations and the western Pacific stations generally have low standard errors below 45 mm (Figure 19). Note the effect of low month-to-month variability for Honolulu in Figure 11 compared to the higher variability for Washington, DC in Figure 12. The central Pacific stations of Johnston Atoll and Wake Island, and the central Atlantic station of Bermuda have high month-to-month variability with standard errors above 60 mm. In the Gulf of Mexico, standard errors are below 50 mm for the eastern Gulf rising above 60 mm in the western Gulf. The lowest standard errors at any of the NWLON stations are below 30 mm for the Caribbean stations.

Table 3. Linear MSL trends for all monthly data up to 1999									
Station Name	First Year	Year Range	MSL Trend and Standard Error (mm/yr)		Year 2000 MSL and Standard Error (mm)		Autoregressive Coefficient and Standard Error		Standard Error of Model (mm)
Nawiliwili	1954	46	1.53	0.38	42.1	11.6	0.66	0.03	39.9
Honolulu	1905	95	1.50	0.14	48.2	8.6	0.75	0.02	33.2
Mokuoloe	1957	43	1.12	0.46	44.2	13.2	0.72	0.04	36.0
Kahului	1954	46	2.09	0.43	55.2	12.4	0.77	0.03	31.1
Hilo	1927	73	3.36	0.21	64.9	9.3	0.62	0.03	40.7
Johnston Atoll	1947	53	0.68	0.31	22.5	13.1	0.43	0.04	65.1
Sand Island	1947	53	0.09	0.31	8.9	12.4	0.55	0.03	54.7
Guam	1948	52	0.10	0.90	13.3	27.4	0.88	0.02	40.1
Pago Pago	1948	52	1.48	0.56	37.9	17.4	0.82	0.02	36.7
Kwajalein	1946	54	1.05	0.51	20.1	16.3	0.83	0.02	33.3
Chuuk	1947	49	0.68	0.90	11.3	29.8	0.85	0.02	42.3
Wake Island	1950	50	1.89	0.35	60.9	14.1	0.46	0.04	66.4
Bermuda	1932	68	1.83	0.30	49.0	14.7	0.47	0.03	77.0
Eastport	1929	71	2.12	0.13	30.3	7.2	0.45	0.03	40.7
Bar Harbor	1947	53	2.18	0.16	52.0	7.6	0.32	0.04	40.1
Portland	1912	88	1.91	0.09	45.8	6.6	0.44	0.03	43.1
Seavey Island	1926	61	1.75	0.17	64.0	9.6	0.38	0.04	45.0
Boston	1921	79	2.65	0.10	68.2	6.9	0.38	0.03	45.2
Woods Hole	1932	68	2.59	0.12	65.1	7.0	0.40	0.03	41.0
Nantucket Island	1965	35	3.00	0.32	87.7	9.5	0.34	0.05	42.6
Newport	1930	70	2.57	0.11	75.7	6.5	0.35	0.03	41.0
Providence	1938	62	1.88	0.17	54.9	7.8	0.47	0.04	39.3
New London	1938	62	2.13	0.15	64.2	7.8	0.40	0.03	44.4
Bridgeport	1964	36	2.58	0.41	73.5	11.7	0.43	0.05	49.2
Montauk	1947	53	2.58	0.19	80.0	8.7	0.36	0.04	46.2
Port Jefferson	1957	36	2.44	0.39	73.9	13.2	0.39	0.05	49.1
Willets Point	1931	69	2.41	0.15	68.6	8.6	0.33	0.03	55.0
New Rochelle	1957	25	0.54	0.85	11.0	28.6	0.48	0.05	51.6
The Battery	1856	144	2.77	0.05	76.9	6.3	0.34	0.02	56.1
Sandy Hook	1932	68	3.88	0.15	110.2	8.7	0.33	0.03	55.1
Atlantic City	1911	89	3.98	0.11	126.5	8.2	0.31	0.03	59.1
Cape May	1965	35	3.88	0.53	102.8	14.2	0.41	0.05	57.5
Philadelphia	1900	100	2.75	0.12	89.8	10.0	0.37	0.03	73.7
Lewes	1919	81	3.16	0.16	92.7	9.8	0.34	0.04	59.7
Cambridge	1943	57	3.52	0.24	95.5	11.0	0.44	0.04	51.2

Table 3. Linear MSL trends for all monthly data up to 1999									
Station Name	**First Year**	**Year Range**	**MSL Trend and Standard Error (mm/yr)**		**Year 2000 MSL and Standard Error (mm)**		**Autoregressive Coefficient and Standard Error**		**Standard Error of Model (mm)**
Baltimore	1902	98	3.12	0.08	90.8	7.1	0.32	0.03	54.8
Annapolis	1928	72	3.53	0.13	101.8	8.3	0.34	0.03	53.3
Solomons Island	1937	63	3.29	0.17	92.9	9.1	0.36	0.04	53.2
Washington	1931	69	3.13	0.21	94.6	12.1	0.36	0.03	76.2
Kiptopeke	1951	49	3.59	0.27	115.7	11.1	0.35	0.04	58.5
Colonial Beach	1972	28	5.27	0.72	133.1	16.4	0.40	0.05	61.6
Lewisetta	1974	26	4.85	0.79	110.4	16.6	0.42	0.05	60.4
Gloucester Point	1950	50	3.95	0.27	116.3	11.6	0.35	0.04	61.3
Sewells Point	1927	73	4.42	0.16	136.8	9.9	0.34	0.03	64.2
Portsmouth	1935	53	3.76	0.23	114.6	12.7	0.29	0.04	61.8
Chesapeake Bay Bridge Tunnel	1975	25	7.01	0.86	163.9	18.0	0.38	0.06	66.6
Beaufort	1973	27	3.71	0.64	115.0	14.7	0.38	0.05	56.8
Wilmington	1935	65	2.22	0.25	70.8	12.3	0.49	0.03	65.2
Springmaid Pier	1957	43	5.17	0.49	110.8	15.9	0.50	0.04	64.2
Charleston, SC	1921	79	3.28	0.14	101.1	9.3	0.40	0.03	59.5
Fort Pulaski	1935	65	3.05	0.20	98.4	10.7	0.38	0.03	63.3
Fernandina Beach	1897	103	2.04	0.12	67.8	9.9	0.42	0.03	67.9
Mayport	1928	72	2.43	0.18	73.2	10.7	0.42	0.03	64.8
Miami Beach	1931	51	2.39	0.22	73.6	12.2	0.39	0.04	47.7
Vaca Key	1971	29	2.58	0.44	88.7	10.4	0.38	0.05	39.6
Key West	1913	87	2.27	0.09	77.8	6.4	0.47	0.03	40.1
Naples	1965	35	2.08	0.43	54.1	11.3	0.54	0.04	41.3
Fort Myers	1965	35	2.29	0.45	69.0	12.2	0.48	0.04	47.1
St. Petersburg	1947	53	2.40	0.18	78.4	7.9	0.40	0.04	41.9
Clearwater Beach	1973	27	2.76	0.65	72.7	13.8	0.50	0.05	42.4
Cedar Key	1914	86	1.87	0.11	61.3	7.6	0.42	0.03	46.3
Apalachicola	1967	33	1.53	0.58	56.2	14.6	0.50	0.05	53.6
Panama City	1973	27	0.30	0.64	40.9	13.5	0.45	0.05	46.4
Pensacola	1923	77	2.14	0.15	66.6	8.8	0.52	0.03	49.2
Dauphin Island	1966	32	2.93	0.59	81.5	15.2	0.47	0.05	52.8
Grand Isle	1947	53	9.85	0.35	157.3	13.1	0.62	0.03	51.0
Eugene Island	1939	36	9.74	0.63	315.0	29.8	0.58	0.04	52.8
Sabine Pass	1958	42	6.54	0.72	29.2*	21.7	0.62	0.04	72.6
Galveston Pier 21	1908	92	6.50	0.16	17.7*	11.1	0.53	0.03	67.2

Table 3. Linear MSL trends for all monthly data up to 1999

Station Name	First Year	Year Range	MSL Trend and Standard Error (mm/yr)		Year 2000 MSL and Standard Error (mm)		Autoregressive Coefficient and Standard Error		Standard Error of Model (mm)
Galveston Pleasure Pier	1957	43	7.39	0.53	26.8*	16.9	0.54	0.04	66.3
Freeport	1954	46	5.87	0.74	42.3	15.7	0.49	0.04	63.6
Rockport	1948	52	4.60	0.41	119.9	15.1	0.53	0.04	65.4
Port Mansfield	1963	35	2.05	0.75	86.7	20.0	0.56	0.04	65.3
Padre Island	1958	37	3.44	0.56	104.5	17.9	0.54	0.05	53.4
Port Isabel	1944	56	3.38	0.27	111.9	11.7	0.50	0.03	56.5
San Diego	1906	94	2.15	0.12	77.0	7.1	0.71	0.02	30.3
La Jolla	1924	76	2.22	0.17	83.6	8.5	0.72	0.02	31.8
Newport Beach	1955	39	2.22	0.53	81.6	15.5	0.76	0.03	30.5
Los Angeles	1923	77	0.84	0.16	39.4	8.0	0.71	0.02	30.9
Santa Monica	1933	67	1.59	0.25	52.2	11.0	0.74	0.03	35.6
Rincon Island	1962	29	3.22	0.85	97.2	22.3	0.75	0.04	34.1
Santa Barbara	1973	26	2.77	0.99	68.2	18.3	0.75	0.05	29.3
Port San Luis	1945	55	0.90	0.32	35.8	11.3	0.71	0.03	36.7
Monterey	1973	27	1.86	1.09	70.8	18.3	0.74	0.04	38.4
San Francisco	1854	146	1.41	0.08	46.0	8.0	0.69	0.02	44.9
San Francisco (Pre EQ)	1854	52	1.12	0.35	23.6	43.5	0.66	0.02	44.5
San Francisco (Post EQ)	1906	94	2.13	0.14	73.1	8.7			
Alameda	1939	61	0.89	0.32	37.0	12.8	0.71	0.03	45.2
Point Reyes	1975	25	2.51	1.27	76.4	21.1	0.70	0.04	48.9
Crescent City	1933	67	-0.48	0.23	-5.1	11.6	0.49	0.03	61.2
Charleston, OR	1970	30	1.74	0.87	30.5	19.4	0.54	0.05	65.7
South Beach	1967	33	3.51	0.73	79.6	18.4	0.50	0.04	69.3
Astoria	1925	75	-0.16	0.24	7.1	14.0	0.46	0.03	83.4
Toke Point	1973	27	2.82	1.05	35.9	22.8	0.43	0.05	83.4
Neah Bay	1934	66	-1.41	0.22	-44.0	12.3	0.35	0.03	75.1
Port Angeles	1975	25	1.49	1.10	54.3	20.9	0.48	0.05	69.1
Port Townsend	1972	28	2.82	0.88	84.0	18.6	0.52	0.05	62.7
Seattle	1898	102	2.11	0.10	67.6	8.1	0.40	0.03	59.7
Cherry Point	1973	27	1.39	0.94	50.5	19.0	0.53	0.05	62.2
Friday Harbor	1934	66	1.24	0.20	48.8	10.6	0.43	0.03	61.0
Ketchikan	1919	81	-0.11	0.16	-4.1	10.8	0.36	0.03	73.2

Table 3. Linear MSL trends for all monthly data up to 1999									
Station Name	**First Year**	**Year Range**	**MSL Trend and Standard Error (mm/yr)**		**Year 2000 MSL and Standard Error (mm)**		**Autoregressive Coefficient and Standard Error**		**Standard Error of Model (mm)**
Sitka	1938	62	-2.17	0.21	-69.6	11.2	0.36	0.03	66.5
Juneau	1936	64	-12.69	0.26	-16.9**	13.2	0.40	0.03	75.3
Skagway	1944	56	-16.68	0.42	-18.3**	19.6	0.48	0.04	89.0
Yakutat	1940	60	-5.75	0.27	-75.1	13.4	0.40	0.04	75.3
Cordova	1964	36	6.97	0.60	148.6	17.6	0.36	0.05	77.4
Valdez	1973	27	-0.34	1.00	35.9	22.1	0.37	0.05	83.7
Seward (Pre EQ)	1925	39	-0.13	0.57	-1019.1	38.8	0.36	0.04	84.0
Seward (Post EQ)	1964	36	-1.46	0.61	-42.8	16.3			
Seldovia	1964	36	-9.93	0.78	-29.5**	21.9	0.43	0.05	90.9
Nikiski	1973	27	-10.71	1.17	-25.5**	38.1	0.17	0.13	88.2
Anchorage	1972	28	2.76	1.16	26.9**	25.0	0.48	0.06	83.1
Kodiak	1975	25	-12.08	1.06	-56.1**	20.1	0.38	0.06	69.0
Sand Point	1972	28	0.07	0.93	-45.5	22.4	0.31	0.05	91.3
Adak Island (Pre EQ)	1943	14	2.48	1.84	116.7	93.0	0.29	0.04	66.0
Adak Island (Post EQ)	1957	43	-2.63	0.35	-38.9	12.2			
Unalaska (Pre EQ)	1934	23	-0.57	1.11	183.8**	63.0	0.37	0.04	75.7
Unalaska (Post EQ)	1957	43	-6.44	0.44	-41.1**	14.7			
Guantanamo Bay	1937	35	1.64	0.41	812.2	19.4	0.65	0.04	28.3
Charlotte Amalie	1975	25	0.50	0.74	17.5	11.8	0.73	0.04	24.7
San Juan	1962	38	1.43	0.36	58.4	9.3	0.68	0.04	27.2
Magueyes Island	1955	45	1.24	0.25	34.5	7.4	0.69	0.03	23.1

* Recently updated datum based on 1990-1994.

** Recently updated datum based on 1994-1998.

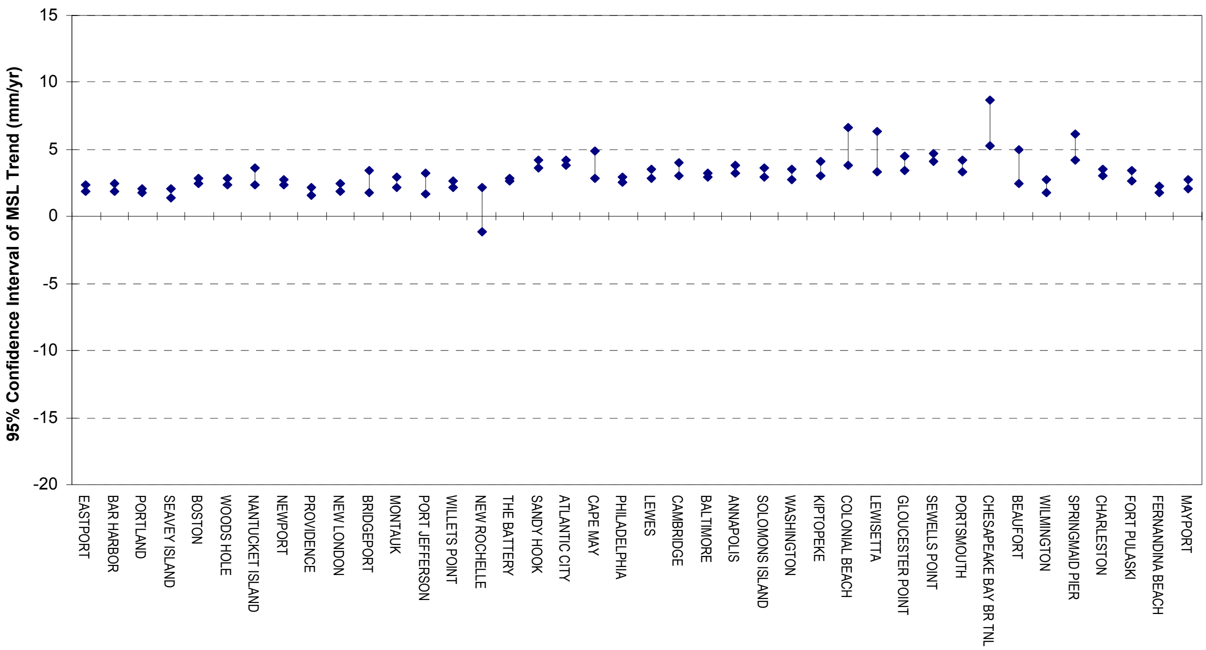

Figure 8. MSL trend range (mm/yr) for all monthly data up to 1999 for U.S. east coast stations.

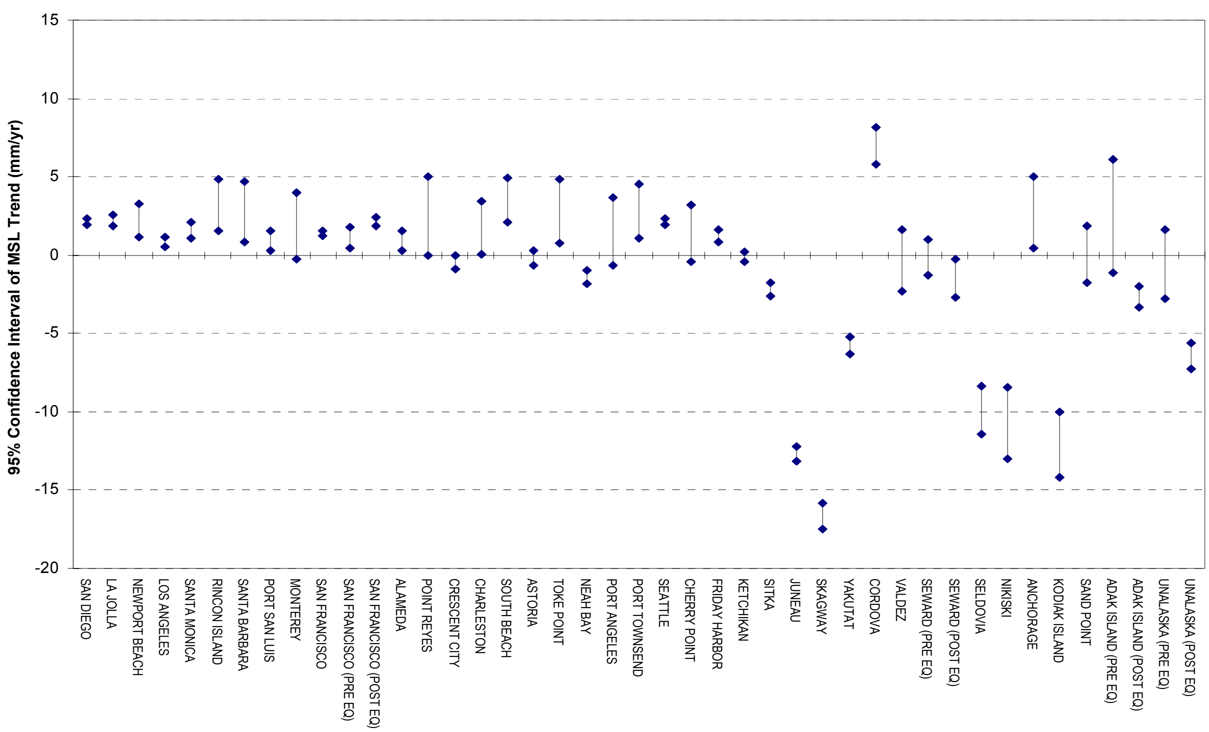

Figure 9. MSL trend range (mm/yr) for all monthly data up to 1999 for U.S. west coast and Alaska stations.

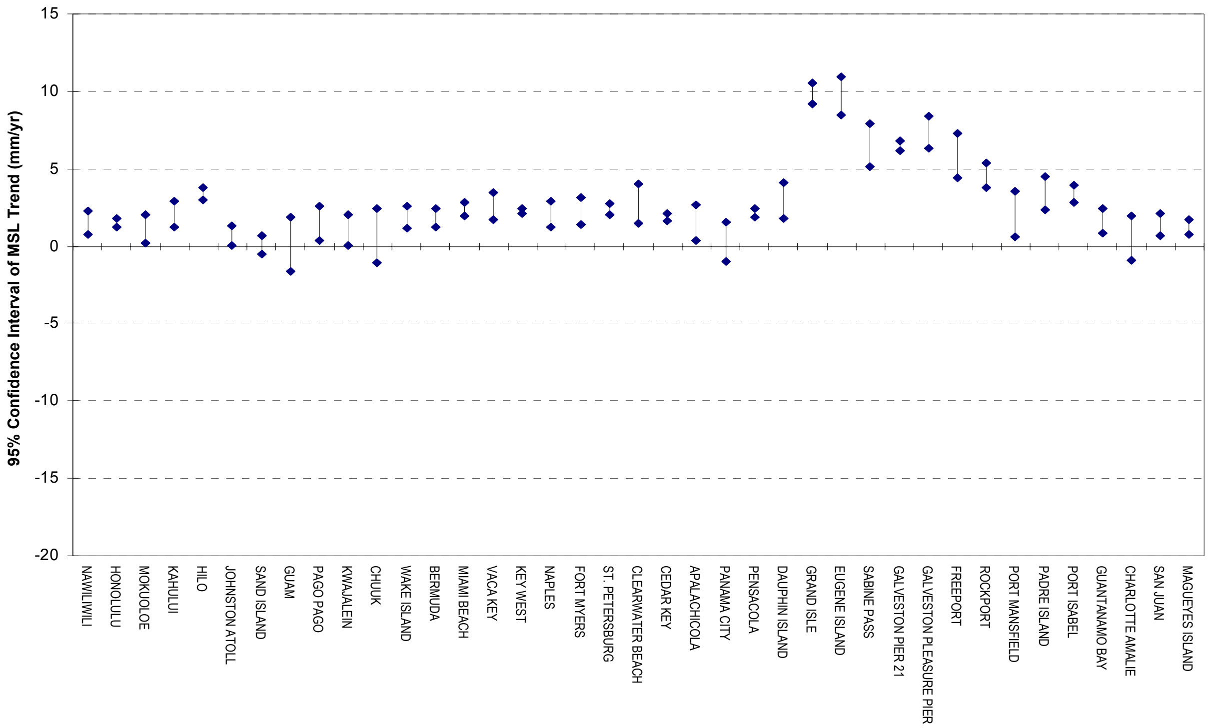

Figure 10. MSL trend range (mm/yr) for all monthly data up to 1999 for the tropical Pacific, Bermuda, Gulf of Mexico, and Caribbean stations.

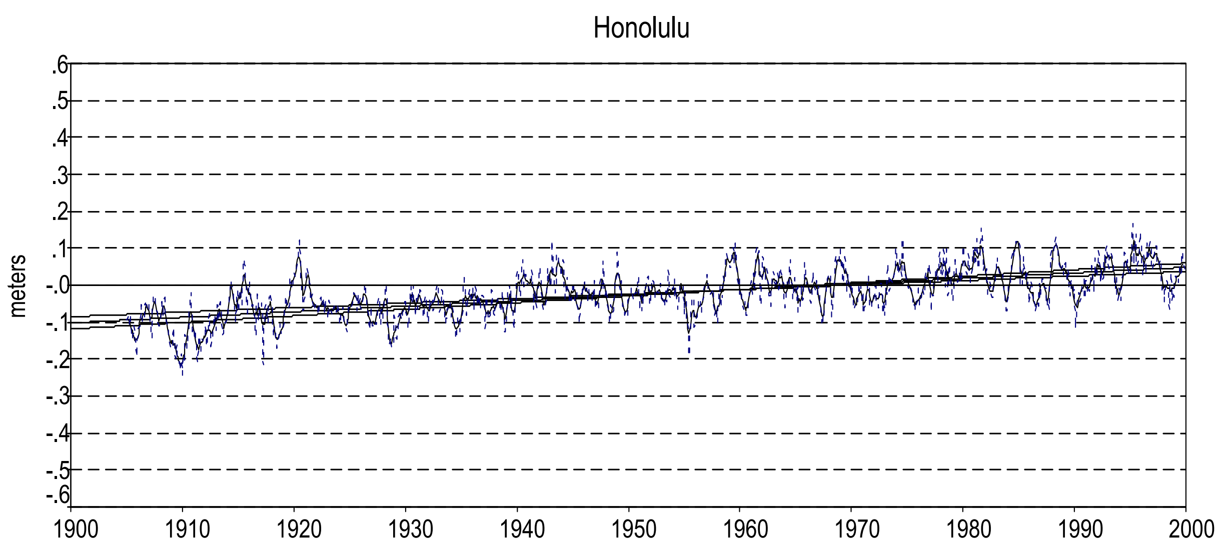

Figure 11. Monthly mean sea level at Honolulu with the average seasonal cycle removed (dashed curve), 5-month running average (solid curve), and the calculated MSL trend with 95% confidence interval.

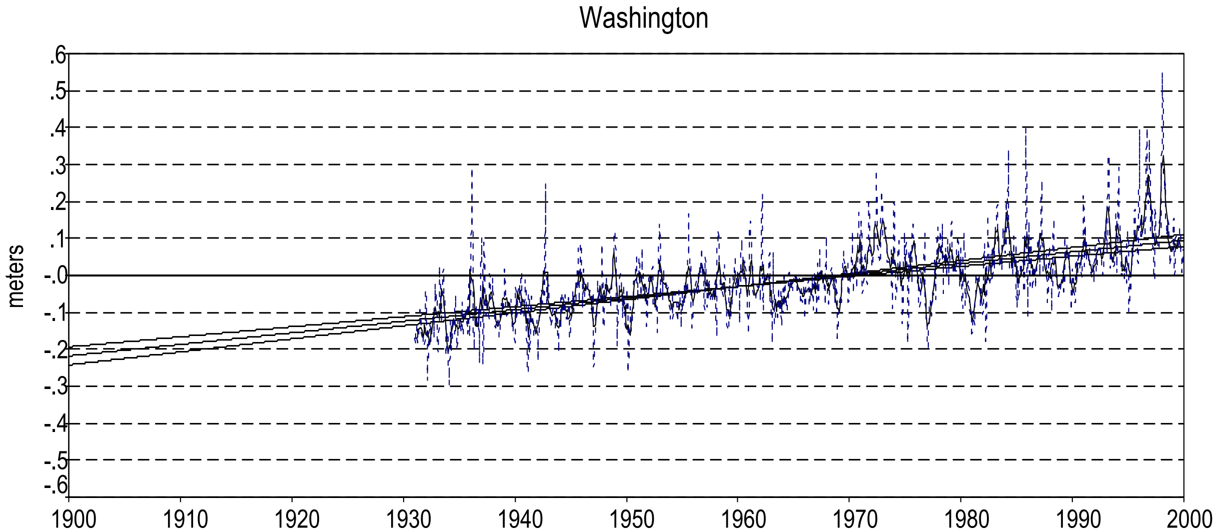

Figure 12. Monthly mean sea level at Washington, DC with the average seasonal cycle removed (dashed curve), 5-month running average (solid curve), and the calculated MSL trend with 95% confidence interval.

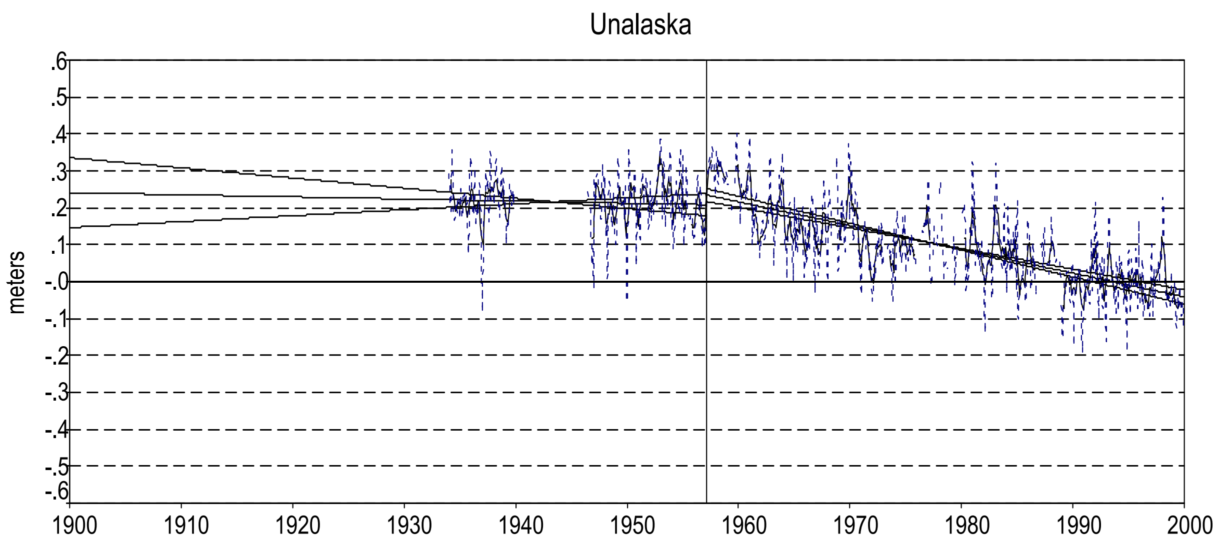

Figure 13. Monthly mean sea level at Unalaska with the average seasonal cycle removed (dashed curve), 5-month running average (solid curve), and the calculated MSL trends for the data before and after the 1957 earthquake with 95% confidence intervals.

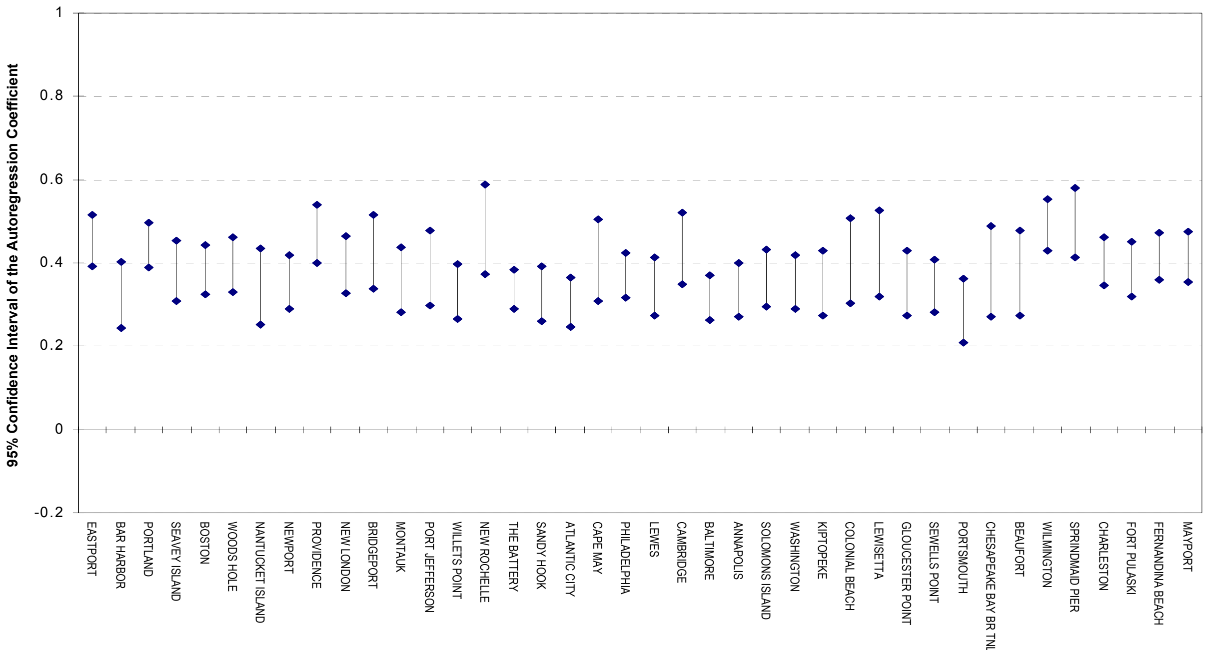

Figure 14. Autoregressive coefficient range for U.S. east coast stations.

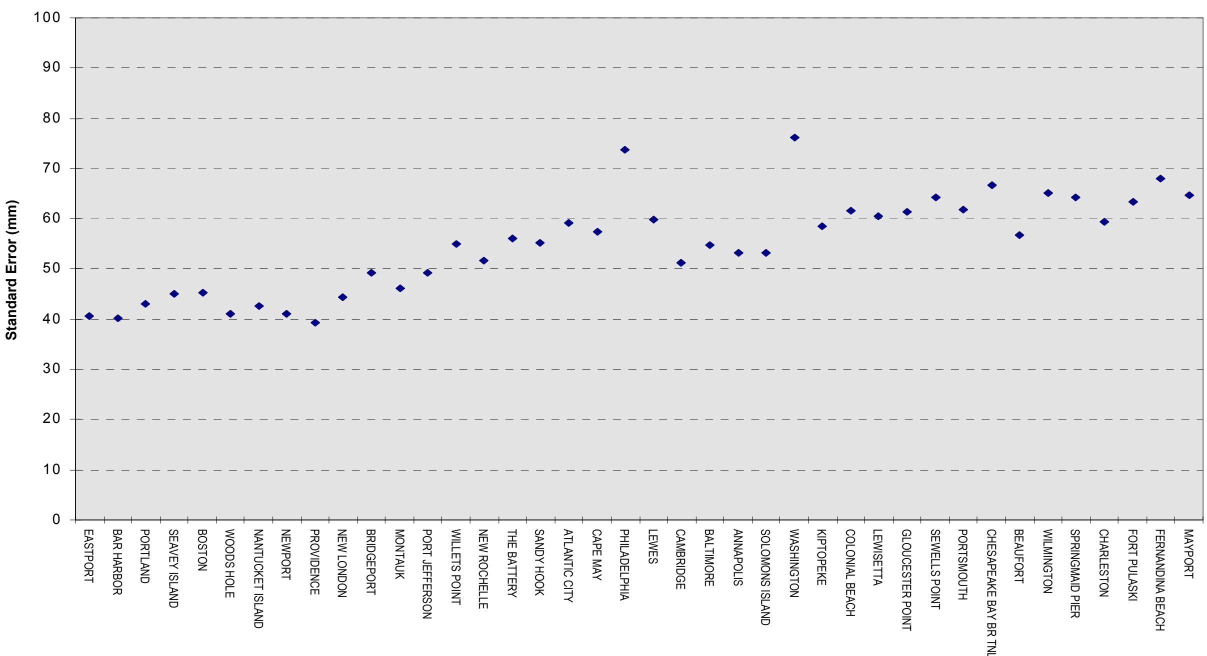

Figure 15. Standard error of the linear regression with autoregressive residuals method for U.S. east coast stations.

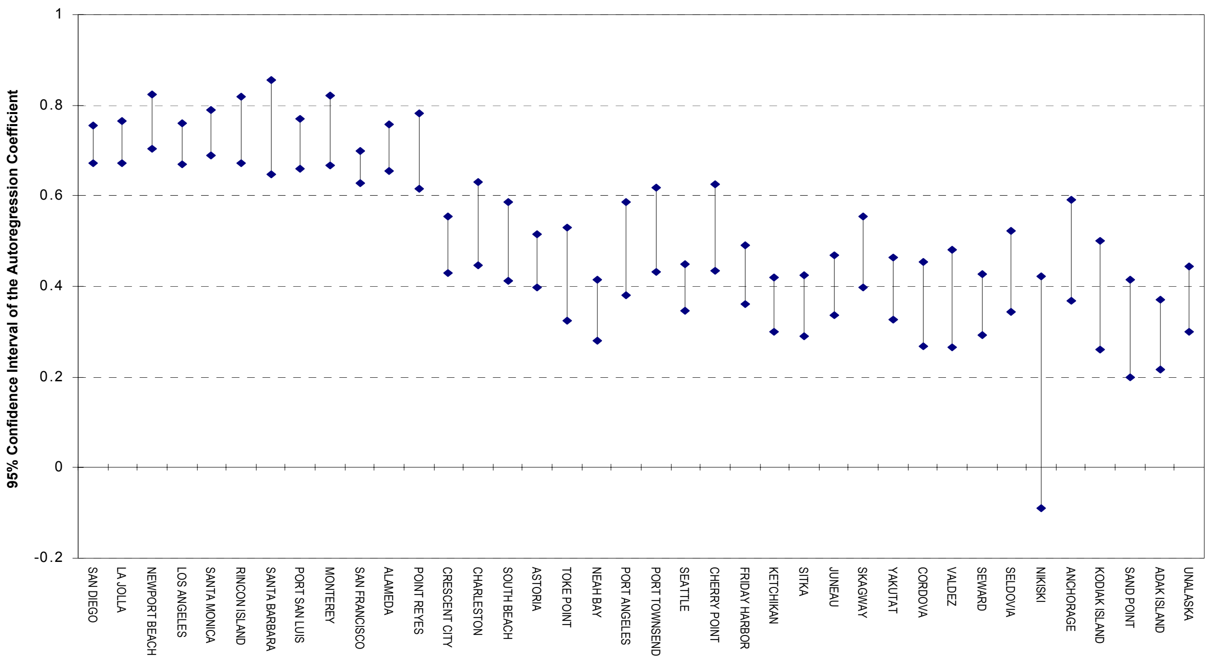

Figure 16. Autoregressive coefficient range for U.S. west coast and Alaska stations.

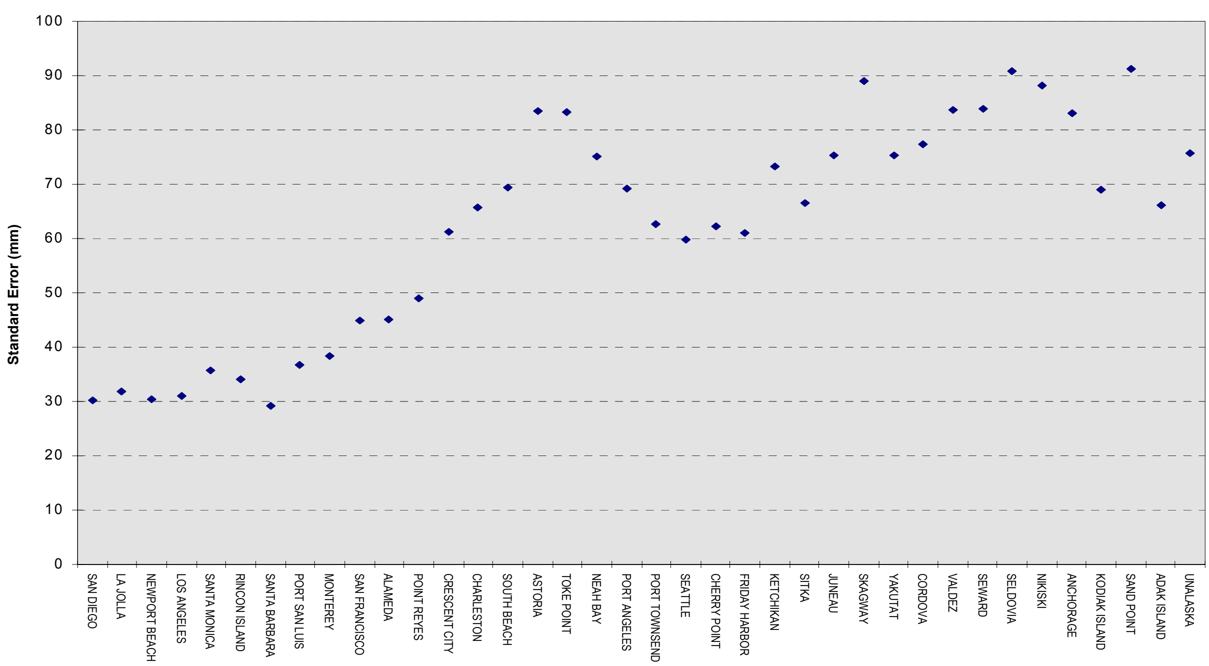

Figure 17. Standard error of the linear regression with autoregressive residuals method for U.S. west coast and Alaska stations.

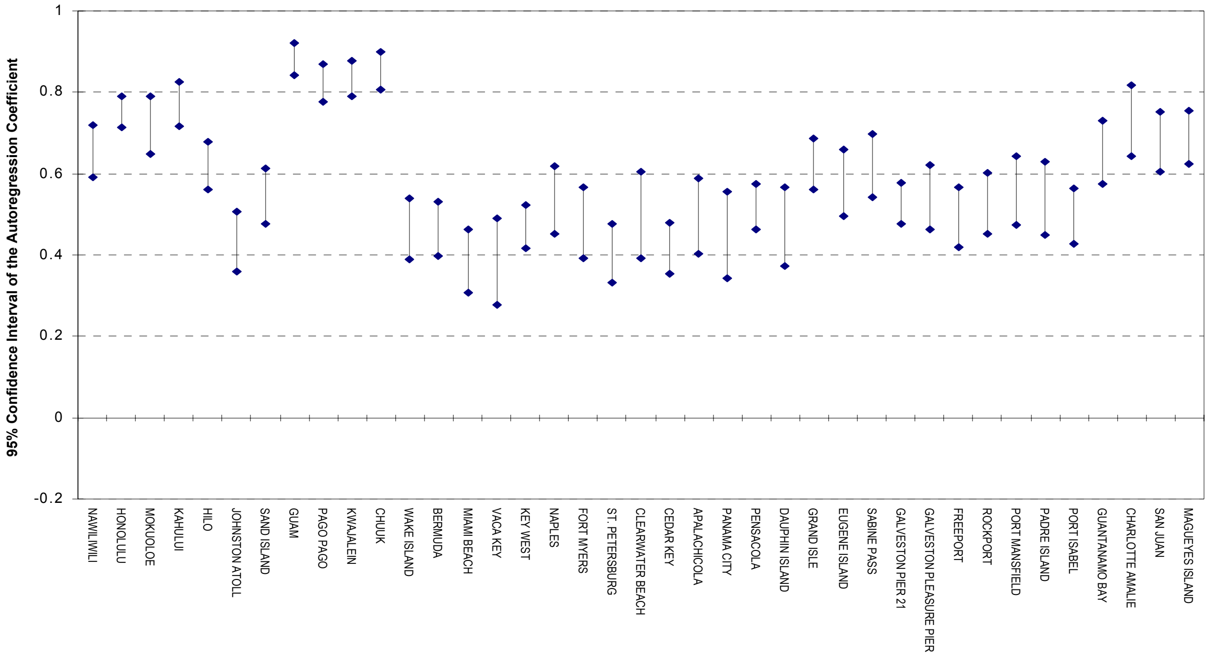

Figure 18. Autoregressive coefficient range for the tropical Pacific, Bermuda, Gulf of Mexico, and Caribbean stations.

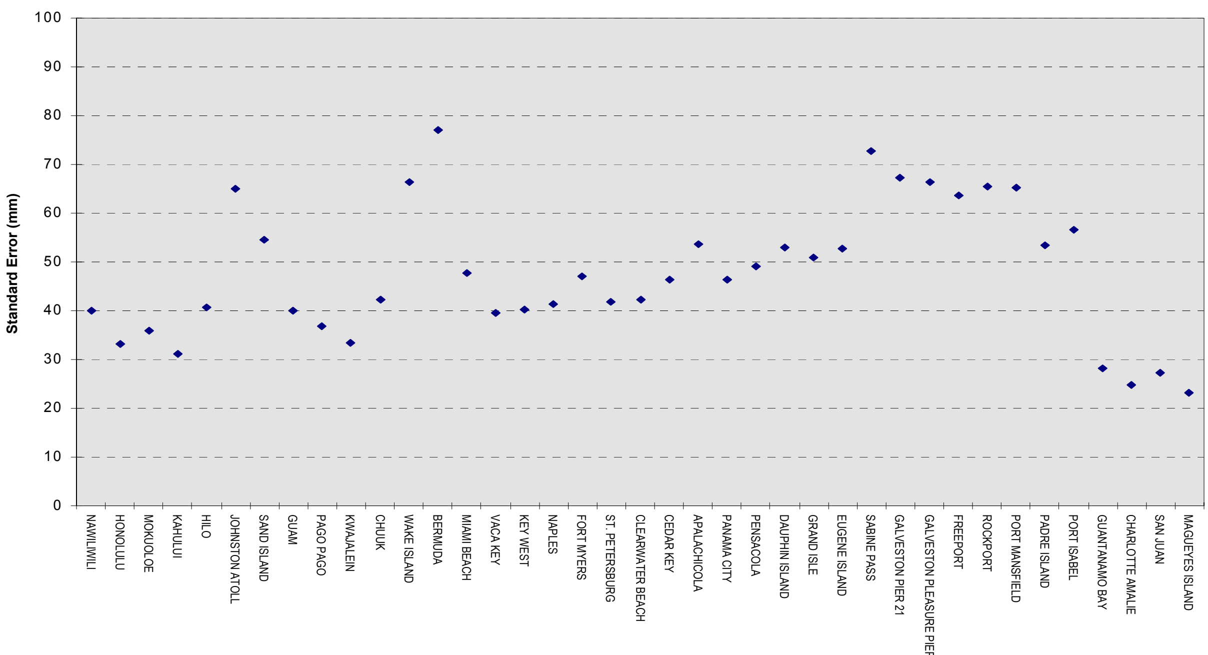

Figure 19. Standard error of the linear regression with autoregressive residuals method for the tropical Pacific, Bermuda, Gulf of Mexico, and Caribbean stations.

V. AVERAGE SEASONAL MEAN SEA LEVEL CYCLE

As a result of using monthly values rather than annual values for the determination of linear MSL trends, an average seasonal cycle is obtained for each station. The average seasonal cycles can show wide variations depending on the water temperature, winds, and currents in the nearby coastal ocean. The results for each NWLON station are given in Table B in Appendix III showing average MSL values for January through December and the mean value for the twelve months. The corresponding standard errors are given in the following line of the table. The mean values are, in effect, the intercept at which the trend crosses the year 2000 axis (and are also listed in Table 3).

The average seasonal cycles at eight selected representative stations are shown in Figures 20 to 27, with their 95% confidence intervals. Two cycles are displayed for clarity. Similar plots for all NWLON stations are found in Appendix III.

At Eastport, there is very little month-to-month variation in average MSL, while Fernandina Beach and Neah Bay have large seasonal variations of nearly 0.3 meters. At most stations, the water levels are highest in the late summer-early fall and lowest in late winter-early spring (Honolulu, Baltimore, and San Diego), reflecting the annual cycle of water temperature. However, at many U.S. west coast and Alaskan stations, the seasonal cycle shows highest water levels in the winter and lowest water levels in the summer (Neah Bay and Yakutat). Moreover, at some of the U.S. southeastern stations, there are two high and two low water level periods each year (Fernandina Beach and Galveston Pier 21). These effects are likely due to dynamic seasonal variations in the California Current, Alaska Current, and the Gulf Stream.

The level of the seasonal cycle reflects positive or negative trends since the establishment of the MSL datum. The monthly MSL values used in the analyses are relative to datums of the present NTDE (1960-1978), except for a few locations recently updated, as noted previously. The seasonal cycle is completely positive for Honolulu, Eastport, and San Diego, and mostly positive for Baltimore and Fernandina Beach, due to rising sea levels at these locations. The seasonal cycle is mostly negative for Yakutat, due to vertical uplift of the land since the datum was established. The cycles at Galveston Pier 21 and Neah Bay have relatively equal positive and negative months. At Neah Bay, the trend is small (-1.41 mm/yr), while at Galveston Pier 21 the MSL datum was recently updated with data from 1990-1994.

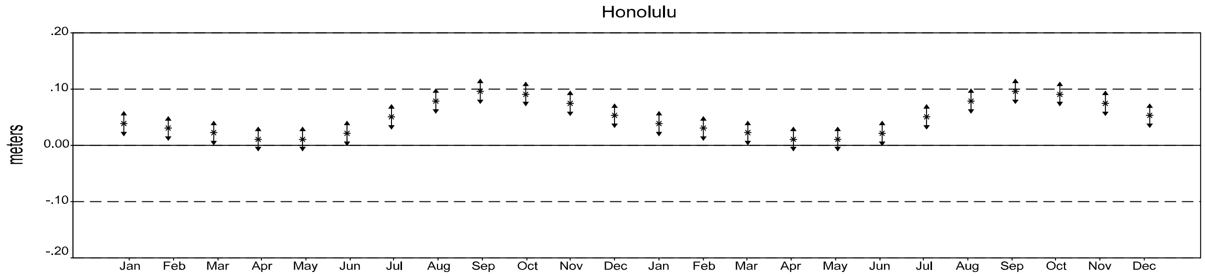

Figure 20. Average seasonal MSL cycle for Honolulu over a 2-year period with 95% confidence intervals.

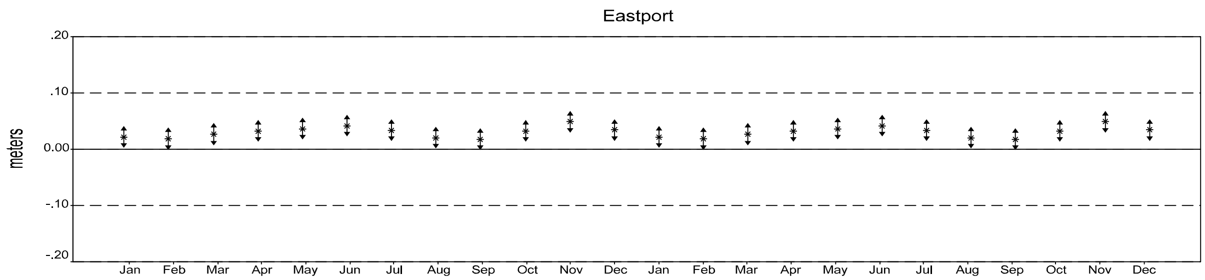

Figure 21. Average seasonal MSL cycle for Eastport over a 2-year period with 95% confidence intervals.

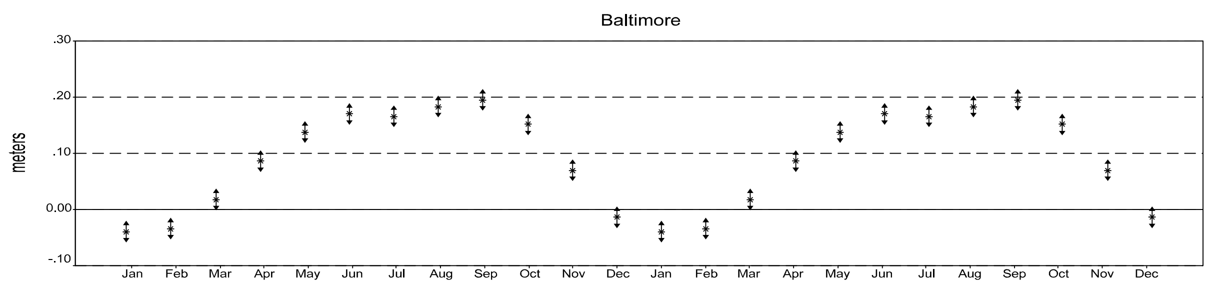

Figure 22. Average seasonal MSL cycle for Baltimore over a 2-year period with 95% confidence intervals.

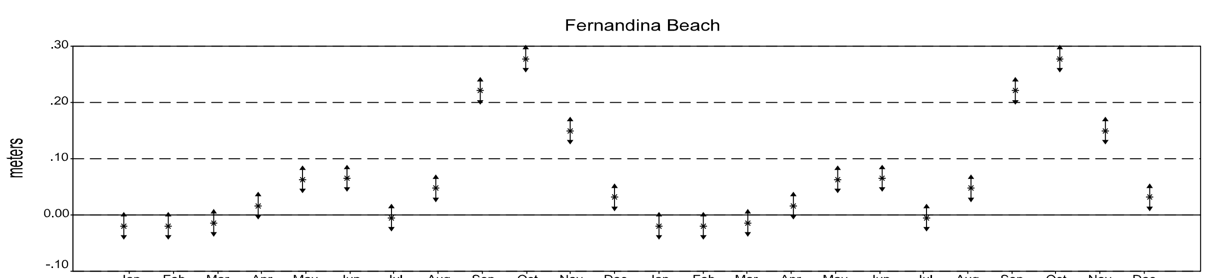

Figure 23. Average seasonal MSL cycle for Fernandina Beach over a 2-year period with 95% confidence intervals.

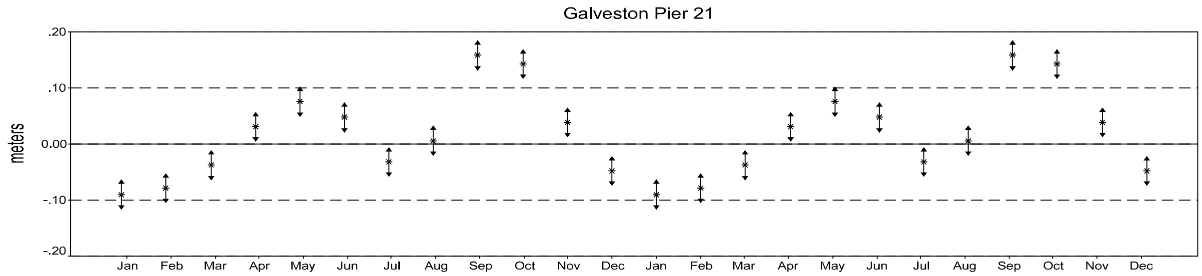

Figure 24. Average seasonal MSL cycle for Galveston Pier 21 over a 2-year period with 95% confidence intervals.

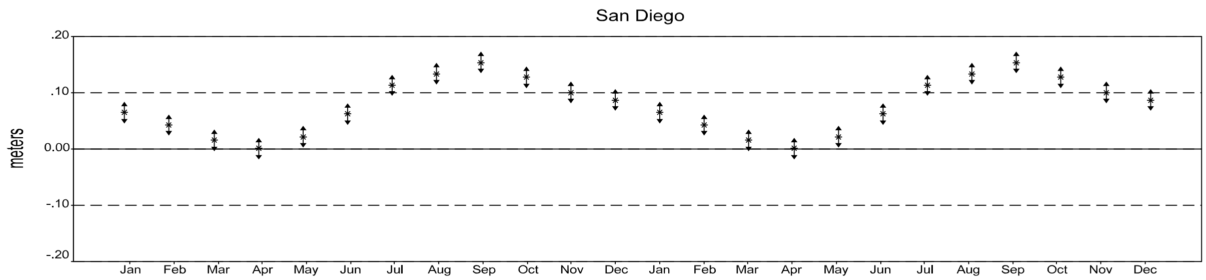

Figure 25. Average seasonal MSL cycle for San Diego over a 2-year period with 95% confidence intervals.

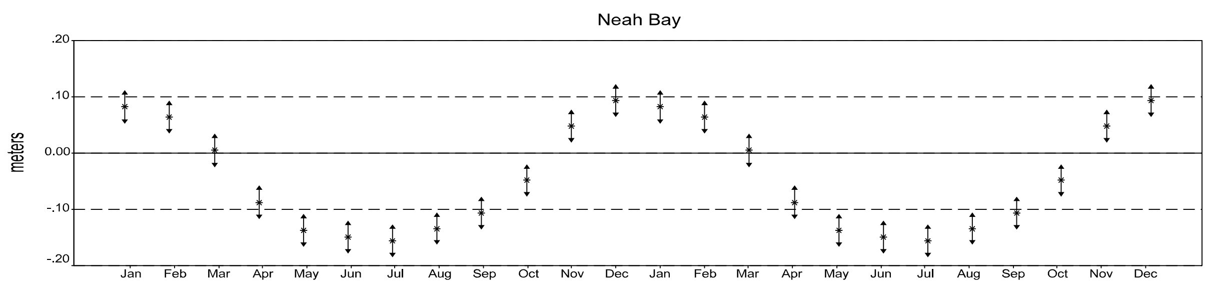

Figure 26. Average seasonal MSL cycle for Neah Bay over a 2-year period with 95% confidence intervals.

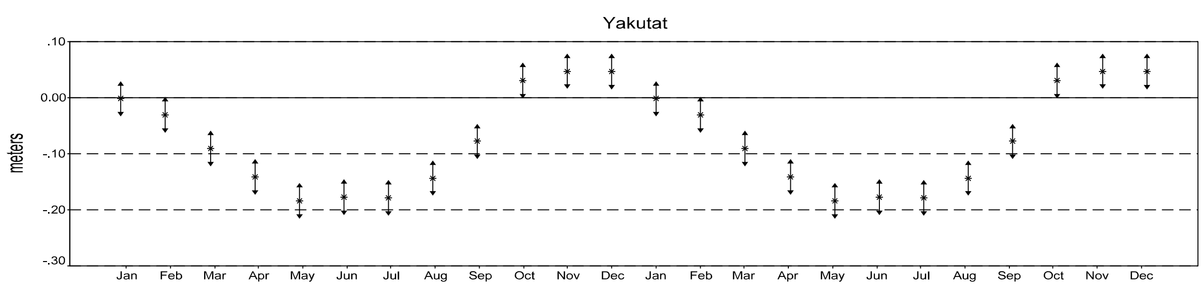

Figure 27. Average seasonal MSL cycle for Yakutat over a 2-year period with 95% confidence intervals.

VI. VARIABILITY OF RESIDUAL MONTHLY MEAN SEA LEVEL

After the linear trend and the average seasonal cycle are removed from monthly MSLs, a residual time series is obtained. The residual represents periods when the MSL is anomalously high or low. This often occurs when regional ocean temperatures are anomalously warm or cool or when there are anomalies in oceanic winds or currents (i.e., the ocean's "weather"). The MSL residuals for all the NWLON stations are plotted in Appendix IV. A sample plot for Honolulu is shown in Figure 28. The 5-month running average is also plotted in order to smooth out any individual anomalous months in order to focus more attention on anomalous seasons. The plots in Appendix IV are also marked with solid vertical lines to show the times of any major earthquakes in the vicinity of each station.

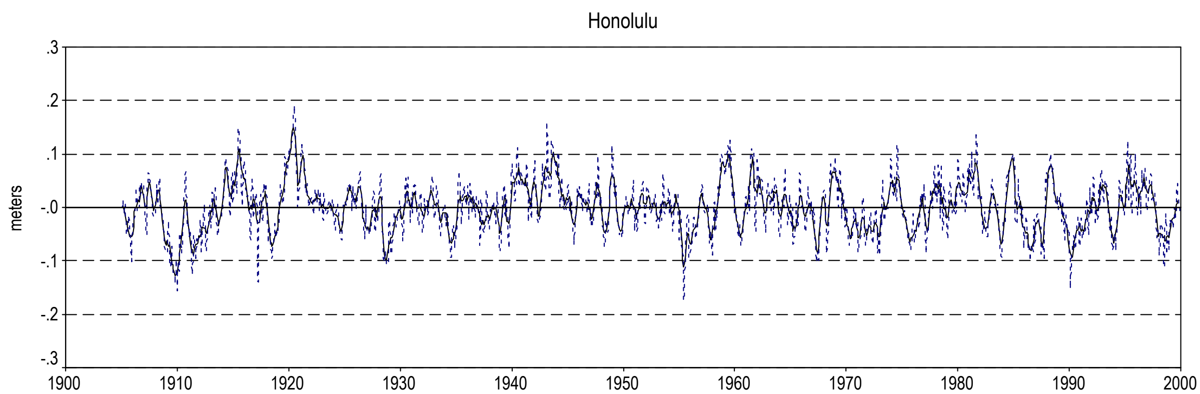

Figure 28. Monthly mean sea level residual at Honolulu with the average seasonal cycle and the linear trend removed (dashed curve), and the 5-month running average (solid curve).

The primary cause of anomalous ocean conditions is the El Nino/Southern Oscillation (ENSO) in the equatorial Pacific Ocean. Westward winds normally maintain slightly higher water levels in the western Pacific relative to the eastern Pacific. Every three to five years, in a non-periodic pattern, the winds weaken and water levels in the western Pacific drop below normal. The southern equatorial current is weakened and water temperatures in the eastern Pacific rise. This condition is known as El Nino. The opposite condition, known as La Nina, occurs when westward equatorial winds are unusually strong and water levels in the western Pacific become anomalously high. The south equatorial current strengthens, accompanied by below normal water temperatures in the eastern Pacific. Anomalous temperatures in the eastern Pacific can eventually affect ocean temperatures, winds, and water levels in many regions of the world's oceans and atmosphere.

In comparing MSL time series between nearby NWLON stations, it appears that a small proportion of the data at a few stations are suspect because of unexplained differences of 0.1 to 0.2 m relative to nearby stations. These periods, lasting from 4 months to 27 months, are easily isolated. Since it appears that these short periods do not significantly affect the trends derived in Section IV, they were not removed from the data sets. However, they are marked as suspect data in the plots in Appendices II and IV and are listed in Table 4.

Table 4. Periods of suspect data			
Station	**Number**	**Period**	**Estimated Error (m)**
Springmaid Pier	8661000	7/71-12/71	0.15
Sabine Pass	8770590	1/74-8/74	0.1
Galveston Pleasure Pier	8771510	1/67-6/67	0.1
Galveston Pleasure Pier	8771510	12/70-4/72	0.1
Santa Monica	9410840	8/83-6/85	-0.1
Santa Monica	9410840	1/92-4/92	0.1
Port San Luis	9412110	1/69-1/70	0.1
Astoria	9439040	6/48-5/49	0.2
Ketchikan	9450460	6/66-9/68	0.1
Skagway	9452400	10/69-3/70	0.2
Skagway	9452400	1/82-12/82	-0.1
Seldovia	9455500	8/77-6/78	0.2

The 5-month average time series in Appendix IV are highly correlated with time series at nearby stations and are representative of the regional ocean "weather". The months when the 5-month average is above 0.1 m or below -0.1 m are defined as periods of extreme conditions. The number of months with extreme levels in each year are listed in Tables 5 and 6 for all the Atlantic and Pacific NWLON stations. These tables show the high regional correlations during extreme conditions. Years with any month above 0.1 m are positive and shaded red. Years with any month below -0.1 m are negative and shaded blue. Zeros indicate years when there were no months with residuals above 0.1 m or below -0.1 m. Blank spaces indicate no data. The suspect data periods in Table 4 are not included in Tables 5 and 6.

For the first quarter of the 20th century, there were few stations operating and little can be inferred about regional residual water level conditions. The first clearly regional events are the low residuals in 1929-1930 from Astoria to Ketchikan, and the low residuals in 1931 at Charleston, Mayport, Pensacola, and Galveston Pier 21. Low residuals also occurred in 1936 from Astoria to Seattle and in 1939 from San Francisco to Friday Harbor.

There were high regional residuals in 1940-1941 from Los Angeles to Crescent City and from Friday Harbor to Yakutat. A period of high residuals on the southeastern U.S. coast occurred in 1947-1948 from Wilmington to Grand Isle followed by high residuals in 1949-1950 from Grand Isle to Port Isabel.

With the establishment of western Pacific NWLON stations at Guam, Pago Pago, Kwajalein, and Chuuk in the late 1940s, the long distance effects of anomalous ENSO conditions can be observed. High residuals at Pago Pago and Chuuk in 1955 were followed by low residuals in 1956-1957 from Ketchikan to Yakutat. Low residuals at Pago Pago, Kwajalein and Chuuk in 1957-1958 were followed in 1958 by high residuals from San Francisco to Ketchikan.

In 1963-1964, low residuals occurred along the Gulf coast from Grand Isle to Port Isabel and in 1964 along the Pacific coast from Crescent City to Friday Harbor. After high residuals at Guam and Pago Pago in 1971, low residuals appeared from Seward to Unalaska in 1971-1972.

The strong 1972 El Nino is represented by low residuals at Guam, Kwajalein, and Chuuk, and was followed by high residuals in 1972-1973 along the Atlantic coast from New London to Mayport and along the Gulf coast from Apalachicola to Rockport. High residuals did not occur on the west coast at this time. There were high residuals in 1975 along the Gulf coast from Pensacola to Padre Island. In 1976, high residuals were observed from Juneau to Unalaska.

In 1976-1977, low residuals occurred along the Atlantic coast from Providence to Beaufort. Residuals were also low in 1980-1981 at Atlantic coast stations from Willets Point to Mayport. The extremely strong El Nino of 1982-1983 resulted in low residuals at Guam, Pago Pago, Kwajalein, and Chuuk and high residuals at all west coast stations from San Diego to Unalaska. High residuals were also observed in 1983 along the Atlantic coast from Gloucester Point to Fernandina Beach.

High residuals in 1985 at Guam, Pago Pago and Chuuk were accompanied by low residuals from Crescent City to Sand Point. Low residuals at Guam in 1987 were accompanied by high residuals from Juneau to Sand Point. The strong La Nina in 1988-1989 is represented by high residuals at Guam and Chuuk and by low residuals from Newport Beach to Sand Point.

Low residuals in 1991 at Guam and Kwajalein were followed in 1992 with high residuals from San Diego to Crescent City and from Cherry Point to Anchorage. Low residuals were observed in 1996 along the Gulf coast from Sabine Pass to Port Mansfield and in Alaska from Juneau to Anchorage. The extremely powerful El Nino of 1997-1998 is represented by low residuals for Guam, Pago Pago, and Kwajalein and high residuals at all west coast stations from San Diego to Unalaska and, as in 1983, along the Atlantic coast from Providence to Wilmington.

Table 5. Number of months with extreme residual water levels for Atlantic stations

Station	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924
Bermuda																									
Eastport																									
Bar Harbor																									
Portland													0	0	0	0	0	0	0	0	0	0	0	0	0
Seavey Island																									
Boston																						0	0	0	0
Woods Hole																									
Nantucket Island																									
Newport																									
Providence																									
New London																									
Bridgeport																									
Montauk																									
Port Jefferson																									
Willets Point																									
New Rochelle																									
The Battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sandy Hook																									
Atlantic City												0	0	0	0	0	0	0	0	0	0			0	0
Cape May																									
Philadelphia	-1	-1	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
Lewes																				0	0	0	0	0	
Cambridge																									
Baltimore			1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Annapolis																									
Solomons Island																									
Washington																									
Kiptopeke																									
Colonial Beach																									
Lewisetta																									
Gloucester Point																									
Sewells Point																									
Portsmouth																									
Ches. Bay Br Tnl																									
Beaufort																									
Wilmington																									
Springmaid Pier																									
Charleston, SC																						0	0	0	0
Fort Pulaski																									
Fernandina Beach	0	0	0	5	0	0	0	-2	2	0	0	0	0	0	0	0	0	-4	0	0	0	0	0	0	0
Mayport																									
Miami Beach																									
Vaca Key																									
Key West														0	0	0	0	0	0	0	0	0	0	0	0
Naples																									
Fort Myers																									
St. Petersburg																									
Clearwater Beach																									
Cedar Key															0	0	0	0	0	0	0	0	0	0	0
Apalachicola																									
Panama City																									
Pensacola																								0	0
Dauphin Island																									
Grand Isle																									
Eugene Island																									
Sabine Pass																									
Galveston Pier 21									2	0	0	0	0	2	0	0	0	-4	-1	1	0	7	0	2	0
Galv. Pleasure Pier																									
Freeport																									
Rockport																									
Port Mansfield																									
Padre Island																									
Port Isabel																									
Guantanamo Bay																									
Charlotte Amalie																									
San Juan																									
Magueyes Island																									

Table 5. Number of months with extreme residual water levels for Atlantic stations

Station	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Bermuda									0	0	0	0	0							0	-2	-4	0	0	0
Eastport					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bar Harbor																							0	0	0
Portland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seavey Island		0	0	0	0	0	0	0	0	0						0	0		0	0	0	0	0	0	0
Boston	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Woods Hole								0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nantucket Island																									
Newport						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Providence															0	0	0	0	0	0	0	0	0		
New London														0	0	0	0	0	0	0	0	0	0	0	0
Bridgeport																									
Montauk																							0	0	0
Port Jefferson																									
Willets Point							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Rochelle																									
The Battery	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sandy Hook									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atlantic City	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cape May																									
Philadelphia	0	0	1	-1	0	-1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
Lewes												0	0	0	0								0	0	0
Cambridge																			0	0	0	0	0	0	0
Baltimore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Annapolis				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solomons Island														0	0	0	0	0	0	0	0	0	0	0	0
Washington							0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0
Kiptopeke																									
Colonial Beach																									
Lewisetta																									
Gloucester Point																									
Sewells Point				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Portsmouth											0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ches. Bay Br Tnl																									
Beaufort																									
Wilmington											0	0	1	0	0	0	-2	0	0	0	4	1	3	6	0
Springmaid Pier																									
Charleston, SC	0	0	0	0	0	0	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	8	0
Fort Pulaski											0	0	0	0	0	0	0	0	0	0	0	0	4	5	0
Fernandina Beach															0	0	0	0	0	0	0	0	3	4	0
Mayport				0	0	0	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	7	0
Miami Beach							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	0
Vaca Key																									
Key West	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0
Naples																									
Fort Myers																									
St. Petersburg																							0	4	0
Clearwater Beach																									
Cedar Key	0													0	0	0	0	0	0	0	0	0	0	4	1
Apalachicola																									
Panama City																									
Pensacola	0	0	0	0	1	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
Dauphin Island																									
Grand Isle																							0	4	1
Eugene Island															0	-4	0	0	0	0	0	0	0	0	2
Sabine Pass																									
Galveston Pier 21	0	-1	0	0	3	0	-6	0	0	0	0	0	0	0	-2	-6	0	0	0	0	1	3	0	0	2
Galv. Pleasure Pier																									
Freeport																									
Rockport																								0	1
Port Mansfield																									
Padre Island																									
Port Isabel																				0	0	2	0	1	0
Guantanamo Bay													0	0	0	0	1	1		0	0		0	0	0
Charlotte Amalie																									
San Juan																									
Magueyes Island																									

Table 5. Number of months with extreme residual water levels for Atlantic stations

Station	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Bermuda	0	0	0	0	0	4	1	4	1	0	0	2	6	0	0	0	0	1	0	-1	-6	-2	0	-2	3
Eastport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Bar Harbor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Portland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0
Seavey Island	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boston	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Woods Hole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0
Nantucket Island																0	0	0	0	0	0	0	0	0	0
Newport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Providence							0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
New London	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Bridgeport																0		0	0	0	0	0	0	2	0
Montauk	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Port Jefferson								0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Willets Point	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0
New Rochelle								0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0
The Battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Sandy Hook	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0
Atlantic City	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	3	0
Cape May																	0	0	0				1	2	0
Philadelphia	0	0	0	2	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	2	4	0
Lewes			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	0
Cambridge	0	0																				0	0	1	0
Baltimore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Annapolis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solomons Island	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Washington	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	0
Kiptopeke		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Colonial Beach																							2	3	0
Lewisetta																									0
Gloucester Point	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	2	0
Sewells Point	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0
Portsmouth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0
Ches. Bay Br Tnl																									
Beaufort																								1	0
Wilmington	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Springmaid Pier								0	0	0	0	0	0	0				0	0	0	0		0	1	0
Charleston, SC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0
Fort Pulaski	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Fernandina Beach	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	2	0
Mayport	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Miami Beach	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaca Key																						0	0	0	0
Key West	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naples																0	0	0	0	0	0	0	0	0	0
Fort Myers																0	0	0	0	0	0	0	0	0	0
St. Petersburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clearwater Beach																								0	0
Cedar Key	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Apalachicola																		0	0	0	0		0	4	0
Panama City																								0	
Pensacola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Dauphin Island																		0	0	0		0	0	0	0
Grand Isle	1	0	0	0	0	0	0	0	0	0	0	0	0	-2	-2	0	0	0	0	0	0	0	0	1	0
Eugene Island	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			1
Sabine Pass									0	0	0	2	0	-6	-4	-3	0	0	0	0	0	1	2	2	
Galveston Pier 21	3	0	0	0	0	0	0	0	0	0	0	2	0	-4	-3	0	0	0	0	0	0	-2	0	1	0
Galv. Pleasure Pier								0	0	0	0	1	0	0	-9	0	0	2	0	0	0			0	
Freeport					0	0	0	0	0	0	0	2	0	0	-1	0	0	0	0	0	0	2	0	0	0
Rockport	3	0	0	0	0									-3	-4	0	0	0	0	0	0	1	0	1	0
Port Mansfield															-1	0	-1	1				2	5	0	0
Padre Island										0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
Port Isabel	1	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0
Guantanamo Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
Charlotte Amalie																									
San Juan													0	0	0	0	0	0	0	0	0	0	0	0	0
Magueyes Island						0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Number of months with extreme residual water levels for Atlantic stations

Station	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Bermuda	3	1	0	0	0	0	0	0	-2	0	-2	0	0	-1	0	0	0	0	-3	0	2	0	0	0	0
Eastport	0		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bar Harbor	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
Portland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seavey Island	0	0	0	0	0	0	0	0	0	0	0	0													
Boston	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Woods Hole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
Nantucket Island	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Newport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Providence	0	-1	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
New London	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Bridgeport	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
Montauk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	3	0
Port Jefferson	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
Willets Point	0	-2	-2	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
New Rochelle	0	0	0	0	0	0	0																		
The Battery	0	-2	-3	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	4	0
Sandy Hook	0	-2	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Atlantic City	0	0	0	0	0	-2	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	-3	0	1	4	
Cape May	0	0		0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	1	4	0
Philadelphia	0	-2	-3	0	0	-3	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	4	0
Lewes	0	-2	-4	0	0	0	0	0	1	0	0	0	1	0	0	-2	0	0	0	0	0	0	1	4	0
Cambridge	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Baltimore	0	-2	-3	0	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	4	0
Annapolis	0		-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0
Solomons Island	0		-2	0	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	4	0
Washington	0	-1	-4	0	0	-2	-5	0	0	2	0	0	0	0	0	-1	0	0	2	0	0	6	2	5	0
Kiptopeke	0	-2	-4	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	0	0	1	4	0
Colonial Beach	0	-2	-4	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lewisetta	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Gloucester Point	0	-2	-4	0	0	-1	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Sewells Point	0	-2	-4	0	0	-2	-1	0	2	0	0	0	0	-3	0	0	0	0	0	0	0	0	1	5	0
Portsmouth	0	-2	-4	0	0	-1	-1	0	4	0	0	0	0												
Ches. Bay Br Tnl	0	-1	-3	0	0	0	0	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0
Beaufort	0	-1	-1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wilmington	0	0	0	0	0	-4	-4	0	3	0	0	0	0	0	0	0	0	0	0	0	1	2	0	4	3
Springmaid Pier			0	0	0	-2	0	0	2	0	0	0	2	0	0		3	0	0	0	0	-2	0	-3	0
Charleston, SC	0	0	0	0	0	0	0	0	2	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
Fort Pulaski	0	0		0	0	0	0	1	2	0	0	0	1	0	0	0	0	0	0	0	5	0	0	0	0
Fernandina Beach	0	0	0	0	0	-1	0	0	2	0	0	0	2	0	-1	0	1	0	0			0	0	0	0
Mayport	0	0	0	0	0	-5	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	5	0	0	0	0
Miami Beach	0	0	0	0	0	0	0																		
Vaca Key	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Key West	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
Naples	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fort Myers	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
St. Petersburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clearwater Beach	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0			0	0	0	0
Cedar Key	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0		
Apalachicola		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panama City	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pensacola	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dauphin Island		-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grand Isle	2		0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eugene Island																									
Sabine Pass	8	0	0	0							0	0	0	0	-1	0	4	0	0	0	0	-7	0	0	0
Galveston Pier 21	5	-3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	-3	0	0	0
Galv. Pleasure Pier				0	0	-8	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	0	0
Freeport	4	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
Rockport	5	0	0	0	0	-2	0	0	0	0	0	0	0	0	-2	0	0		0	0	0	0	0	4	0
Port Mansfield	5	0	0	0	0	-1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	-3	0		
Padre Island	5	-3	0	0					0	0	0	0	0		0	0	0	0	0						
Port Isabel		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Guantanamo Bay																									
Charlotte Amalie		0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Juan				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Magueyes Island	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6. Number of months with extreme residual water levels for Pacific stations

Station	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924
Nawiliwili																									
Honolulu						0	0	0	0	-6	-2	0	0	0	0	2	0	0	0	0	7	0	0	0	0
Mokuoloe																									
Kahului																									
Hilo																									
Johnston Atoll																									
Sand Island																									
Guam																									
Pago Pago																									
Kwajalein																									
Chuuk																									
Wake Island																									
San Diego							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La Jolla																									
Newport Beach																									
Los Angeles																									0
Santa Monica																									
Rincon Island																									
Santa Barbara																									
Port San Luis																									
Monterey																									
San Francisco	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2
San Francisco w/EQ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
Alameda																									
Point Reyes																									
Crescent City																									
Charleston, OR																									
South Beach																									
Astoria																									
Toke Point																									
Neah Bay																									
Port Angeles																									
Port Townsend																									
Seattle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cherry Point																									
Friday Harbor																									
Ketchikan																				-1	0	0	0	0	0
Sitka																									
Juneau																									
Skagway																									
Yakutat																									
Cordova																									
Valdez																									
Seward																									
Seldovia																									
Nikiski																									
Anchorage																									
Kodiak Island																									
Sand Point																									
Unalaska																									
Adak Island																									

Table 6. Number of months with extreme residual water levels for Pacific stations

Station	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Nawiliwili																									
Honolulu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Mokuoloe																									
Kahului																									
Hilo			0	0	0	0	0	0															0	0	0
Johnston Atoll																							0		
Sand Island																							0	0	0
Guam																									0
Pago Pago																								0	0
Kwajalein																							0	0	0
Chuuk																									
Wake Island																									
San Diego	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La Jolla	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Newport Beach																									
Los Angeles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Santa Monica									0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Rincon Island																									
Santa Barbara																									
Port San Luis																					0	-1	0	0	0
Monterey																									
San Francisco	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4	1	4	0	0	0	0	0	0	0	0
San Francisco w/EQ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	0
Alameda															0	1	5	0	0	0	0	0	0	0	0
Point Reyes																									
Crescent City									0	0	0	0	0	0	-2	1	4	0	0	0	0	0	0		
Charleston,OR																									
South Beach																									
Astoria	0	0	2	-1	-6	-1	0	0	1	0	0	-3	-1	-1	-2	0	0	0	0	-5	-1	0	0		
Toke Point																									
Neah Bay										0	1	-3	-1	0	-2	0	0	0	0	0	0	0	0	0	0
Port Angeles																									
Port Townsend																									
Seattle	0	0	0	0	-4	-1	0	0	0	0	0	-2	0	0	-2	0	0	0	0	0	0	0	0	0	0
Cherry Point																									
Friday Harbor										0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0
Ketchikan	0	2	0	0	-2	-1	3	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
Sitka														0	0	2	1	0	0	0	0	-1	-1	0	0
Juneau												0	0	0	3	3				0	0	0	-1	0	0
Skagway																				0	0	-1	0	0	0
Yakutat																0	1	0	0	0	0	-1	-1	0	0
Cordova																									
Valdez																									
Seward	0	5	0	0	0	1	3	0	0	0	0	0	0	0						0	0	0	0	0	0
Seldovia																									
Nikiski																									
Anchorage																									
Kodiak Island																									
Sand Point																									
Unalaska										0	0	0	-2	0	0							0	0	0	0
Adak Island																			0	0	0	0	0	0	0

Table 6. Number of months with extreme residual water levels for Pacific stations

Station	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Nawiliwili						-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honolulu	0	0	0	0	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mokuoloe								0	0	0	0	0	0	0	0	0	0	0	0	0					0
Kahului					0	-2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Hilo	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnston Atoll	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	1	0	0	0	0
Sand Island	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	-1	0	0	0		0
Guam	3	0	0	3	4	0	0	0	0	0	0	0	0	0	0	0	0	-1	-3	-3	5	4	-7	0	1
Pago Pago	0	0	0	0	0	2		0	-2	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Kwajalein	0	0	0	0	0	0	0	-3	-1	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1	0	0
Chuuk	0	0		0	0	3	1	-3	-2	0	0	0	0	-1	0	-4	-1	0	0	0	0	0	-7	2	0
Wake Island	0	0	1	4	0	0	0	0	0	0	2	0	0	0	0	0	-2	0		0	0	0	0	0	
San Diego	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La Jolla	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Newport Beach						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Los Angeles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Santa Monica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0									0
Rincon Island													0	0	0	0	0	0	0	0	0	0	0	0	0
Santa Barbara																									0
Port San Luis	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0		0		0	0	0
Monterey																									0
San Francisco	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
San Francisco w/EQ	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Alameda	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Point Reyes																									
Crescent City	0	0	0	0	0	0	0	1	4	0	0	0	0	0	-3	0	0	0	0	0	0	0	0	0	0
Charleston, OR																					0	0	0	0	0
South Beach																		0	1	1	0	0	0	0	0
Astoria	1	0	0	0	0	-1	-2	-1	2	0	0	-2	-1	0	-3	0	0	0	1	1	-2	0	2	-4	2
Toke Point																								0	
Neah Bay	0	0	0	0	0	0	-1	0	3	0	0	-1	0	0	-1	2	1	0	1	0	0	0	0	0	0
Port Angeles																									
Port Townsend																							0	0	0
Seattle	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	1	1	0	0	0	0	0
Cherry Point																								0	0
Friday Harbor	0	0	0	0	0	0	0	0	3	0	0	0	0		-1	0	0	0	0	0	0	0	0	0	0
Ketchikan	0	0	0	0	0	0	-1	-2	1	0	0	0	0	1	0	-2	0			0	0	0	0		0
Sitka	0	0	0	0	0	0	-2	-3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Juneau	0	0	0	0	0	0	-2	-3	0	0	0	0	0	3	0	0	0	0	0	0	-2	-4	-1	0	0
Skagway	-1	-3	2	2	0	-2	-4	-2	0	0	1	1	-2	0		0	1	0	0						
Yakutat	0	0	0	0	0	0	-3	-3	0	0	0	-1	-4	1	0	0	0	0	0	0	0	0	0	0	0
Cordova															0	0	0	0			0	0	0	0	0
Valdez																									0
Seward	0	0	3	3	0	-1	-1		0	0		0	0	2	0	0	0	-3	0	0	-1	-1	-3	0	
Seldovia															0		0	0	0	0		-3	-5	-1	0
Nikiski																								0	
Anchorage																							-2	-2	-1
Kodiak Island																									
Sand Point																								-1	0
Unalaska	0	0	2	3	0	0	0	0	0	2	0	0	0	0	0	0	-1	0	0	1	2	-2	-3	0	0
Adak Island	0	0	0	0	0	0	0	2	1	0	0		-1	0		0	0	0	0	0	0	0	0	0	0

Table 6. Number of months with extreme residual water levels for Pacific stations

Station	1975	1976	1977	1978	197	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Nawiliwili	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0
Honolulu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mokuoloe							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kahului	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hilo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnston Atoll	0	0	0	-1	-2	0	0	0	0	0	0	0	0	5	-1	0	-1	0	0	0	0	0	0	0	0
Sand Island	0	1	0	-2	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guam	0		0	0	0	0	1	-5	-6	7	1	0	-3	3	3	0	-2	0	0	0	1	9	-3		1
Pago Pago	0	0	0	-1	0	0	0	0	-7	0	2	0	0	0	0	0	0	0	0	0	0	2	0	-10	0
Kwajalein	0	0	0	0	0	0	0	-6	-3	0	0	0	0	0	0	0	-2	-2	0	0	0	0	-6	-1	0
Chuuk	1	0	0	0	0	0	0	-7	-2	0	2	0	0	5	2	0				-4	0				
Wake Island	0	0	0		0	0	0	0	0	7	0	-1	0	0	-2	0	0	-2	0	0	0	0	0	0	0
San Diego	0	0	0	0	0	0	0	2	6	0	0	0	0	0	0	0	0	2	0	0	0	0	4	1	0
La Jolla	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0
Newport Beach	0	0	0	0	0	0	0	2	4	0	0	0	0	-2	-1	0	0	0	0						
Los Angeles	0	0	0	0	0	0	0	2	3	0	0	0	0	-2	-1	0	0	1	0	0	0	0	4	1	0
Santa Monica	0	0	0	0	0	0	0	1	0	0		0	0	-1	-1	0			0	0	0	0	4	1	0
Rincon Island		0		0	0	0	0	2	7	0	0	0	0	0	0	0									
Santa Barbara	0	0	0	0	0	0											0	0	0	0	0	0	2		
Port San Luis	0	0	0	0	0	0	0	2	4	0	0	0	0	-1	0	0	0	1	0	0	0	0	4	1	0
Monterey	0	0	0	0	0	0	0	2	9	0	0	0	0	0	0	0	0	3	0	0	0	0	3	1	0
San Francisco	0	0	-1	0	0	0	0	3	11	0	0	0	0	0	0	0	0	3	0	0	1	0	4	4	0
San Francisco w/EQ	0	0	-3	0	0	0	0	3	11	0	0	0	0	-1	-1	0	0	0	0	0	0	0	3	4	0
Alameda	-2	-3	-2	0	0	0	0	3	11	0	0	0	0	-2	-2	0	0	0	0	0	1	0	4	4	0
Point Reyes	0	-1	0	0	0	0	0	2	10	0	0	0	0	-2	-2	0	0	3	0	0	0	0	3	2	0
Crescent City	0	-2	0	1	0	0	0	2	6	0	-1	0	0	-2	-1	0	0	4	1	0	0	0	2	3	0
Charleston,OR	0	0	1	2	0	0	0	3	4	0	-1	0	0	-1	0	-1	0	0	0	0	0	0	4	3	0
South Beach	0	0	-3	0	0	0	0	2	6	0	-2	0	0	-1	0	0	0	0	0	0	0	0	5	3	0
Astoria	0	-1	-6	-2	-1	0	0	3	5	0	-3	0	0	-1	0	0	0	0	0	0	1	3	8	3	1
Toke Point			2	-1	0	0	0	3	5	0	-2	0	0	-1	-2	0	0	0	0	0	0	0	6	3	0
Neah Bay	0		0	0	0	0	0	2	6	0	-2	0	0	-1	0	0	0	0	0	0	0	0	6	3	0
Port Angeles	0	0	0	0	0	0	0	2	5	0	-2	0	0	-1	0	0	0	0	0	0	0	0	5	3	0
Port Townsend	0	0	0	0	0	0	0	2	6	0	-2	0	0	-1	0	0	0	0	0	0	0	0	4	2	0
Seattle	0	0	-1	0	0	0	0	2	5	0	-1	0	0	0	0	0	0	0	0	0	0	0	4	3	0
Cherry Point	0	0	0	0	0	0	0	3	6	0	-1	0	0	-1	-1	0	0	1	0	0	0	0	4	3	0
Friday Harbor	0	0	0	0	0	0	0	2	5	0	-1	0	0	-1	-1	0	0	0	0	0	0	0	5	3	0
Ketchikan	0		0	0	0	0	0	1	5	0	-1	0	0	0	0	0	1	3	-2	0	0	0	2	2	0
Sitka	0	0	0	0	0	0	0	0	3	0	-2	0	0	0	-1	0	0	3	0	0	0	0	2	3	0
Juneau	0	4	0	0	0	0	0	1	3	0	-2	0	1	0	0	0	1	4	0	0	0	-2	0	2	0
Skagway									1	0	-2	0	6	3	0	0	1	4	0	0		-3	1	2	0
Yakutat	0	2	2	0	0	0	1	1	4	1	-1	0	4	0	-3	-2	-2	1	-3	0	0	0	1	-1	0
Cordova	0	0	0	0	0	0	0	1	3	0	-2	0	2	0	0	0	0	3	0	0	0	-1	1	1	0
Valdez	-1	0	0	-1	-2	0	0	0	2	0	-2	0	3	3	0	0	0	3	0	0	0	-2	1	1	0
Seward			0	0	0	0	0	1	3	0	-2	1	4	2	-2	-1	0	2	0	0	0	-2	1	2	0
Seldovia	0	4			0	0	0	1	3	0	-2	0	4	0	-4	-2	-1	2	0	0	0	0	2	3	0
Nikiski						0	0															0	2	2	0
Anchorage	0	2								2	0	1	4	2	0	0	2	3	0	0	0	-2	1	2	0
Kodiak Island	0	0						0	1	0	0	0	0	0	-3	0	-1	0	0	0	0	0	2	3	0
Sand Point	0	2	0	0	0	0	1	1	4	0	-1	1	3	0	-4	-2	-1	0	0	0	0	0	1	2	0
Unalaska	0	1	0		0	0	1	0	4	0	0	0	0	0	0	0	0	0	1	0	0	0	1	3	0
Adak Island	0				0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

VII. DISCUSSION

In Section IV, linear MSL trends were calculated for all NWLON stations with greater than 25 years of data. As Figures 8-10 showed, there are a wide range of error bars associated with the trends. Most of this variation can be attributed to the length of the data time series. Figure 29 is a plot of the standard errors of the linear trends from Table 3 versus the year range of the MSL data. The scatter implies an inverse power relationship. There are two stations that are clear outliers, Guam and Chuuk. These stations have 52 and 49 years of data respectively, but their standard errors of 0.9 mm/yr are similar to those of stations with only 25-30 years of data. This greater uncertainty in trend is due to the large magnitude of the ENSO events in the western Pacific Ocean.

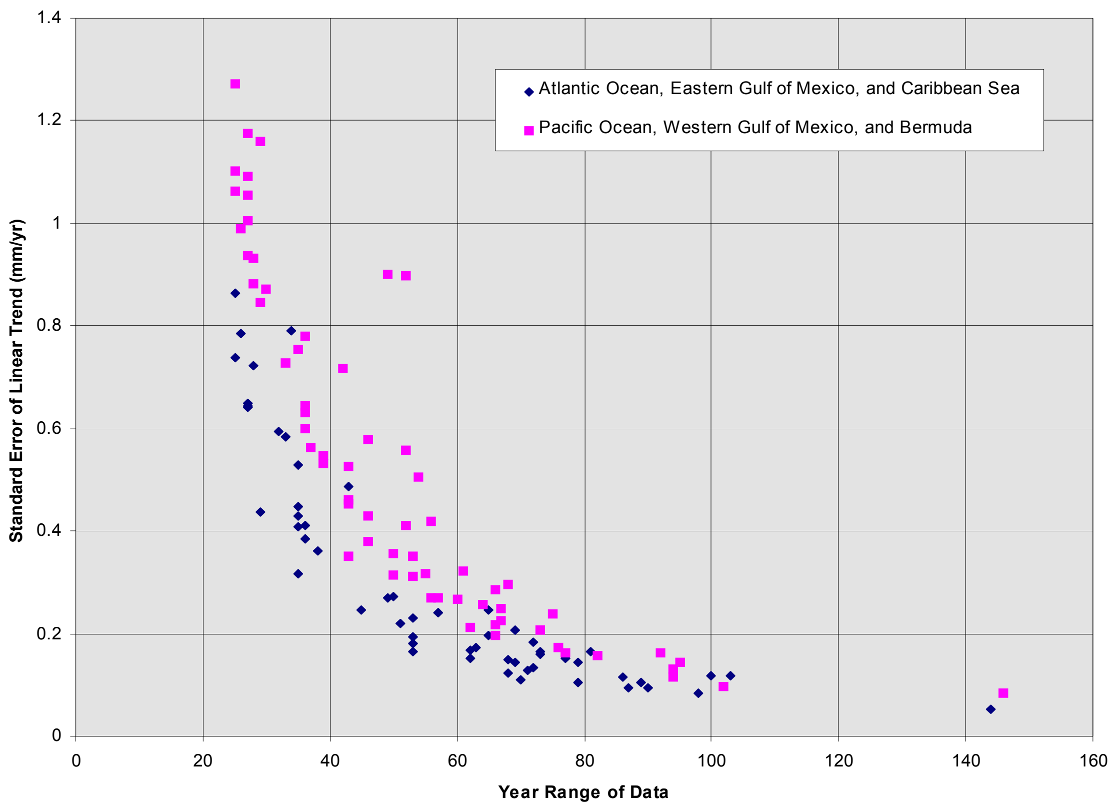

Figure 29. Standard error of linear MSL trends (mm/yr) versus year range of data.

The relationship between the trend standard error (y) and the year range of data (x) can be seen more clearly in a log-log plot (Figure 30). The best-fit regression line to the points (with associated 95% confidence intervals) is

$$y = \frac{10^{(2.257 \pm 0.217)}}{x^{(1.614 \pm 0.127)}} = \frac{180.8}{x^{1.614}} \qquad \textbf{(6)}$$

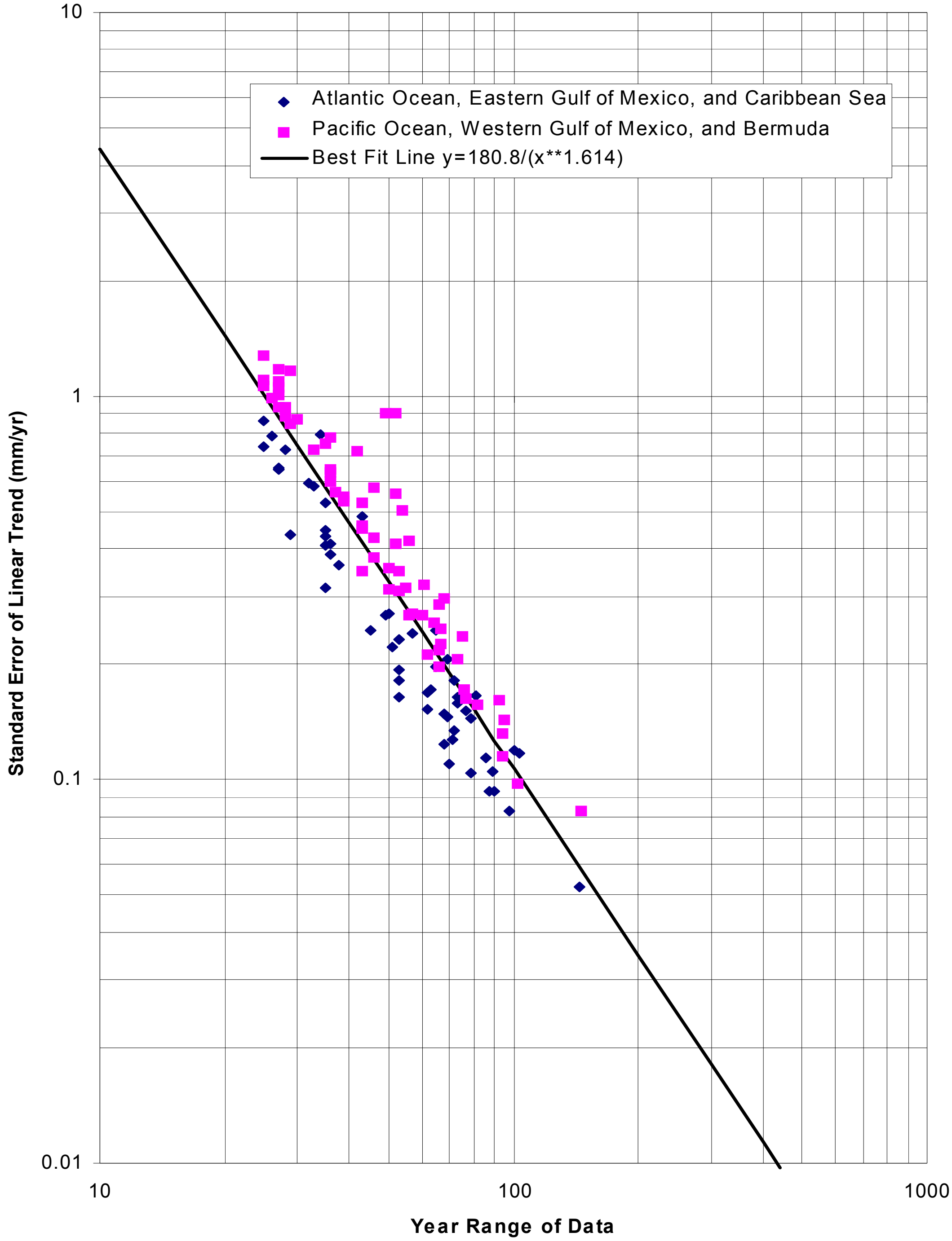

Figure 30. Standard error of linear MSL trends (mm/yr) versus year range of data. The least squares fitted line is also shown.

It can be observed that, for a given length of data, the stations in the Pacific Ocean, the western Gulf of Mexico, and Bermuda have greater standard errors than stations in the Atlantic Ocean, eastern Mexico, and the Caribbean Sea. This is because ENSO events result in roughly twice the variability for the first group of stations compared to the second group of stations. Furthermore, Guam and Chuuk have roughly twice the standard errors of the second group of stations.

Figure 31 shows the expected width of the 95% confidence interval (+/- 1.96 times the standard error) as a function of data length based on the relationship in equation 6. A confidence interval or precision of 1 mm/yr should be obtainable at most stations with 50-60 years of data on average, providing there is no acceleration in sea level change or abrupt shifts in trend due to tectonic events.

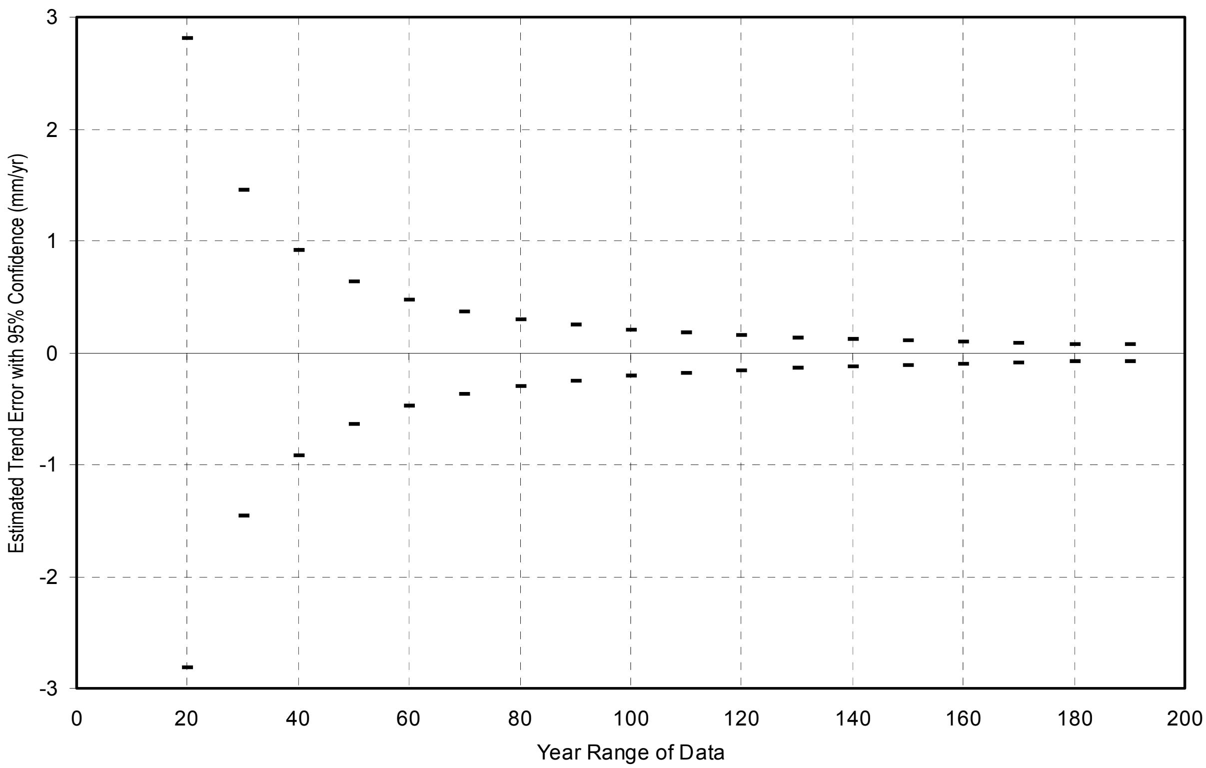

Figure 31. 95% confidence intervals for linear MSL trends (mm/yr) versus year range of data set based on equation 6.

In order to compare linear MSL trends between NWLON stations without dependence on the lengths of the time series, trends were obtained for the common period of 1950-1999. Sixty stations have at least 50 years of monthly MSL data. The trends were obtained using the linear regression with autoregressive residuals method described in Section III. The results are listed in Table 7 and the 95% confidence intervals of the trends are plotted in Figures 32 to 33. The differences between stations are mostly due to differences in vertical land motion. Note the wider confidence intervals of the western Pacific stations of Guam, Pago Pago, and Kwajalein which are greatly affected by ENSO events.

Table 7. Linear MSL trends for 1950-1999 monthly data			
Station Number	Station	MSL Trend (mm/yr)	Standard Error (mm/yr)
1612340	Honolulu	1.44	0.34
1617760	Hilo	3.26	0.31
1619000	Johnston Atoll	0.58	0.34
1619910	Sand Island	-0.01	0.34
1630000	Guam	-0.09	0.95
1770000	Pago Pago	1.24	0.58
1820000	Kwajalein	1.15	0.58
1890000	Wake Island	1.90	0.36
2695535	Bermuda	0.98	0.42
8410140	Eastport	1.44	0.22
8413320	Bar Harbor	2.09	0.18
8418150	Portland	1.20	0.22
8443970	Boston	2.02	0.21
8447930	Woods Hole	2.39	0.21
8452660	Newport	2.35	0.20
8454000	Providence	1.82	0.28
8461490	New London	1.99	0.22
8510560	Montauk	2.60	0.21
8516990	Willets Point	2.05	0.25
8518750	The Battery	2.72	0.25
8531680	Sandy Hook	3.41	0.25
8534720	Atlantic City	4.47	0.27
8545530	Philadelphia	2.74	0.35
8557380	Lewes	3.04	0.29
8574680	Baltimore	2.73	0.24
8575512	Annapolis	3.18	0.23
8577330	Solomons Island	3.37	0.25
8594900	Washington	3.15	0.35
8637624	Gloucester Point	3.95	0.27
8638610	Sewells Point	4.48	0.30
8658120	Wilmington	2.76	0.34
8665530	Charleston, SC	3.05	0.27
8670870	Fort Pulaski	3.43	0.28
8720030	Fernandina Beach	2.66	0.31

Table 7. Linear MSL trends for 1950-1999 monthly data			
Station Number	Station	MSL Trend (mm/yr)	Standard Error (mm/yr)
8720220	Mayport	2.58	0.31
8724580	Key West	2.42	0.20
8726520	St. Petersburg	2.67	0.18
8727520	Cedar Key	1.72	0.24
8729840	Pensacola	2.00	0.27
8761720	Grand Isle	10.37	0.36
8771450	Galveston Pier 21	7.24	0.37
8774770	Rockport	4.98	0.45
8779770	Port Isabel	4.03	0.31
9410170	San Diego	2.45	0.36
9410230	La Jolla	2.66	0.37
9410660	Los Angeles	1.14	0.34
9410840	Santa Monica	1.27	0.42
9412110	Port San Luis	0.71	0.37
9414290	San Francisco	2.23	0.40
9414750	Alameda	1.07	0.44
9419750	Crescent City	-0.41	0.37
9439040	Astoria	-0.19	0.43
9443090	Neah Bay	-1.71	0.35
9447130	Seattle	2.26	0.30
9449880	Friday Harbor	1.14	0.32
9450460	Ketchikan	0.09	0.35
9451600	Sitka	-1.87	0.30
9452210	Juneau	-12.25	0.37
9452400	Skagway	-16.37	0.51
9453220	Yakutat	-5.63	0.37

The linear MSL trends from Section IV, determined with the entire data sets for each station, are also marked in Figures 32 and 33 with filled circles. At only three out of the 60 stations is the longer term trend clearly outside of the 95% confidence interval for the 1950-1999 trend. At Eastport, Portland, and Boston, the MSL rise over the past 50 years has been significantly lower than the longer term trends. At no station is the trend for the past 50 years significantly greater than the longer term trend.

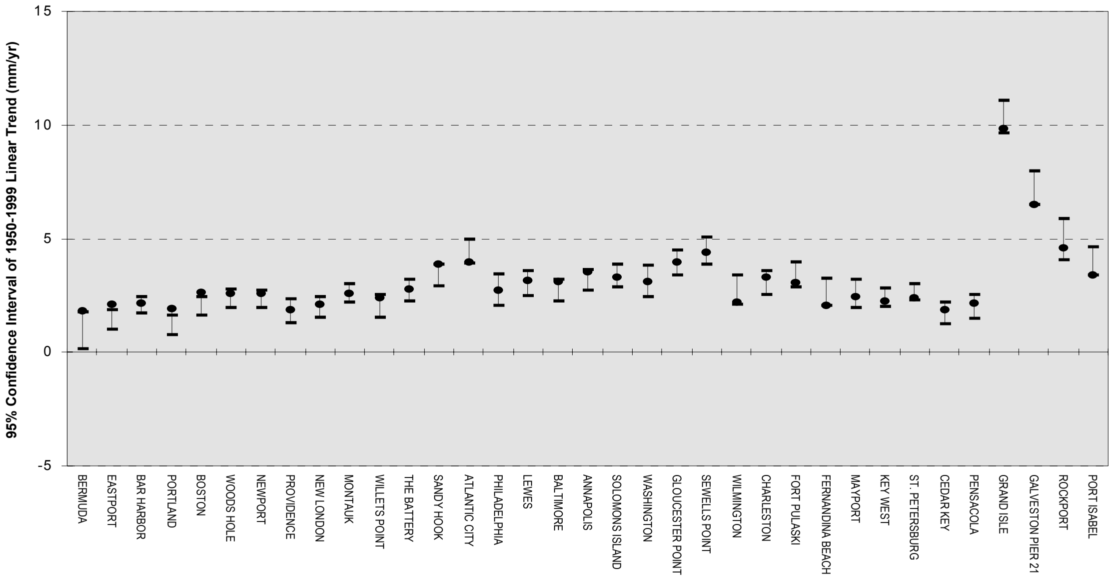

Figure 32. 95% confidence intervals for 1950-1999 linear trends (mm/yr) from monthly MSLs at Atlantic NWLON stations. Also shown as filled circles are the linear trends determined from all available data.

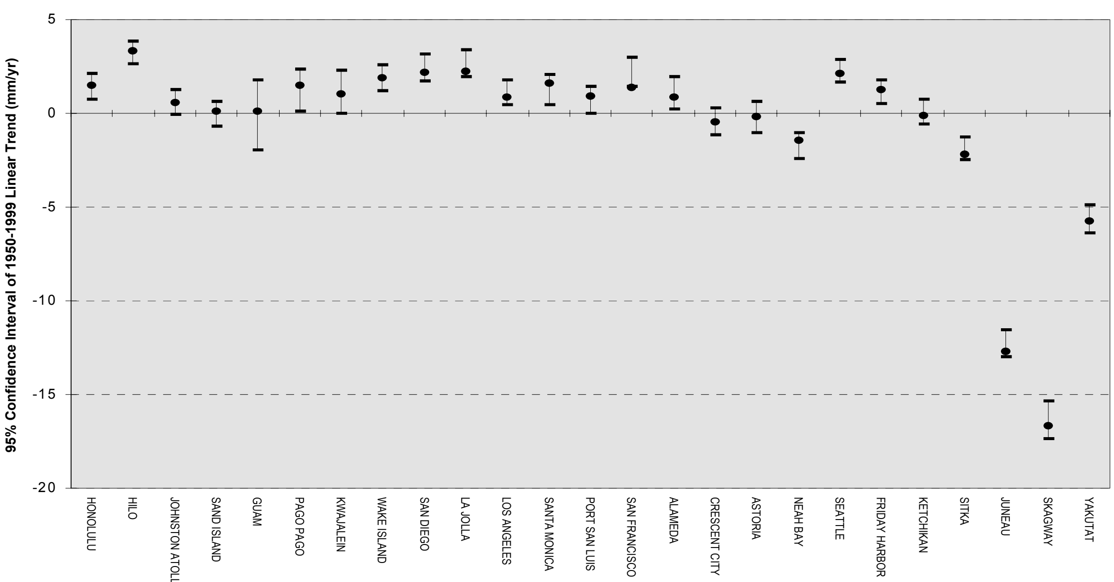

Figure 33. 95% confidence intervals for 1950-1999 linear trends (mm/yr) from monthly MSLs at Pacific NWLON stations. Also shown as filled circles are the linear trends determined from all available data.

Linear MSL trends were also calculated for every possible 50-year period at 5-year intervals for sixteen of the NWLON stations with the longest records. The results are listed in Table C in Appendix V. The 95% confidence intervals for the trends are plotted versus the mid-year of the 50-year periods in Figures 34 to 49. A horizontal line is also plotted showing the overall station trend obtained with all available data (Table 3). An examination of Figures 34 to 49 can identify periods when the 50-year linear trend was significantly different than the overall linear trend. These periods are listed in Table 8.

Table 8. 50-year periods when linear MSL trend differs significantly from overall trend

Station	Mid-year of periods with higher trends	Mid-year of periods with lower trends
Portland	1945, 1950, 1955	1970, 1975
Boston	1945, 1950	1965, 1970, 1975
The Battery	1930, 1935, 1940, 1945, 1950	1970
Baltimore	1935, 1940, 1945, 1950	1965, 1970
Charleston		1965, 1970
Cedar Key		1965
San Francisco	1935, 1940, 1945, 1950, 1970	1890, 1895, 1900, 1905, 1910, 1915
San Francisco*		1885, 1890, 1895, 1900, 1905, 1910, 1915
Seattle	1945	1925

* Relative to the trend since the 1906 San Francisco earthquake.

For some Atlantic stations, periods centered on the years 1930 to 1955 tend to have MSL trends higher than the overall trend, while periods centered on the years 1965 to 1975 tend to have MSL trends lower than the overall trend. For Seattle, the period centered on 1925 had a trend lower than the overall trend while the period centered on 1945 had a trend higher than the overall trend.

For San Francisco, where the 50-year MSL trend actually changes sign and becomes negative for a period around 1900, the situation is less clear and depends on whether the overall trend or the trend since the 1906 earthquake is used. In either case, the periods centered on 1890 to 1915 had significantly lower trends. In fact, the greatest deviation at any station from the overall trend was at San Francisco for the period 1875-1924. The 50-year trend was -0.76 mm/yr, which is 2.17 mm/yr less than the overall trend and 2.88 mm/yr less than the trend since 1906. The San Francisco earthquake, which resulted in substantial fault slippage less than 6 km from the water level gauge, may have caused a small drop in water level and may also have changed the rate of vertical land motion.

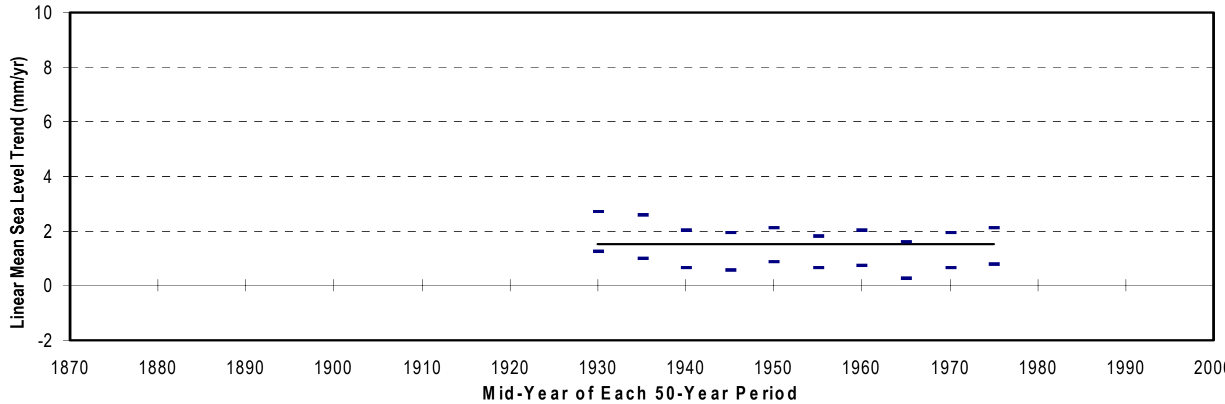

Figure 34. 95% confidence intervals for Honolulu MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

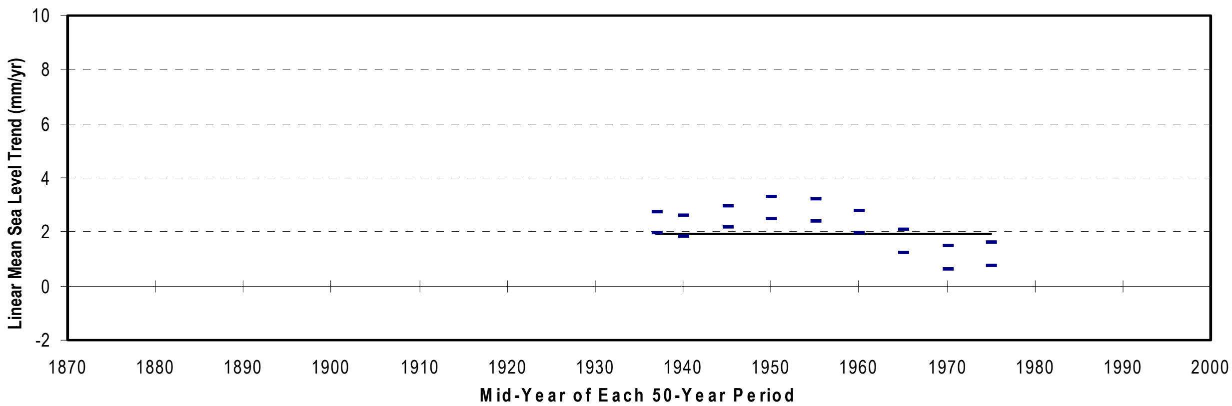

Figure 35. 95% confidence intervals for Portland MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

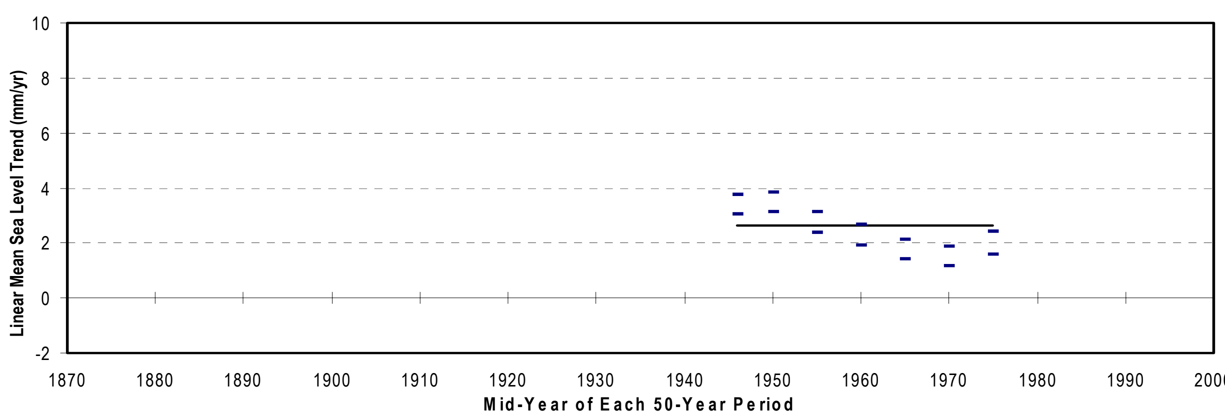

Figure 36. 95% confidence intervals for Boston MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

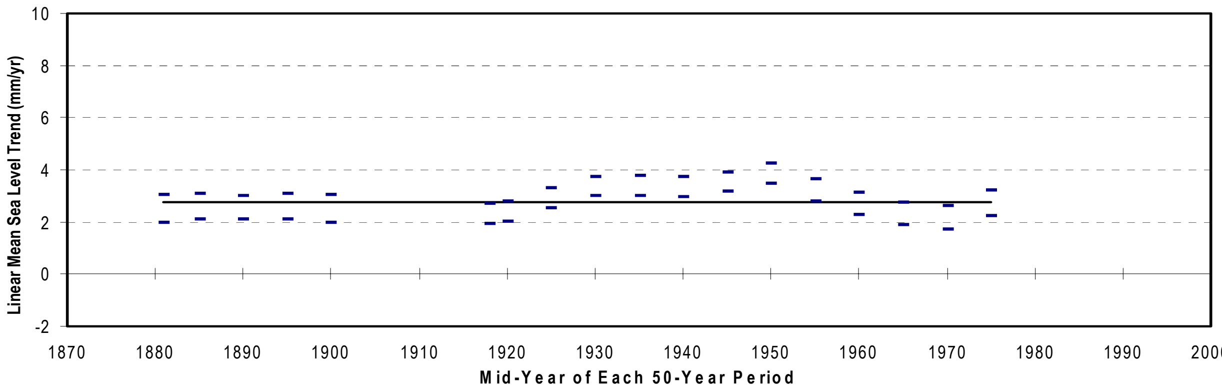

Figure 37. 95% confidence intervals for The Battery MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

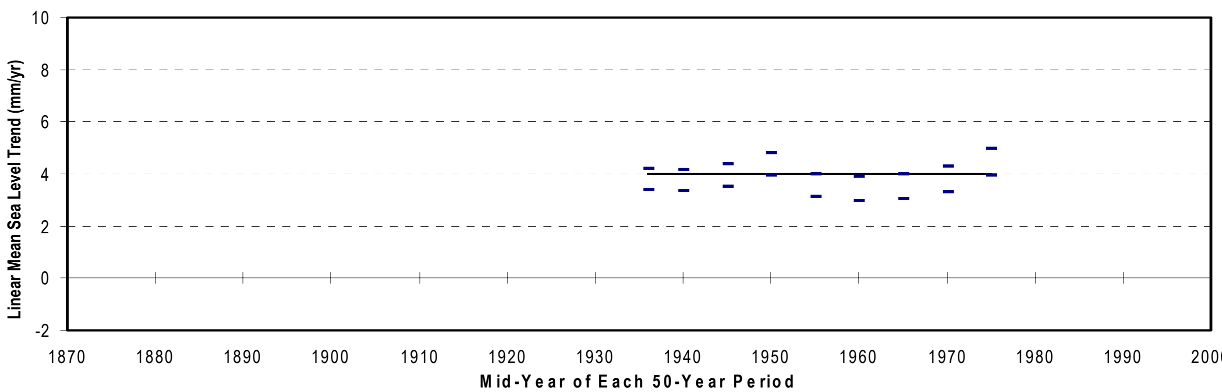

Figure 38. 95% confidence intervals for Atlantic City MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

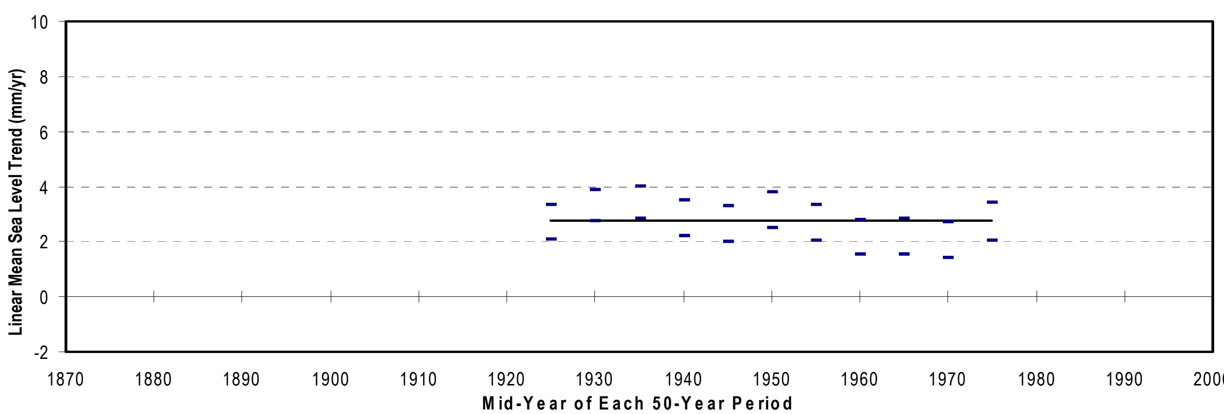

Figure 39. 95% confidence intervals for Philadelphia MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

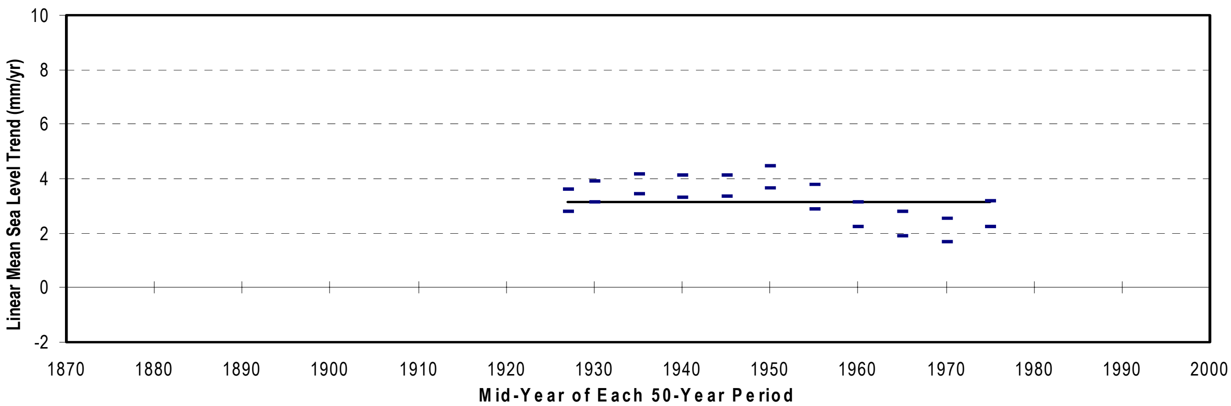

Figure 40. 95% confidence intervals for Baltimore MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

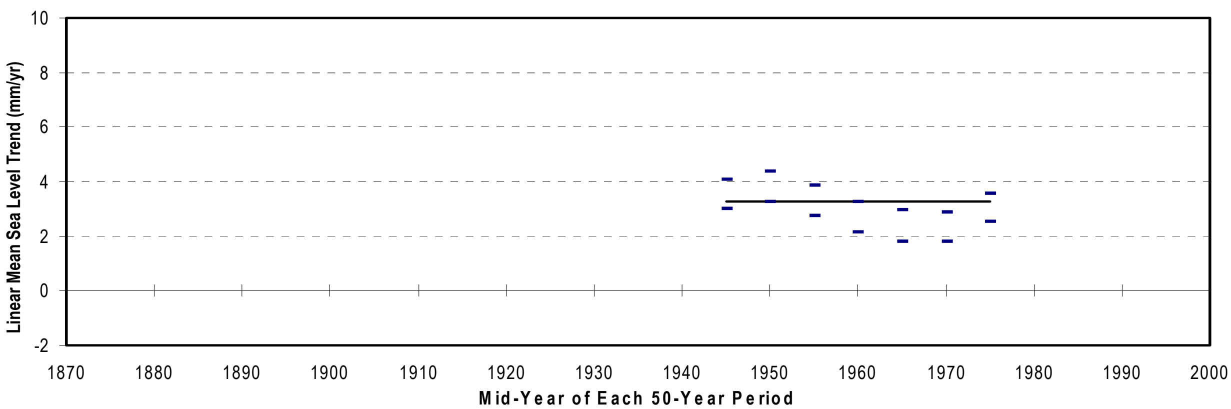

Figure 41. 95% confidence intervals for Charleston, SC MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

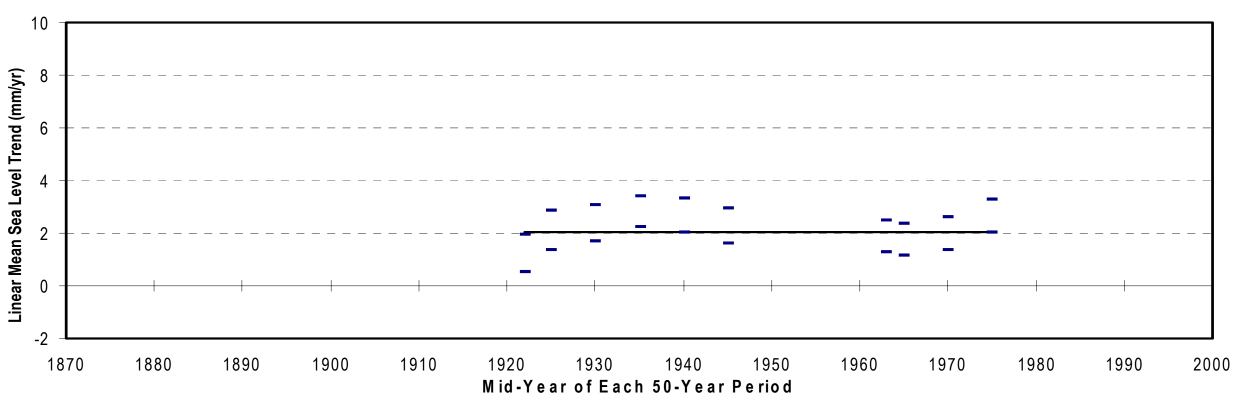

Figure 42. 95% confidence intervals for Fernandina Beach MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

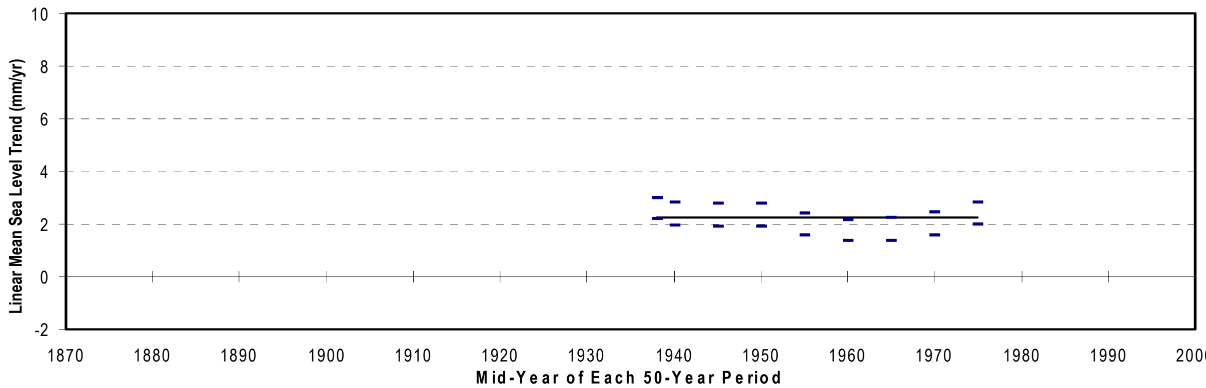

Figure 43. 95% confidence intervals for Key West MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

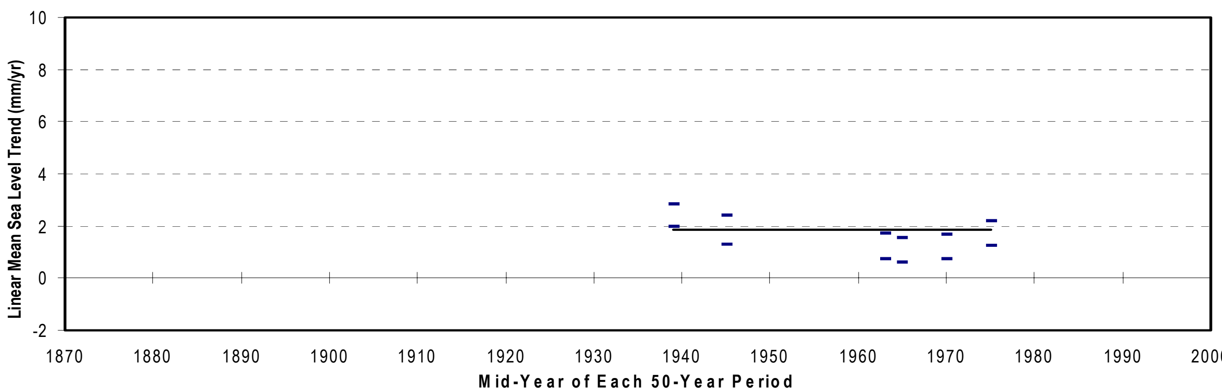

Figure 44. 95% confidence intervals for Cedar Key MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

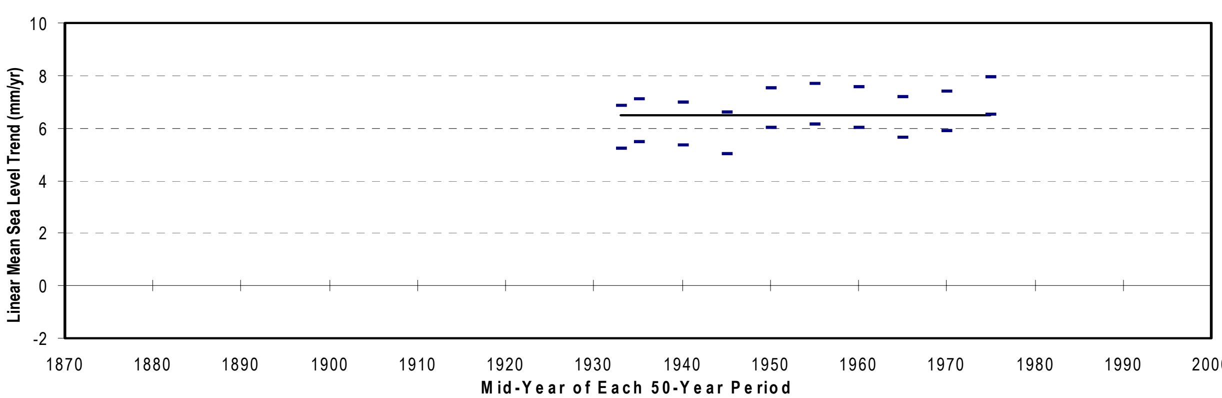

Figure 45. 95% confidence intervals for Galveston Pier 21 MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

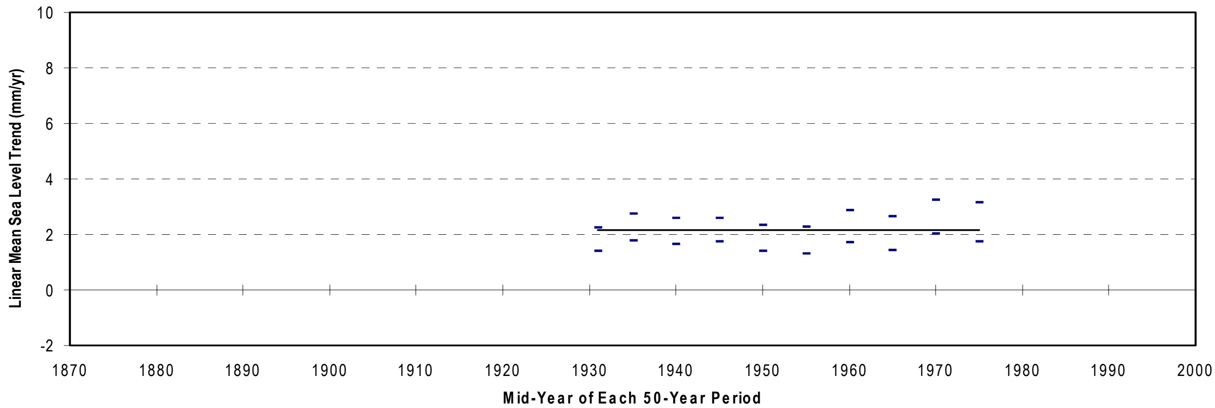

Figure 46. 95% confidence intervals for San Diego MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

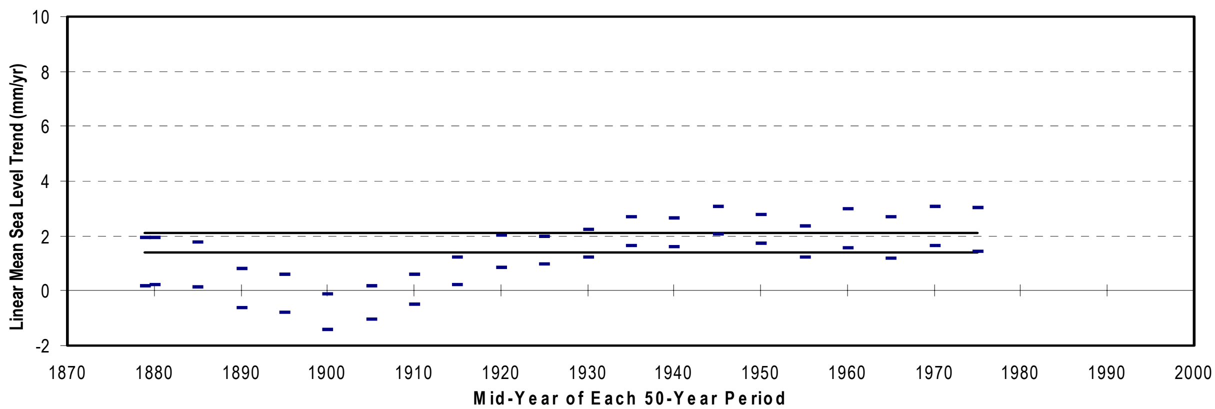

Figure 47. 95% confidence intervals for San Francisco MSL trends determined from 50-year periods. Lower horizontal line is MSL trend from all data (1.41 mm/yr). Upper horizontal line is the MSL trend from data since the 1906 San Francisco earthquake (2.13 mm/yr).

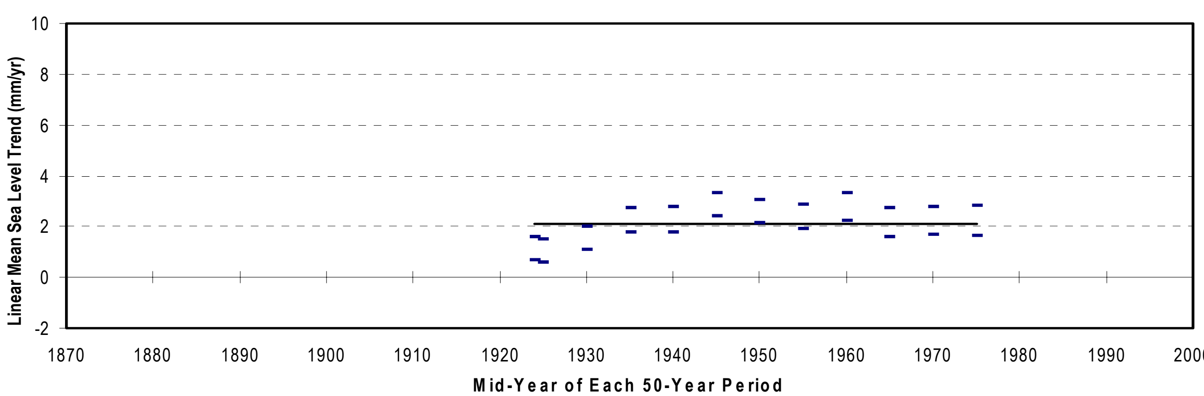

Figure 48. 95% confidence intervals for Seattle MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

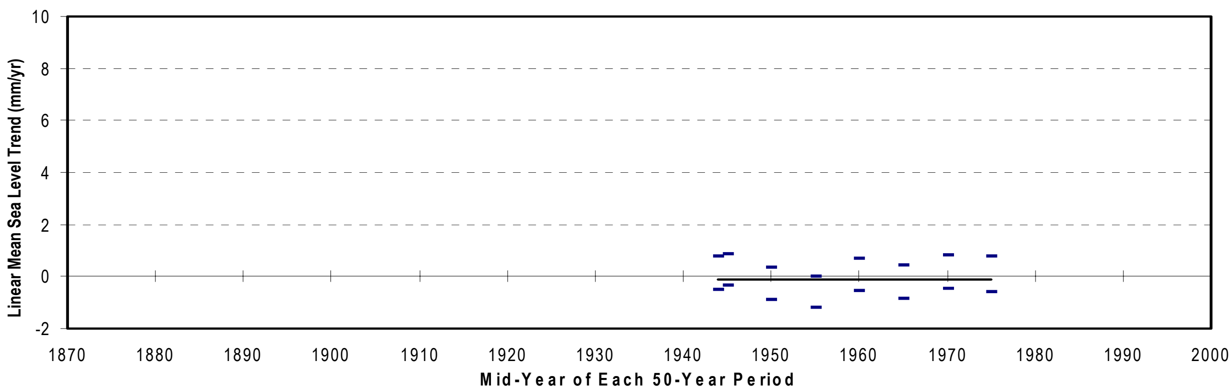

Figure 49. 95% confidence intervals for Ketchikan MSL trends determined from 50-year periods. Horizontal line indicates MSL trend from all data.

In the past, MSL and other tidal datums for NWLON stations have been updated periodically using a NOS-defined 19-year period of data incorporating one 18.6-year cycle of the nodal revolution of the moon. The present datums are established for the 1960-1978 epoch, and they are in the process of being updated to the 1980-1998 epoch. However, in recent years, several NWLON stations in Texas and Alaska with rapid vertical land motions were shifted to a more recent MSL datum in response to concerns for safe navigation. A more frequent MSL datum update may become necessary for these stations. Given the long term sea level trend at a station, it should be possible to predict when a new, statistically different datum can be established.

For a station with a large mean sea level trend, the average of 19 years of data will likely fall close to the annual MSL value of the middle year. For example, the 1960-1978 epoch MSL datum should be close to the 1969 intercept of the long term MSL trendline. In Figure 50, the square symbols indicate the expected sea level 10 years after the mid-point of a datum epoch (e.g., in 1979), as a function of the long term trend at each NWLON station (from Table 3). The 95% confidence interval estimates the uncertainty of the sea level change, given the possible deviation from the long term trend over a 10-year period as described by equation 6. Although the stations with slow trends may still be close to their established MSL datum, those with rapid trends (above 8 mm/yr) will have already moved by a statistically significant amount.

NOS has traditionally updated the tidal datums to a new epoch about every 20 years. Therefore, a period of about 30 years will elapse after the middle year of the established datum epoch to the time that a new datum comes into effect. The present process of updating to a new epoch is expected to be competed in 2002. In this case, 33 years will have elapsed from the middle year of the current epoch to the time a new epoch is in place (1969 to 2002). Figure 51 shows the expected 30-year change in sea level as a function of trend. All stations with trends greater than 1.5 mm/yr will have shifted by a statistically significant amount from their established MSL datum. The stations with rapid MSL trends, greater than 8 mm/yr, will have shifted by at least 0.2 m and as much as 0.4 m. To prevent these station's sea levels from drifting away from their datum by such a large amount, their datums require updating more often than every 20 years.

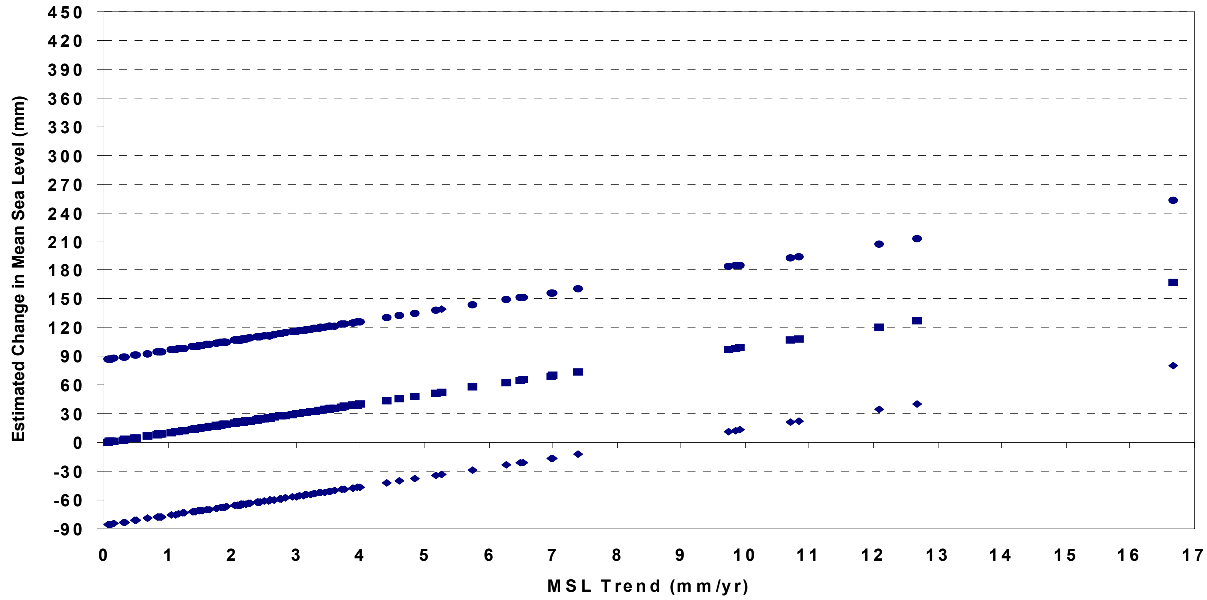

Figure 50. Expected absolute value of sea level change in 10 years (mm) as a function of the MSL trends of NWLON stations. 95% confidence intervals derived from equation 6.

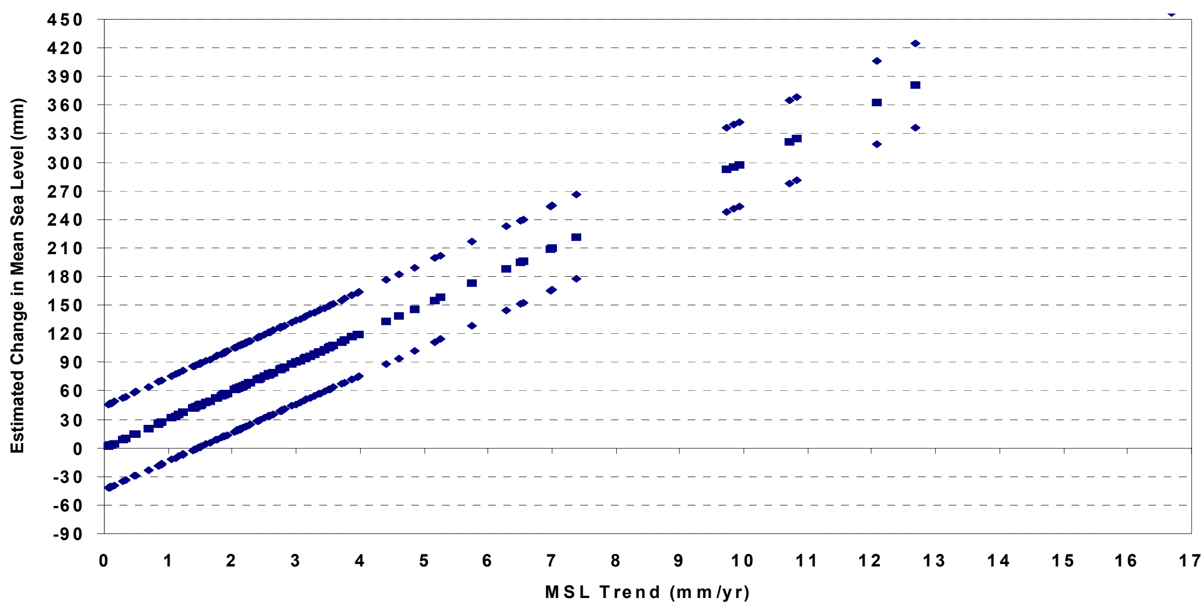

Figure 51. Expected absolute value of sea level change in 30 years (mm) as a function of the MSL trends of NWLON stations. 95% confidence intervals derived from equation 6.

VIII. CONCLUSIONS

The primary purpose of this report is to update the calculated mean sea level trends for NWLON stations up to the end of 1999. The data set analyzed consisted of a total of 117 NWLON stations having monthly MSL records over a span of at least 25 years. NWLON stations are located on the U.S. east and west coasts, the Gulf of Mexico, the Caribbean, Bermuda, Alaska, and Pacific Ocean islands (Figures 1 to 7). The two oldest stations, San Francisco and The Battery (New York) have monthly MSL records beginning in 1854 and 1856, respectively. The data were collected over the years using a variety of different technologies and with some small shifts in instrument location. However, there has been careful maintenance of station datums through regular leveling to stable benchmarks, thus allowing diverse data sets to be combined into time series.

MSL trends are usually obtained by a simple linear regression of annual MSL data. To obtain an annual MSL value requires a complete year of data to average out the seasonal cycle. The standard error of trends from a linear regression assumes that the residual time series is random. However, the residuals are dominated by a 3-5 year variability, most commoly caused by ENSO conditions in the tropical Pacific Ocean affecting ocean temperatures, winds, and currents around the globe. The residual is not a random time series but is, to first order, an autoregressive process of order 1. Therefore, in this report, MSL trends are determined by a linear regression of monthly data with autoregressive residuals of order 1. In addition to the linear trend, the average seasonal cycle, the monthly residual time series, and the autoregressive coefficient of order 1 are determined along with accurate estimates of their standard errors.

The calculated MSL trends (Figures 8 to 10) range between 9.85 mm/yr for Grand Isle, LA to -16.68 mm/yr for Skagway, AK. The MSL trends combine the global MSL rise (which is estimated by numerous studies to be between 1.0 and 2.4 mm/yr) and the local vertical land motion. The calculated MSL trends are consistent with previously published station trends. In Appendices II, III, and IV, are time series plots for each station of the monthly MSL with the seasonal cycle removed, the seasonal cycle, and the MSL residual after both the seasonal cycle and the trend are removed.

The location and timing of any major earthquakes near stations in tectonically-active areas are noted since an associated vertical offset or a change in the MSL trend is possible. At three stations (Unalaska, Adak Island, and Seward), there are clear offsets caused by earthquakes in 1957 and 1964. At Unalaska and Adak Island, there are significant changes in MSL trends. For San Francisco, there is the possibility of a small offset and/or a change in MSL trend caused by the 1906 earthquake. Therefore, three trends are presented for San Francisco: an overall trend, and the trends before and after the earthquake.

The MSL residual plots, after both the seasonal cycle and the trend are removed, show broad regional correlations between stations. Years with extreme high or low residuals are defined by first applying a 5-month running average to the residual time series and then summing the number of months with values above 0.1 m and the number of months with values below -0.1 m. Tables 5 and 6 show the regional extent of periods of anomalous mean sea levels which are primarily caused by ENSO events.

The standard errors of the calculated trends are found to be inversely related to the time span of data available (Figures 29 and 30). An inverse power relationship was derived empirically by fitting a least squares line to a log-log plot of the standard errors for each station versus the year range of the data. This relationship gives an estimated requirement of 50 to 60 years of data for obtaining linear MSL trends having a 1 mm/yr precision with a 95% statistical confidence interval (Figure 31). For a given length of data, the standard errors for trends at Pacific Ocean and western Gulf of Mexico stations tend to be greater than the standard errors for Atlantic coastal stations, due to the greater amplitude of the ENSO events in the Pacific. Two outlier stations, Guam and Chuuk, in the western Pacific Ocean have standard errors even greater than the other Pacific stations.

In order to investigate whether MSL trends have been changing recently, the trend for the period 1950-1999 is calculated for the sixty NWLON stations with data spanning these years. When the trend from each station's entire data set is compared to the 1950-1999 trend, at only three stations (Eastport, Portland, and Boston) is there a statistically significant difference (Figures 32 and 33). At these three northern U.S. Atlantic stations, the recent trends are significantly lower than each station's overall trends. At none of the stations is the 1950-1999 trend significantly higher than the station's overall trend.

The possibility that there are other 50-year periods with MSL trends statistically different than the overall trend is examined for sixteen of the NWLON stations with the longest data sets (Figures 34 to 49). Six Atlantic stations (Portland, Boston, The Battery, Baltimore, Charleston, and Cedar Key) had periods centered on years between 1930 and 1955 with significantly higher trends and/or periods centered on years between 1965 and 1975 with significantly lower trends. Seattle had a period centered on 1925 with a significantly lower trend and a period centered on 1945 with a significantly higher trend. For San Francisco, trends for 50-year periods centered from 1890 to 1915 are significantly lower than both the overall trend and the trend since the 1906 San Francisco earthquake. For periods centered on 1895, 1900, and 1905, the trend is actually negative. This suggests that there may have been a small vertical offset and/or a change in trend caused by the earthquake.

At most NWLON stations, the monthly MSL data are relative to the MSL datum established from the present National Tidal Datum Epoch (1960-1978). However, at a number of stations in Texas and Alaska where there are rapid rising or falling MSL trends, the datum was recently updated using data from 1990-1994 in Texas and 1994-1998 in Alaska. Projections of future changes in MSL (Figures 50 and 51) should be useful in deciding which station datums will require more frequent updates.

ACKNOWLEDGMENTS

Tom Huppmann assisted in the collection of monthly mean sea level data from the DPAS database by creating several SQL queries. Raymond Smith cleared up questions about anomalous data points and provided leveling information for linking several data sets at nearby locations. This report was reviewed by William Stoney, Stephen Gill, Stephen Lyles, Leonard Hickman, James Hubbard, Steacy Hicks, and Kurt Hess and their comments helped to improve the report. The document was prepared for publication by Brenda Via and Gina Stoney. The high quality of the data collected over many decades is attributable to the personnel of the Center for Operational Oceanographic Products and Services and its predecessors. Their sustained efforts in the operation and maintenance of the water level stations and the processing and archiving of data over the years has resulted in an invaluable resource for scientific research.

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