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SEA LEVEL RISE AT KEY WEST, FLORIDA, 1846-1992: AMERICA'S LONGEST INSTRUMENT RECORD?

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Abstract. The continuous series of sea level at Key West, Florida commenced in 1913, but we have discovered sporadic measurements that date back to 1846. From records at the U.S. Army Corps of Engineers and the U.S. Coast and Geodetic Survey, the sea level series has been connected to a Summary (common) Datum. Thus, a gappy record of monthly and annual mean heights (H[t]), perhaps the United States' longest series over San Francisco (*ca.* 1854) or New York (*ca.* 1856), can be tested to ascertain if the rise in relative sea level at this site is stationary. Applying first and second order least squares and two-phase regression analyses, we find that dH/dt is 0.19 ± 0.01 cm/yr, and that $d^2H/dt^2 = [9.6 \pm 8.6] \cdot 10^{-3}$ cm/yr^2; the two-phase regression shows H[t] rising 0.15 ± 0.03 cm/yr before *ca.* 1925 and 0.23 ± 0.01 cm/yr afterwards. Neither the second-order regression coefficient nor d^2H/dt^2 nor the two-phase calculation are significant above the 75% confidence level, but all three are weakly consistent with accelerated rise. For the epoch 1951-1987, Key West sea level, corrected for post-glacial rebound, is best explained by concurrent measurements of 0-1,000 db dynamic height anomaly change.

Introduction

Since the last glacial maximum *ca.* 18,000 years before the present (ybp), global sea level has risen about 120 m, but the rate of rise has not been uniform. After the Holocene optimum, 5,000-7,000 ybp, the rate of rise has been very small compared to that during the 10 millennia preceding. Wanless *et al.* [1988] show that Florida sea level rose at a rate of ~0.25 cm/yr through the Holocene optimum, only ~0.04 cm/yr for the last few thousand ybp, and about 0.23 cm/yr since the instrumental records began in this century. Few U.S. records of sea level extend back to the last century, so when one of us (D.M.M.) discovered that some measurements were made at Key West in the 1840's, 1850's, 1890's and 1903, it offered a long record at a site less affected by tectonics than San Francisco or by glaciation than New York. The limestone rock of the area and the distance from the nearest tectonic plate boundary makes Key West geologically ideal for measuring relative sea level over the last ~150 years.

A sketch of part of Key West Island is used in Figure 1 to show the location of the tide gauges; the map of the environs of Florida shows other gauge sites used in this study. In the period 1846-1903 the Key West tide gauge was located at Fort Taylor, on the western extremity of the island. In 1913 it was reestablished at a site known as Curry's Wharf, about 3 km to the north-northeast, and in 1926 it was moved to the Key West Naval Base (about 2 km south) where it is located to this day. The Naval Base sites (three in all) are about half way between Fort Taylor and Curry's Wharf, so the gauge sites have always been on the western side of Key West Island within a short distance of each other. Before calculating trend or acceleration, data from the five sites had to be referred to a Summary (common) Datum, *i.e.*, a unified tide staff zero had to be computed from historical differential leveling records.

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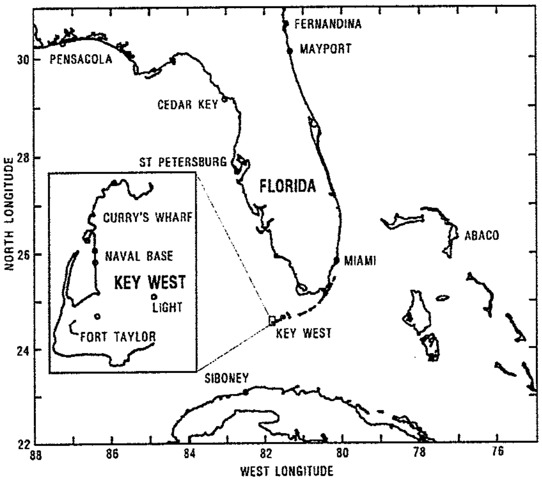

Fig. 1. Map of the region showing locations discussed in the text; inset shows the western end of Key West Island with the locations of the tide gauges. Note that Fort Taylor was surrounded by water and connected to the island by a causeway in the 19th century. BM 1, 5, and 6 were located at Fort Taylor; PBM 13 at Curry's Wharf; PBM 29 at the Naval Station. BM 5 was last leveled to BM 1 and BM 6 in 1913; BM 1 was last leveled to BM 29 in 1923.

Determining a Summary Datum

A combination of mean tide level (MTL), mean diurnal tide level (DTL), and mean sea level (MSL) were used for the series because during this period hourly heights were not routinely tabulated. When only the high and low waters or the higher high and lower low waters were tabulated, MTL or DTL were computed, respectively. The difference between the MSL, MTL and DTL monthly means, computed from the 1926-1992 series, were less than 1.2 cm (0.04 ft), typically on the order of 0.6 cm (0.02 ft) or less. Since the sea level rise at Key West was ~30 cm (~1 ft) during 1846-1992, and because there was no change in the tidal regime between the 1800's and the present, these differences were not significant for our purposes.

Sea level stations consist of a combination of the following components: a water level recorder, a stilling well, a tide staff, a benchmark network, a shelter, and the structure supporting the shelter and equipment. The benchmark is an important part of the station because it is used to establish the staff-to-gauge relationship. This procedure is used for transferring the tide gauge readings to the staff for tabulation and reduction to MSL, DTL, or MTL. Monthly mean values relative to the tide staff zero are related to the primary benchmark (PBM) by differential levels. Thus, the continuity of the series is maintained by referring the data to the Summary Datum through the relationship between the staff zero and the PBM.

The information required to connect the series was recorded in a recapitulation table in the data summary file for the Key West tide station. MTL values for the 1846-1850, 1851-1852, and 1857-1858 series were provided on the 1846, 1847, and 1913 staffs relative to BM 5 and BM 6. Historical station documentation confirmed that the 1846 staff zero was 17.13 ft and the 1913 staff zero was 13.23 ft below BM 5. Similar documents confirmed that the 1847 staff zero was 8.50 ft and the 1913 staff zero was 14.59 ft below BM 6. The height difference (14.59-13.23=1.36 ft) between BM 5 and BM 6 was computed from the relationship to the 1913 staff zero. Table 1 shows the relationship between the BMs and staff zeros that were used to connect the series to the 1927 Summary Datum and the constants applied to the data from the different series to refer that data to the 1927 Summary Datum.

The original data from July 1847 to May 1850 were actually DTL, since only the higher high and lower low waters were tabulated for this series. Hourly height data were available for 1857 to 1858, so MSL was recomputed to verify the historical MSL computation. High and low waters were tabulated on the staffs installed in 1882, 1898, 1899, and 1903; therefore, MTL was computed from the original tabulations and compared to data published in historical BM descriptions to verify the authenticity of these data. MTL for these four series was published relative to BM 1. The 1913 staff zero was determined to be 14.66 ft below BM 1 by differential levels in 1913.

After verification of the original data, the connection between the BMs and the various staff zeros from 1846 to 1903 were related to PBM 29 and the 1927 staff zero, the present Summary Datum for the Key West series. Data from 1913 to 1926 were transferred to the 1927 staff using PBM 13. BM 1 was connected to PBM 29 by three sets of differential levels in 1923, 1933, and 1934, an average height difference of 1.66 ft. BM 1 and BM 6 were connected by leveling in 1913, which provided the 0.06 ft height difference and made the connection to the 1927 staff.

Finally, a benchmark stability analysis was conducted for the BMs used to connect the 1846-1903 data to the 1913 series. Unfortunately, during the early years of station operation it was not uncommon to use only one BM to monitor staff stability and to maintain a chart datum for future use. The dearth of BM and leveling information for this period makes it difficult to prove BM stability conclusively, although it appears from the data that the BM network showed relative stability from 1899 to 1933 with typical r.m.s. differences of ±0.02 ft (±0.6 cm). These BMs were all within 1.5 km of each other and, therefore, one could assume local stability from 1846 to 1899. This is consistent with the geological structure of southern Florida [*q.v.* Wanless *et al.*, 1988].

Table 1. Summary Datum for Key West 1927 tide staff. Constants in feet (cm).

Year	Benchmark	Constant
1846	BM 5	-3.84 (-117.0)
1847	BM 6	6.16 (187.4)
1851	BM 6	-1.11 (-33.8)
1857	BM 6	-0.15 (-4.6)
1882	BM 1	0.32 (9.8)
1898	BM 1	1.44 (43.9)
1899	BM 1	4.20 (128.0)
1903	BM 1	2.06 (62.8)
1913	BM 1	0.06 (1.8)
1913	PBM 13	0.06 (1.8)
1927	PBM 29	0.00 (0.0)

Monthly and Annual Mean Sea Level Data

The annual mean sea levels for Key West, 1846-1992, are presented in Figure 2. There is a clear trend from lower values in the 1800's to higher values today. The inset in Figure 2 is a bootstrap calculation [Efron, 1982] of the least squares linear trend and its associated variation. The overall mean trend is 0.194 cm/yr, and the distribution about the mean trend ($\sigma = \pm 0.014$ cm/yr) can be seen to be slightly skewed from Gaussian, the median value being 0.193 cm/yr. The spectrum of the monthly sea levels (not shown) is dominated by annual (A) and semiannual (SA) energy with amplitude and phase of

$$H[t] = 7.88 \cos(2\pi\omega_A t - 263^\circ) + 3.82 \cos(2\pi\omega_{SA} t - 221^\circ),$$

where t is the decimal Julian Year. This equation is employed to convert partial years from 1882, 1898, 1899, 1903, 1945, 1946, and 1953 into equivalent annual values; all other data are based on a full 12 months of observations.

The serial correlation coefficient (r_1, the non-circularly defined lag-1 autocorrelation) for detrended H[t] is $r_1=0.43$. When $r_1>0$, the effective sample size, n' is less than n. An approximate value for the effective sample size [WMO, 1966] is given by

$$n'=n[1-r_1]/[1+r_1].$$

Thus, we estimate $n' \approx 0.4n$, or $n' \approx 36$ instead of $n=90$ for the annual values of H[t], and reduce the degrees of freedom in the statistical tests accordingly. We have used both L_1 (median absolute deviation, MAD) and L_2 (least squares) curve fitting routines and can report that the regression coefficients determined by either method are essentially identical; L_2 is used in the following analyses.

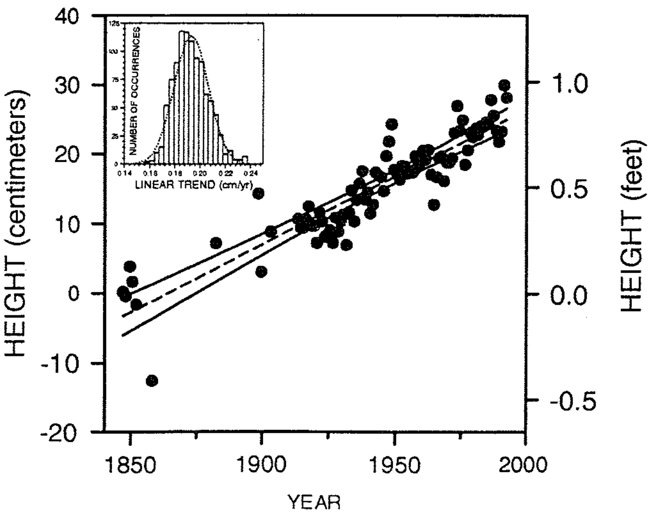

Fig. 2. Annual mean sea level at Key West from 1846-1992; inset shows the bootstrap estimate of the linear trend and its variability. The dashed line is the least squares linear trend and the solid lines are the 99% CI for the trend.

Sea Level Change

Table 2 is a compilation of the trend analysis for the monthly and annual means; all ± values are the standard error (ε) of the regression coefficient. The upper half of the table shows the statistics of fitting first and second order polynomials to H[t], where r^2 is the coefficient of determination, *i.e.*, the fraction of the variance explained by a linear or quadratic fit respectively, and the 99% confidence interval (CI) of the correlation coefficient (r). Woodworth [1990] and Douglas [1992] investigated acceleration in sea level by studying the statistical significance of the second-order regression coefficient b. In the lower half of Table 2 are first order fits to the first derivative, dH/dt, which is an alternate test for acceleration.

The statistical question for either approach applied to Key West regards the null hypothesis concerning b or 2b respectively, *i.e.*, is $10^3b=0.44\pm0.19$ cm/yr^2 or is $10^32b=9.6\pm8.6$ cm/yr^2 significantly different from $10^3b=10^32b=0$? Alternately, is a second order polynomial a statistically significantly better fit than a linear fit? We compute the t-Statistic, $t_b=0.44/0.19=2.3$ and $t_{2b}=9.6/8.6=1.2$, and for a two-sided test of significance, with n'-2 degrees of freedom and $\alpha=0.01$, we find that $t\geq2.7$ is judged significant. For Key West, particularly in view of the gaps in the record, we conclude that the linear description of sea level rise is the most plausible interpretation, but we note that the sign of 10^3b and 10^32b using annual means are both positive, which is appropriate for acceleration. We also note that computing trends to dH/dt (*cf.* Table 2) involves so much "noise" that the Woodworth [1990] and Douglas [1992] approach is preferable, although the L_1 parameters for 10^32b (monthly= 65.1 cm/yr^2; annual=8.9 cm/yr^2) seem less influenced by taking the derivative than do L_2 parameters.

An alternative hypothesis to acceleration is that there has been a statistically significant change in the trend. We apply the two-phase regression test of Solow [1987] to Key West annual means, *i.e.*, we fit the following equation:

$$H[t] = c + a_o t + a(t-t_o)I[t] + \varepsilon$$

where $I[t]=0$ if $t\leq t_o$, $I[t]=1$ if $t>t_o$, and $a=a_1-a_o$. We then employ the Likelihood Ratio Statistic

$$U = [(S_o-S)/3]/[S/(n-4)],$$

where S_o is the residual sum of squares from fitting the model $H[t]=c+a_ot+\varepsilon$ to the ensemble n=90 points and S is from the two-phase regression model, in an F-test of significance with 3 and n-4 degrees of freedom. For Key West annual mean sea level we find a maximum U=2.24 centered on 1925 with $a_o=0.15\pm0.03$ cm/yr, and $a_1=0.23\pm0.01$ cm/yr. U is not statistically significant above the 75% CI, and we conclude that the two-phase regression ($r^2=0.84$) is not significantly better than the linear fit ($r^2=0.83$).

Table 3 summarizes the rate of sea level rise at several stations around Florida for the epoch 1951-1987; all $\pm\sigma$ values are standard deviations. Maul and Hanson [1990] computed over these two lunar nodal cycles (2 × 18.61 yr) the steric height change (0-1,000 db) in the vicinity, and we can apply models of PGR to the concurrent sea level trends. We note that the PGR model of Nakiboğlu and Lambeck [1991] and the observational data of Wanless *et al.* [1988] give moderately different results in this region compared to the one used herein [Peltier, 1986], but that the sign of either PGR model and the observations imply subsiding land relative to sea level; the different PGR results modelled by Tushingham and Peltier [1991] are discussed below.

Sea level rise at Key West for this time period is very similar to that at surrounding stations, and is almost equal to the average of all stations. The two stations with the largest difference in trend are Cedar Key and St. Petersburg, which are adjacent stations (*cf.* Figure 1). To each station we apply the PGR values from Peltier's [1986] model to estimate relative sea level change (ΔRSL), shown in the right-hand column of Table 3. We note that ΔRSL averages 0.15±0.04 cm/yr for these data using Peltier [1986], 0.17±0.05 cm/yr using Nakiboglu and Lambeck [1991], 0.25±0.05 cm/yr using Tushingham and Peltier [1991], and that the dynamic height trend during the same period [1951-1987] is 0.14±0.05 dyn-cm/yr.

Discussion

We have joined partial records of sea level at Key West, Florida from 1846-1903 to the continuous record, which started in 1913, and have investigated the long-term trend. The linear sea level rise has been about 30 cm during this time, and there is statistically weak but consistent evidence that the rate of rise may have increased slightly starting in the mid-1920's. We also have found that the 1951-1987 rise can be explained by modelled PGR of Florida and the change in dynamic height anomaly of the upper 1,000 m of the adjacent water column (Aubrey and Emery [1993] report an additional +0.04 cm/yr in the 1,000-3,000 db water column for 1957-1972, but we have no way to confirm this herein). The rate of sea level rise for Key West (1846-1992), corrected for positive PGR, averages 0.13 cm/yr, a number that is quite consistent with IPCC [1990] estimates of global rise, ~0.12 cm/yr.

Douglas [1991] used the PGR model of Tushingham and Peltier [1991] to estimate 0.18±0.01 cm/yr for global sea level rise and an average of 0.24 cm/yr for Florida. In Florida, Tushingham and Peltier typically have PGR being

Table 2: Summary of linear least squares trend analysis in Key West relative sea level; n (annual)=90; n (monthly)=1007.

Data	Degree	a (cm/yr)	$b\cdot10^3$ (cm/yr^2)	r^2	99% CI
		$H[t]=c+at+bt^2+\varepsilon$:			
Monthly	1	0.21±0.01		0.45	0.72>r>0.63
	2	-0.95±0.58	0.30±0.15	0.46	0.72>r>0.63
Annual	1	0.19±0.01		0.83	0.95>r>0.85
	2	-1.51±0.73	0.44±0.19	0.84	0.95>r>0.86
		$dH/dt=a+2bt+\varepsilon$:			
Monthly	1	9.3±137.1	-4.7±70.4	0.00	0.08>r>-0.08
Annual	1	-18.6±16.8	9.6±8.6	0.01	0.37>r>-0.16

Table 3: Sea level change (1951-1987) in centimeters and dynamic height anomaly change (0-1,000 db) in dynamic-centimeters.

Station Name	PSMSL Years	n	Trend	ε	r	PGR	ΔRSL
Cedar Keys	1951-1987	33	0.14	±0.05	0.42	0.07	0.07
Fernandina Beach	1951-1987	37	0.22	±0.05	0.61	0.07	0.15
Key West	1951-1987	35	0.25	±0.04	0.77	0.09	0.16
Mayport	1951-1987	37	0.19	±0.05	0.54	0.06	0.13
Miami Beach	1951-1987	31	0.24	±0.04	0.72	0.08	0.16
Pensacola	1951-1987	37	0.24	±0.05	0.62	0.06	0.18
Siboney	1966-1990	21	0.22	±0.12	0.39	0.10	0.12
St. Petersburg	1951-1987	36	0.30	±0.03	0.83	0.08	0.22
Mean:			0.22				0.15
±1σ:			±0.05				±0.04
Dynamic Height	**NODC Years**	**n**	**Trend**	**ε**	**r**	**PGR**	**ΔRSL**
Abaco (monthly)*	1951-1987	68	0.14	±0.05	0.32	----	----

*Adjusted from a 10° × 10° latitude × longitude region to a "single" point, and adjusted from monthly to "annualized" values with the annual cycle. See Maul and Hanson [1990] for details.

-0.03 cm/yr, as compared with +0.05 cm/yr in Nakiboglu and Lambeck [1991], +0.08 cm/yr in Peltier [1986], and +0.04 cm/yr in Wanless *et al.* [1988]; over longer time scales, Rona and Clay [1966] estimate subsidence for Florida as 150 m in 1.5 × 10^6 years (*i.e.*, +0.01 cm/yr). Aubrey and Emery [1993] used Peltier [1986] and show a consistent RSL from tide gauges for Florida and the eastern United States. We note that Doulgas' 0.24 cm/yr for Florida is +6σ from his global value of 0.18 cm/yr, but had he used Nakiboglu and Lambeck, his Florida values would have averaged 0.16 cm/yr. Tushingham and Peltier [1991] use no ^{14}C in Florida to constrain their model, and it probably should be re-examined in this region.

We have also compared the shoreline of Key West (*ca.* 1850) with today's (not shown) and find that the sea level rise of 30 cm has not resulted in significant shoreline regression. In fact, the area of Key West Island has increased since the last century due to dredging and construction. Given the importance of long records to problems in shoreline migration and climate analysis, and the potential that there are others like Key West in the archives of both federal and local agencies, we urge that an effort be established to seek them out and provide the data to the public.

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