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Sea level accelerations at globally distributed tide gauge stations during the satellite altimetry era

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Abstract: This observational study reports that several globally distributed tide gauge stations exhibit a propensity of statistically significant sea level accelerations during the satellite altimetry era. However, the magnitudes of the estimated tide gauge accelerations during this period are systematically and noticeably smaller than the global mean sea level acceleration reported by recent analyses of satellite altimetry. The differences are likely to be caused by the interannual, decadal and interdecadal sea level variations, which are modeled using a broken trend model with overlapping harmonics in the analyses of tide gauge data but omitted in the analysis of satellite altimetry.

Keywords: Climate change; Satellite altimetry; Sea level acceleration; Tide gauges. Broken trend model.

1 Introduction

Evidence for global mean sea level (GMSL) rising faster during the 20th century with global warming is an important indicator in understanding anthropogenic contributions to the climate change mechanisms. In the past, several studies investigated the presence of a global acceleration in sea-level rise with mixed results (see, e.g., Woodworth, 1990, Douglas, 1992, Church and White, 2006, Holgate, 2007, Merrifield et al., 2009, Woodworth et al., 2009, Houston and Dean, 2011, Jevrejeva et al., 2013, Kopp, 2013, Hogarth, 2014, Watson, 2016a, 2016b). More recently, Iz (2017) verified that there is no statistically significant observational evidence for a global mean sea level acceleration during the 20^{th} century by analyzing mean sea level data at globally distributed tide gauge (TG) stations with long records. However, this conclusion cannot be cast into the future confidently given the recent observational evidence for a global sea surface temperature acceleration (Iz, 2017) and its lagged impact as a thermosteric effect on sea levels at TG stations (Iz, 20016a, 2016b).

Along these lines, Yi, et al. (2015) reported an increase in GMSL over 1.4 mm/yr. since 2010 with respect to background sea level trend of 3 mm/yr by analyzing satellite altimetry data. Davis and Vinogradova's (2017) findings through the analysis of satellite altimetry time series was along an acceleration on the east coast of North America. Dieng et al. (2017) determined an increase of about 0.8 mm/yr in the global GMSL velocity since 2004. Nerem, et al. (2018) reported 0.084±0.025 mm/yr^2 GMSL acceleration since 1993 inferred from the satellite altimetry data.

Satellite altimetry measurements are effective in monitoring GMSL variations, yet the global coverage is only available since 1993, a time span not long enough to allow to identify and model low frequency sea level variations. This limitation is likely to bias GMSL trend and acceleration estimates. In contrast, tide gauges sample only local and regional sea level variations, but several stations' records span over a century. Despite the limited global coverage, globally distributed TG stations can serve effectively to verify satellite altimetry findings regarding the GMSL rise at globally distributed locations and quantify the bias introduced by the omission error due to the unmodeled low frequency sea level variations in satellite altimetry.

Consequently, this study aims to verify the recent satellite altimetry findings about a GMSL acceleration during the satellite altimetry era by analyzing sea level trends at globally distributed TG stations using a broken trend model. The model accommodates concurrently changes in sea level velocities and interannual, decadal, and interdecadal sea level variations before and during the same period, and

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therefore, less prone to the limitations of shorter GMSL time series.

In the following sections, a brief presentation of the monthly records of the twenty-seven TG stations is given. A broken trend model is discussed and used to analyze TG records to quantify sea level trends before and after the satellite altimetry era. The change in the estimated sea level trends are then used to evaluate the mean sea level acceleration at each TG station.

1.1 Tide Gauge Records

The locations of twenty-seven globally distributed TG stations are shown in Figure 1. These stations are selected mainly because of their long records predominantly over a century, therefore, enable the detection and modelling low and high frequency sea level variations. They were downloaded from the Permanent Mean Sea Level (PSMSL) repository on February 2016 (PSMSL, 2016, Holgate et al., 2013). They are all referenced to the Revised Local Reference (RLR). No corrections for the post glacial rebound (PGR) were applied to the data. Therefore, all inferences refer to *relative sea level changes*. However, the reported velocity differences and accelerations are free from the PGR effects experienced at the tide gauge stations because of their cancellations.

Figure 1: The locations of the TG stations used in this study are indicated with drops (Google map, 2016).

1.2 Sea level variations

Sea level variations experienced at TG stations are multicausal. Some of the effects are well known, such as, local subsidence, vertical crustal movements caused by regional tectonics, global isostatic adjustment. Some of the others are induced by wind, atmospheric pressure, external forcing such as lunar of solar origin, thermosteric effects of warming oceans or eustatic in nature. They may be secular, episodic or transient in nature, or periodic at semi-annual, annual, interannual, decadal, or longer time scales, all contributing to sea level changes.

Among the periodic changes, annual sea level variations are dominant (Pugh, 1996), the others were detected and quantified by Iz (2014, 2015). They are excited by the compounding of the periodic variations induced by the regression of the lunar node, which completes its cycle in P=18.613 yr., with other effects to produce subharmonics with periods including: $2\times P$ = 37.226 yr.; $3\times P$ = 55.839 yr.; $5\times P$ = 74.452 yr., and its super harmonics with periods: $P/2$ = 9.306 yr.; $P/3$ = 6.204 yr. Some of the others are caused by solar radiation with a period of P = 11.1 yr., with its subharmonics with periods: $2\times P$ = 22.2 yr. and longer (Iz, 2014).

These sub and super harmonics compound with their nearby frequencies, which are caused by natural or forced sea level variations and broadband internal ocean–atmosphere interactions including steric and eustatic contributions producing signatures at decadal and multi-decadal time scales. Iz (2016a, 2016b) has shown that one of the two major compounders of sea level variations in tandem with luni-solar effects have been the thermosteric effect of the warming oceans, which also exhibits low frequency sea level changes (Iz, 2016a). The other is the atmospheric pressure through the inverted barometric effects (Iz, 2018a).

As early as 2006, Iz has shown that, these periodicities despite their small amplitudes, if not modelled, will bias the sea trends estimated from shorter TG records. Moreover, their effects may also be mistakenly interpreted (confounding) as an acceleration at sea level rise if not incorporated into the models for short as well as longer series. Table 1 lists the periodicities of the effects of luni-solar origin activated by compounding with the sea level variations discussed above.

In addition, Iz (2015) demonstrated that once these effects are modeled and the corresponding model parameters are estimated, spectral analysis of the TG residuals reveals additional statistically significant sea level variations at decadal scale due to the ocean surface wind forcings and periodic changes in atmospheric pressure along the coastal lines of some of the TG stations (Figure 2).

In the following section, a broken trend harmonic model that accommodates all these potential systematic sea level variations in estimating sea level trends before and after 1990 is presented. The model solutions at 27 TG stations are discussed.

Table 1: Luni-Solar compounded periodicities (yr.) to be modeled in the broken trend model in the following section.

Nodal Subharmonics	Nodal Superharmonics	Nodal Superharmonics	Solar	Annual Subannuals	Chandler
74.5	18.6	3.7	11.1	1.00	429.5/365.4
55.8	9.3	3.1	22.2	0.50	
37.2	6.2	2.6		0.25	
	4.7	2.3			

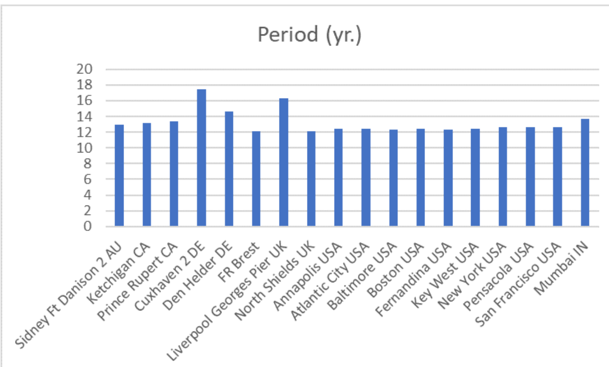

Figure 2: Additional statistically significant decadal periodicities in years at 27 globally distibuted TG stations with long records (Iz, 2015).

1.3 Broken trend model with compounding harmonics

This is an observational study, which deploys only recorded TG data. The following broken trend model with harmonics can be effectively used to represent the effect of the statistically significant systematic sea level variations of various origins and to detect any changes on sea level trend during the satellite altimetry era at the TG stations.

The inclusion of ancillary information through the harmonics is essential to account for the persistent sea level variations at each TG station during the recent satellite altimetry era. Otherwise, such variations may falsely be interpreted as accelerations. The sea level trends before and during the satellite altimetry era estimated through the broken trend model can then be compared to evaluate sea level accelerations at TG stations.

The broken trend model is stated as,

$$h_t = h_{t_0} + v^{TG}(t^{TG} - t_0) + v^{SA}(t^{SA} - t_0) + \\ + \sum_{k=1}^{37} \left[\alpha_h \cos \left(\frac{2\pi}{P_k} \right) (t - t_0) + \gamma_h \sin \left(\frac{2\pi}{P_k} \right) (t - t_0) \right] + \varepsilon_t \tag{1}$$

with,

$$\varepsilon_t = \rho\, \varepsilon_{t-1} + u_t \qquad 0 \le |\rho| < 1 \qquad u_t \sim (0, \sigma_u^2) \tag{2}$$

In this representation, a monthly TG observation at an epoch t is denoted by h_t. The time index $t = 1 \ldots n$, where n is the number of months and includes all the available TG data whereas t^{TG} and t^{SA} refer to the epochs of the monthly TG data before and after the satellite altimetry era respectively (the broken trend). The intercept h_{t_0} is the height of the sea level defined at the reference epoch t_0 chosen to be in the middle of the whole TG series. Accordingly, there are two unknown trends v^{TG} and v^{SA} in the sea level referenced to the period before 1990, and after 1990 respectively[1]. The periodicities listed in Table 1 and Figure 2 are modeled to account for the persistent periodic variability in the TG data and extend their effects into the satellite altimetry era. *It is important to emphasize that the harmonics are common to the whole-time span of the TG records in contrast to the two broken trends before and after 1990.* Each periodicity introduces two additional unknown parameters, α_h, γ_h for the sine and cosine components from which the amplitudes α_h and the phase angles of the periodic terms are determined. In total, the model includes 37 unknown parameters common to all TG stations in addition to the decadal periodicities for some of the stations listed in Figure 2. The final number of model parameters depends on the statistically significant components at each TG station.

Equation (2) lists assumed statistical properties of the disturbances ε_t. They are autocorrelated with an unknown first order autocorrelation coefficient denoted by ρ, and include random noise $u_t$assumed to be homogeneous with variance $\sigma^2_{u_t - u_{t-1}} = \sigma^2_{u_t} = \sigma^2_u$ and serially independent , i.e. $\sigma^2_{u_{t-1,t}} = 0$.

As stated before, these tide gauge stations do not exhibit statistically significant uniform accelerations during the 20th century (Iz, 2017). Therefore, no acceleration parameters are included for the period before 1990. Similarly, accelerations for the tide gauge records since 1990 were not parameterized because of the noisy data and short span of the records ($yr^{SA} \sim 26\,yr.$, Table 2). Instead these

1 The choice of the year 1990 is dictated by the earliest availability of the satellite altimetry time series since 1993.

accelerations $\hat{a}^{SA}$ will be inferred from the estimated two broken trends $\hat{v}^{SA}$ and $\hat{v}^{TG}$ as follows,

$$\hat{a}^{SA} = \frac{\hat{v}^{SA} - \hat{v}^{TG}}{yr^{SA}} \quad (3)$$

The model solutions were carried out for each 27 TG stations using the least squares method. The Hildreth-Lu procedure (Hildreth and Lu, 1960) was used to estimate the first order autocorrelation coefficients, which accounts for the effect of the first order autocorrelation during the least squares solutions. Two solutions were carried out for each TG station during which the estimates with *p-values*[2], $p > 0.05$, were removed from the full model (backward elimination) or parameters with $p < 0.05$ were added one at a time (forward selection). Both model building approaches gave similar results thanks to the near orthogonality of the harmonics.

Table 2 exhibits some of the summary statistics for the 27 TG stations. The second column lists the length of the all available data at each TG station, which are used in setting up part of the observation equations for the periodicities, the harmonics in eq. (1). Tide gauge records before 1990 were used in estimating the sea level trend before 1990. The corresponding broken trend estimates (mm/yr.) are listed under yr^{TG} column together with their standard errors in the following $\hat{\sigma}^{TG}$ column. Because of the long-time span of the series in modelling the systematic sea level variations, all the listed parameter estimates are statistically significant (p<0.05).

The lengths of the records used after 1990 for estimating the trends during the satellite altimetry era are predominantly 26 years long (yr^{SA}). Simultaneously estimated broken trends and its standard errors during the satellite altimetry era for 27 TG stations are listed under v^{SA} and $\hat{\sigma}^{SA}$ columns. These estimated broken trends during the SA era are also statistically significant (p<0.05). In sum, the use of long TG time series with common harmonic variations stabilized estimating the sea level trends during the SA era, improved their standard errors, as well accounted for the effect of the compounding sea level variations.

Durbin-Watson test (*DW* [3]) verifies that the systematic variabilities in sea level variations were taken care of properly by the model. The magnitude of the estimated first order correlations, $\hat{\rho}$, are also listed in the same table. They are considerably smaller in magnitude, as compared to global satellite altimetry time series, which could be as large as 0.8 [4]. Given the fact that the TG records are serially correlated, modeling their effects mattered in testing the statistical significance of the estimates. The a posteriori variances, $\hat{\sigma}_0$, if interpreted in the context of rms residuals, are mostly uniform and less than decimeter level. The R^2[5] values however, are heterogenous. The unexplained part of the R^2 values can be attributed partly to the unmodeled atmospheric pressure variations that are departed from annual and semiannual cyclicities, which are a function of the TG station location, as well as model imperfections (Iz, 2018).

Figure 3 displays the sea level accelerations (mm/yr^2) at 27 TG stations with long records since 1990 for an easy comparison. The accelerations at the TG stations were calculated using eq. 3. Differencing of the broken trends cancels the common unmodeled PGR induced trends.

Majority of the TG stations reveal a propensity for acceleration experienced during the satellite altimetry era (Figure 3). Large acceleration at Swinoujscie, PL TG station is due to the short data span of 7 years. Nonetheless, the magnitudes of the accelerations are considerably smaller than the GMSL acceleration of 0.084±0.025 mm/yr^2, which is inferred from the global satellite altimetry (Nerem et. al, 2018).

2 Conclusion

This study reports that twenty-seven globally distributed TG stations with long records experienced statistically significant sea level accelerations since 1990 during the satellite altimetry era. The analyses of the TG records used a broken trend model with common harmonics that are extended to account for the low frequency sea level variations during the satellite altimetry era. The magnitudes of the mean sea level accelerations at these globally distributed TG stations are markedly smaller than the GMSL acceleration, 0.084±0.025 mm/yr^2, reported by a recent satellite altimetry study (Nerem et al., 2018). The differences are likely to be caused by the omission of the effect

2 The *p-value* is the probability of obtaining a test statistic result at least as extreme or as close to the one that was observed, if the null hypothesis is true (Goodman, 1999). Smaller *p-values* for the model parameters in this study, provide statistical evidence (*independent of the significance level*) that the magnitudes of estimates cannot be attributed to chance alone.

3 *DW* is an indicator of remaining autocorrelation in residuals (~2 when the residuals are independent). It is unfortunate that this statistic has not been reported so far in any TG time series analyses.

4 It is observed that recent GMSL studies fail to report this number, which is of importance not only to get insight about the nature of sea level variations, but also in making statistical assessments and accounting for potential pitfalls.

5 Adjusted for the degrees of freedom.

Table 2: The solutions' statistics for the 27 TG stations. The corresponding broken trend estimates (mm/yr.) before the SA era (before 1990) are listed under column together with their standard deviations in the following column. is the a posteriori variance of unit weight, DW refers to the Durbin-Watson statistics, is the adjusted coefficient of determination, and is the estimated first order autocorrelation coefficient.

Station	yr^{TG}	v^{TG}	$\hat{\sigma}^{TG}$	yr^{SA}	v^{SA}	$\hat{\sigma}^{SA}$	$\dot{v}$	$s^{\dot{v}}\hat{\sigma}^{\dot{v}}$	$\hat{\sigma}_0$	R^2	DW	$\hat{\rho}$
Annapolis USA	87	4.49	0.30	26	4.33	0.32	-0.006	0.017	53.4	73.37	2.07	0.3
Atlantic City USA	104	3.76	0.11	26	4.43	0.12	0.026	0.006	57.0	78.61	1.92	0.2
Baltimore USA	113	2.84	0.09	26	3.64	0.12	0.031	0.006	53.1	81.44	1.98	0.2
Boston USA	89	2.63	0.12	26	2.44	0.15	-0.007	0.007	43.5	64.64	2.14	0.3
Fernandina USA	118	1.92	0.15	26	2.32	0.22	0.015	0.010	76.2	52.75	1.98	0.4
Key West USA	102	1.69	0.14	26	3.19	0.14	0.058	0.007	40.8	70.75	1.97	0.4
New York USA	159	2.68	0.06	26	3.23	0.09	0.021	0.004	65.9	76.95	2.09	0.3
Pensacola USA	92	2.41	0.19	26	2.55	0.18	0.005	0.010	48.1	64.83	2.03	0.4
San Francisco USA	161	1.28	0.08	26	2.22	0.15	0.036	0.006	44.9	37.71	2.1	0.6
Honolulu USA	110	1.51	0.14	26	1.18	0.17	-0.013	0.008	33.0	30.16	1.99	0.7
Cuxhaven DE	167	2.14	0.09	21	2.11	0.15	-0.002	0.008	142.4	38.29	1.96	0.1
Den Helder DE	146	1.40	0.07	27	1.60	0.10	0.007	0.005	92.0	45.71	2.01	0.1
Travemunde DE	158	1.62	0.06	25	1.57	0.08	-0.002	0.004	77.2	46.89	1.99	0.1
Brest FR	205	0.83	0.05	26	1.46	0.08	0.024	0.003	73.6	34.15	2.05	0.3
AmsIjmuiden NL	144	1.52	0.08	26	2.92	0.16	0.054	0.007	88.7	49.41	1.92	0.1
Delfzjil NL	150	1.53	0.10	26	2.21	0.14	0.026	0.006	114.6	36.83	1.99	0.1
Harlingen NL	150	1.36	0.09	26	1.31	0.14	-0.002	0.006	114.6	33.91	2.00	0.1
Terscelling NL	94	0.62	0.23	26	1.93	0.24	0.050	0.013	99.8	35.65	1.99	0.1
Swinoujscie PL	188	0.61	0.06	7	1.04	0.16	0.062	0.024	99.8	16.53	1.91	0.3
Landsort SE	128	-3.03	0.20	16	-2.69	0.31	0.022	0.023	124.4	29.60	1.94	0.4
Stockholm SE	126	-4.01	0.21	26	-3.43	0.27	0.022	0.013	127.3	37.15	1.92	0.4
Liverpool UK	125	2.49	0.25	20	2.49	0.25	0.000	0.018	86.3	49.86	1.92	0.0
N. Shields UK	120	1.72	0.10	26	2.16	0.13	0.017	0.006	55.0	56.99	2.06	0.3
Sydney AU	101	0.63	0.10	26	1.40	0.12	0.030	0.006	45.0	43.34	1.98	0.2
Ketchikan CA	101	-0.43	0.19	26	0.00	0.00	0.016	0.007	72.8	41.21	2.08	0.3
Prince Rupert CA	106	0.94	0.19	26	2.03	0.37	0.042	0.016	71.3	45.99	2.08	0.3
Mumbai IN	133	0.73	0.05	22	1.05	0.10	0.014	0.005	49.0	36.77	2.04	0.2

of perpetual sea level variations extending into the satellite era in the analysis of global satellite altimetry time series. Because of the effect of major contributors to the sea level variations in the past as well as during the satellite era are not accounted for in modelling global satellite altimetry time series, the estimated GMSL acceleration by the satellite altimetry may be biased. Any unmodeled periodic decadal or interdecadal sea level variations of lunar node forcing or of solar radiation origin and their subharmonics in combination with random or systematic natural sea level variations may mimic an acceleration during the satellite altimetry era and bias the GMSL estimate using satellite altimetry. There is already observational evidence for variable sea level accelerations and decelerations during the 20^{th} century as revealed by the TG records (Iz et al., 2013) and subsequently explained by the low frequency sea level variations, supporting this possibility.

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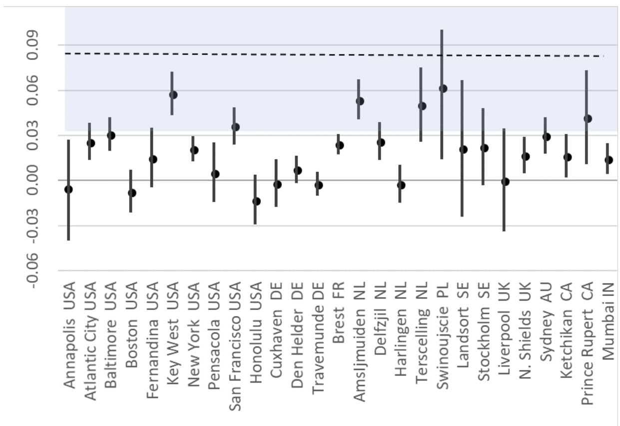

Figure 3: Sea level accelerations (mm/yr^2) at 27 TG stations with long records since 1990. Differences were converted into accelerations by dividing the velocity differences by the time span of the series since 1990, i.e. $\hat{a}^{SA} = (\hat{v}^{SA} - \hat{v}^{TG})/yr^{SA}$. Dashed line and shaded area mark the GMSL acceleration determined by the analysis of satellite altimetry is 0.084 mm/yr^{2}with 95 % CI (0.035,0.133).

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