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Sea level acceleration under the magnifier

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Abstract: Detection and quantification of sea level accelerations at tide gauge stations are needed for assessing anthropogenic contributions to the climate change. Nonetheless, uniform or non-uniform sea level accelerations/decelerations are particularly difficult to discern partly because of their small magnitudes and partly because of the low frequency sea level variations as confounders. Moreover, noisy excursions in the observed sea level variations also exacerbate reliability of estimated sea level accelerations. This study explores the uniformity of a sea level acceleration graphically that is left unmodeled in the residuals of a least squares solution using cumulative sum charts. Key West, USA tide gauge station's record is studied for a demonstration. The cumulative sum charts of the residuals of a rigorous kinematic model solution without the acceleration parameter revealed its crisp and uniform signature experienced at this station since 1913.

Keywords: Tide gauge; Sea level rise; Uniform sea level acceleration; Cumulative sum charts

Some lines are clearly bent whereas others appear to be straight; but under a magnifying glass even the straightest of lines will show up imperfections.

Kees Van Deemter,
Not Exactly: In Praise of Vagueness, 2010.

1 Introduction

Evidence for mean sea level rising faster during the 20th and 21st centuries with warming is an important indicator in assessing anthropogenic contributions to the climate change mechanisms. There are several tide gauge, TG, stations available for scrutinizing contemporaneous seal level accelerations for this purpose. In the past, several studies investigated the presence of mean sea level accelerations 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) and Iz et al., (2018) reported mean sea level accelerations during the 20^{th} and 21^{st} centuries respectively by analyzing mean sea level data at globally distributed tide gauge (TG) stations with long records.

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, SA, 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 SA data.

Common to all the previously mentioned studies[1] and others is the explicit or implicit assumption that sea level accelerations/decelerations are uniform in nature. Nonetheless, uniformity of mean sea level accelerations/decelerations are particularly difficult to discern at coastal regions partly because of their small magnitudes and partly because of the confounding low frequency sea level variations that are location specific. Noisy excursions in the observed sea level variations also exacerbate reliability of estimated sea level accelerations. *Hence, this study aims to establish and demonstrate a graphical tool based on cumulative sum, CUSUM, charts to explore the uniformity of a sea level acceleration.* The residuals of a least squares solution of a kinematic model that does not include a uniform acceleration parameter would contain its signature. It will be demonstrated that the CUSUM chart of the residuals enhances a heightened a cubic like plane curve of the unmodeled acceleration buried in the random noise providing a check about the uniformity of the acceleration. This is a novel idea in sea level studies given no background to cite.

In the following sections, first, the basis of the CUSUM chart as an exploratory tool that reveals the uniformity of a sea level acceleration is established to supplement

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1 Except Iz et al., 2018.

and to verify its statistically significant estimate from a TG record. A rigorously parametrized kinematic model is then stated in a separate section for the subsequent analyses. A brief information about Key West, USA tide gauge record is provided, and a CUSUM chart of the residuals are demonstrated to verify the uniformity of a statistically significant the sea level acceleration at this station.

2 Cumulative sum of a uniform acceleration signal

Consider the following overly simplified representation[2] of an observed sea level height at an epoch t,

$$h_t^{obs} = h_0 + v_0 \Delta t + \frac{a}{2}\Delta t^2 + u_t, \quad \Delta t := t - t_0 \tag{1}$$

In this expression, v_0 is the initial velocity at t_0, which is the reference epoch chosen to be in the middle of the series, h_0 is the reference sea level at this epoch. The uniform acceleration is denoted by a. Random disturbances $u \sim (0, \sigma_u^2)$, have a variance σ_u^2.

The following cumulative sum, CUSUM, of a parabolic uniform acceleration component with zero initial velocity enhances the magnitude of the uniform acceleration signal. The CUSUM also suggests a visually recognizable variant of a cubic parabola with two critical points and one inflection point (Fig. 1),

$$CUSUM(\frac{a}{2}\Delta t^2) = \sum \frac{a}{2}\Delta t^2 \propto a\Delta t^3 \tag{2}$$

If the acceleration is not modeled in a kinematic model, then its signature is embedded in the residuals of a Least Squares, LS, solution. The CUSUM of such residuals is given by,

$$\sum Residual_t = \sum u_t + \sum \frac{a}{2}\Delta t^2 \cong \sum \frac{a}{2}\Delta t^2 \tag{3}$$

in which the CUSUM of the disturbances has the propensity of cancelling because of their random nature[3] because of their *assumed* zero expected value. Hence, a heightened, a cubic like plane curve comes forward when the residuals are inspected graphically (Fig. 1). Enhancement of the acceleration becomes markedly large as the length of the series increases. The critical points of the plane curve occur as maximum and minimum. At $t_0 = 0$, the plane curve exhibits an inflection-point-like change in curvature where the convexity or concavity of the plane curve flips (the red curve in Fig. 1).

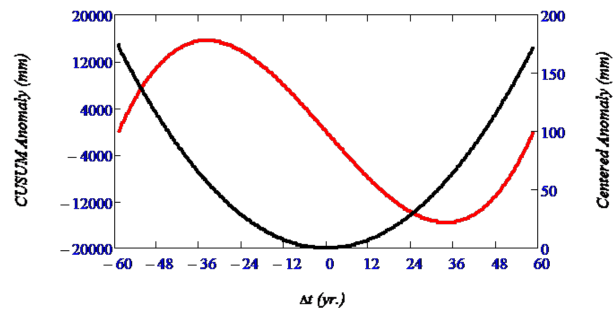

Fig. 1. The graph is intended to show the discernable properties of the CUSUM of a uniform acceleration and its magnification (referenced to the two different vertical axes for clarity). Parabolic behaviour of a centered sea level anomaly due to a uniform acceleration $a = 0.10$ mm/yr. is shown in *black* and referenced to the right vertical axis. Its CUSUM, shown in *red*, is referenced to the left vertical axis.

The following section is a rigorous extension of the kinematic model given by Eq. (1) in which a nested uniform (constant) sea level acceleration is incorporated with other model parameters of deterministic and stochastic in nature. This is a top-down approach in modelling sea level anomalies because of the inclusion of systematic sea level variations whose periods are known *a priori*.

3 An extended kinematic model of sea level variations

The following extended kinematic model represents observed sea level height anomalies at a TG station. It consists of a trend, a uniform acceleration, and periodic sea level variations (Iz et al., 2012, Iz, 2014) with an AR(1) noise,

$$h_t^{obs} = h_0 + v_0 \Delta t + \frac{a}{2}\Delta t^2 \sum_{h=1}^{17}\left[\alpha_h \cos\left(\frac{2\pi}{P_h}\right)\Delta t + \gamma_h \sin\left(\frac{2\pi}{P_h}\right)\Delta t\right] + \epsilon_t \tag{4}$$

In this representation, a sea level anomaly h_t at an epoch t is referenced to a datum defined in the middle of the record

2 This kinematic model is equivalent to a second order polynomial, which has been widely used in sea level studies. It is used to demonstrate the acceleration CUSUM chart to be discussed in this section. A more rigorous kinematic model will be presented in the subsequent sections to ensure that all the other systematic variations in sea level are properly represented in the model.

3 Provided that the disturbances are stationary with an expected value of zero.

at an epoch t_0. The trend is the initial velocity v_0 at t_0 when $a \neq 0$, and a is the constant rate of change in the sea level velocity (i.e. the uniform acceleration).

What is markedly different in this model as compared to all the previous studies of similar nature[4] is the inclusion of various potential low frequency sea level variations *explicitly in a top-down* approach. The origins of these oscillations in sea level are multi-causal. Their presence was conjured by Munk et al. (2002) and Keeling and Whorf (1997) and was demonstrated by Iz (2014) at the global scale. Under their scenarios, interactions of ocean, meteorological forcing, and sea surface temperature materialize as natural broad band sea level variations. They modulate astronomical forcings, such as lunar node tide systematically or as random beatings resulting in sub and super harmonics of known periods (Table 1). Similarly, the variations in total solar radiation with a period of $P = 11.1$ yr., yield subharmonics with periods: $2{\times}P = 22.2$ yr. and longer. An earlier wavelet analysis by Yndestad (2006) also identified a number of lunar node sub and super harmonics in Arctic sea level, temperature, ice extent and winter index time series data, including the signature of nodal harmonics in pole position time series (Table 1 in Yndestad, 2008), and a strong cross correlation with *Chandler wobble*.

Although the observed amplitudes of the 18.6-year nodal constituent are small, within the range of 15 to 35 mm empirically, compounding of the nodal tide with natural sea level variations can potentially bias sea level trend and acceleration estimates as confounders for short TG and satellite altimetry, SA, time series and thereby hinder the search of a global GMSL acceleration caused by anthropogenic global warming (İz, 2006). Moreover, their effects may also be mistakenly interpreted as an accelerated sea level rise if they are not incorporated into the models in analyzing short as well as longer series (İz, 2014, Iz and Shum, 2020). A follow up study by Iz (2015) demonstrated that once these effects are modeled and the corresponding model parameters are estimated, spectral analyses of the TG residuals revealed 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 (İz, 2018). Hence, these effects are also incorporated into this model. The periodicities include a mix of seventeen sub and super harmonics attributed to the node tides, solar radiation, annual and sub annual variations as shown in Table 1. Each period introduces two parameters, α_h, γ_h for the sine and cosine components from which the amplitudes a_h, and the phase angles of the periodic terms are determined. In total, the extended kinematic model includes 37 unknown parameters.

As far as the statistical properties of the model are concerned, the disturbances denoted by may be autocorrelated of first order, AR(1). First order autocorrelation AR(1) exists with varying magnitudes in globally distributed tide gauge stations as shown by Iz, (2015) once the low frequency sea level variations are modeled. The autocorrelations can be as large as $\rho = 0.4$ or more. Such AR(1) disturbances can be represented as follows,

$$\epsilon_t = \rho\epsilon_{t-1} + u_t \tag{5}$$

where the random disturbances are assumed to be independently and identically distributed, i.i.d.[5], i.e., $u_t \sim (0, \sigma_u^2)$, where σ_u^2 is the variance of u_t. The square root of its estimate will be denoted by, or stated simply as the standard error, SE. The error of omission of a positive AR(1) correlation reduces the effective length of the total series statistically in proportion to the magnitude of the autocorrelation coefficient, ρ and leads to a Type I error in testing null-hypotheses throughout the assessment of the model solution.

If the observation Eq. (4) at t_{t-1} is multiplied with ρ and subtracted from the following observation equation at t , the AR(1) correlation is eliminated,

$$h_t - \rho h_{t-1} = [h_{t_0} - \rho h_{t_0}] + v_0[(t - t_0) - \rho\,(t_{t-1} - t_0)] + \\ + \frac{a}{2}[(t - t_0)^2 - \rho(t_{t-1} - t_0)^2] + \tag{6}$$

$$+ \sum_{k=0}^{n} \left\{ \begin{array}{l} \alpha_k \sin\left[\left(\frac{2\pi}{P_k}\right)(t - t_0)\right] - \rho\alpha_k \sin\left[\left(\frac{2\pi}{P_k}\right)(t_{t-1} - t_0)\right] + \\ +\gamma_k \cos\left[\left(\frac{2\pi}{P_k}\right)(t - t_0)\right] - \rho\gamma_k \cos\left[\left(\frac{2\pi}{P_k}\right)(t_{t-1} - t_0)\right] \end{array} \right\} \\ + u_t \tag{7}$$

Note again that, the random errors in this representation are *i.i.d.*, with zero expected value, i.e., $u(0, \sigma_u^2)$. The observation equation given by Eq. (6) is a function of the unknown AR(1) correlation coefficient ρ on the left-hand side. If several OLS solutions are carried out for the values within the interval $[-1 \le \rho \le 1]$, the one which gives the smallest SE is adopted as the optimal solution to the model based on Eq. (6). This process is known as the Hildreth-Lu procedure (Hildreth and Lu, 1960). Therefore, the observation equations based on Eq. (6) can be solved using Ordinary Least Squares, OLS, method iteratively. In the following section an OLS solution is carried out to generate

4 Except by this investigator.

5 This statement also assumes that the disturbances as stationary, which may not. See Iz, and Ng, (2005)

Table 1. Compounded Luni-Solar and other periodicities (yr.).

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			

the residuals needed for the graphical exploration of a uniform acceleration at a TG station, namely Key West, USA.

4 Tide Gauge Records

Key West, USA, monthly TG time series data displayed in Fig. 2 will be used for the graphical analyses. The record is referenced to the Revised Local Reference, RLR, defined by the Permanent Mean Sea Level, PSMSL. No corrections including post glacial rebound[6], PGR, nor inverted barometric effects were applied to the data. The records were downloaded from PSMSL repository on November 2020 (PSMSL, 2020). In the following section, the graphical exploration of a uniform acceleration will be carried out at this station.

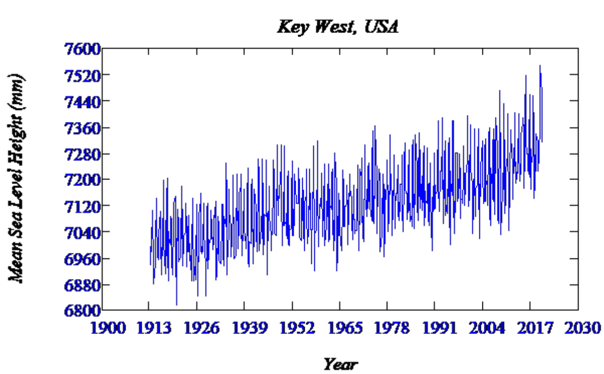

Fig. 2. Monthly averaged mean sea level heights at Key West, USA, TG station.

5 Solutions and graphical exploration

All the statistically significant parameters for the Key West TG station, i.e. those with *p-values*[7], $p < 0.05$, were estimated using the OLS solution to the rigorous kinematic model described in the previous section. The solution statistics tabulated in Table 2 and Table 3 indicate that the model explains more than 70% of the sea level variations together with a well-defined trend estimate. The Durbin-Watson, DW, statistic close to its expected value 2 indicates the solution residuals are free from unmodeled systematic effects.

The statistically significant low frequency sea level variations experienced at Key West TG station shown in Table 3 have amplitudes large enough to confound the trend and acceleration estimates and their statistics if they are not incorporated into the model.

To get better insight, a second round of solutions were carried out using again the same model but *without* the uniform acceleration parameter. Because the dominant contributor, the trend, is linear whereas the uniform acceleration is of non-linear, they are statistically independent as verified by calculating the variance inflation factors, VIF. Consequently, the unmodeled acceleration does not bias the estimated trend and the estimated amplitudes of the periodicities, and its signature is carried over into the residuals.

The systematic sea level variations due to the unmodeled uniform acceleration in Fig. 2 is hard to detect because of the dominant linear trend and periodicities. Fig. 3 depicts the residuals embedded with the signature of the unmodeled uniform acceleration superimposed with its parabolic representation estimated in the previous step. In this figure, despite the removal of the systematic ef-

6 A PGR correction does not have any impact on the estimated acceleration/deceleration because the linear trend (initial velocity) and non-linear uniform acceleration parameters are statistically independent from each other.

7 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 (NIST, 2020). 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.

Table 2. OLS solution statistics. Trend and uniform acceleration estimates are statistically significant at $\alpha = 0.05$.

Time Span yr.	Initial Velocity mm/yr.	Uniform Acceleration mm/yr^2	SE mm	Adj R^2 %	DW	ρ
1913-2020	2.45±0.06	0.018± 0.005	41.2	71.8	1.9	0.4

Table 3. Statistically significant estimated components of periodicities and their SEs. C is for cosine, S is for the sine component of a periodicity. The concatenated numbers to C and S are the rounded periods in years given in Table 1. Units are in mm.

S75	C37	C37	C12.4	C11	C6	Sann	Cann	Ssemi	Csemi
-11.78	-18.05	-18.05	-6,77	-6.49	6.95	80.79	8.91	-25.28	-29.99
±2.87	±2.89	±2.79	±2.76	±2.75	±2.70	±2.38	±2.38	±1.87	±1.87

fects, the unmodeled uniform acceleration signal, which is buried as a parabolic (since it is centered in the middle of the series), is again difficult to identify visually because of the random sea level variations and measurement errors as part of the solution residuals. The histogram of the residuals, (Fig. 4), is not helpful either since the residuals exhibit a Normal-like distribution.

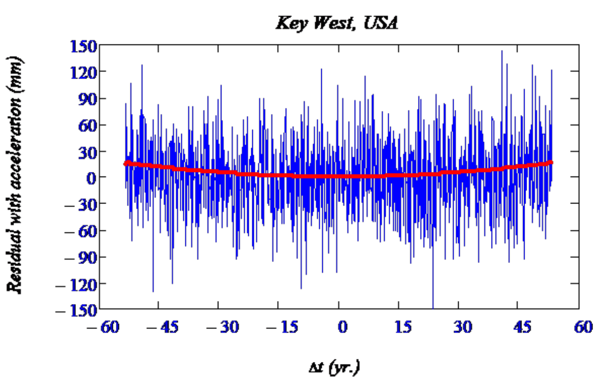

Fig. 3. The unmodeled uniform acceleration, shown in red, is embedded in the residuals, which is difficult to discern snd verify if it is uniform.

The CUSUM articulated in the previous section will become helpful now. The CUSUM of the residuals makes the signature of the acceleration lucid and its uniformity verifiable because of the uniquely identifiable critical points as shown in Fig. 5. The histogram of the residuals also compartmentalizes the residuals before and after the critical points and the inflection point. The ability of the CUSUM to identify the unmodeled acceleration is evident in the display of CUSUM chart of the Key West TG residuals.

A sea level acceleration starting at a later epoch of a TG record would have been *a non-uniform* acceleration. Therefore, the CUSUM of the residuals may also be useful in detecting non-uniform accelerations at other TG stations. If that is the case, the residual CUSUM chart will exhibit

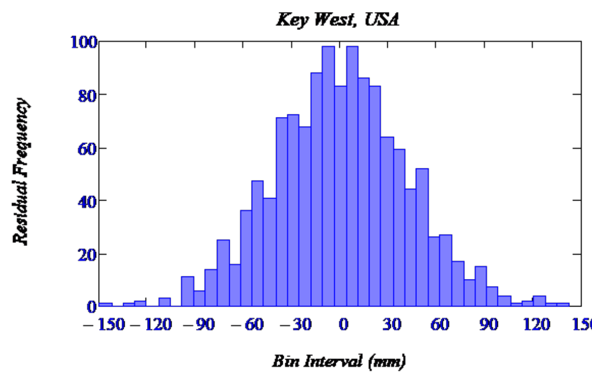

Fig. 4. The histogram of the residuals still exhibits a Normal-like distribution despite the unmodeled acceleration.

random excursions flatlined around zero[8] till the starting epoch of the acceleration.

The effectiveness and the reliability of the CUSUM results nonetheless are not foolproof. They depend on an optimal time span of the series to confirm the presence of an acceleration statistically (Iz and Shum, 2020a) and in detecting and successfully removing low frequency sea level variations. Meanwhile, its reliability will always be questionable to the extent that any unknown, consequently unmodeled, low frequency sea level variation will mimic a uniform sea level acceleration (Iz and Shum, 2020b).

A marginal outcome of this study is the demonstration of the performance of the underlying kinematic model. Although the model explains 72 % of the variation at this TG station, this number now is more meaningful than before because CUSUM of the residuals revealed that the model represents all the systematic sea level variability in the records since the remainder portion is indeed attributable to the random effects. The residuals are unambiguously free from any unmodeled deterministic sea level variations once the uniform acceleration parameter is introduced to

8 The sum of the residuals of a OLS solution is always zero.

the model and estimated. This outcome is also a testament to the validity of the top-down modeled low frequency sea level changes.

Particular to this study, the graphically demonstrated signature of the sea level acceleration at the Key West TG station is unarguably extremely crisp and reliable as far as its uniformity is concerned throughout the series starting 1913. This finding by itself is important because it invites an intriguing question; *where is the evidence for an anthropogenic impact on the sea level acceleration at this station spanning a record over a century long if the acceleration has started in early 20th century?*

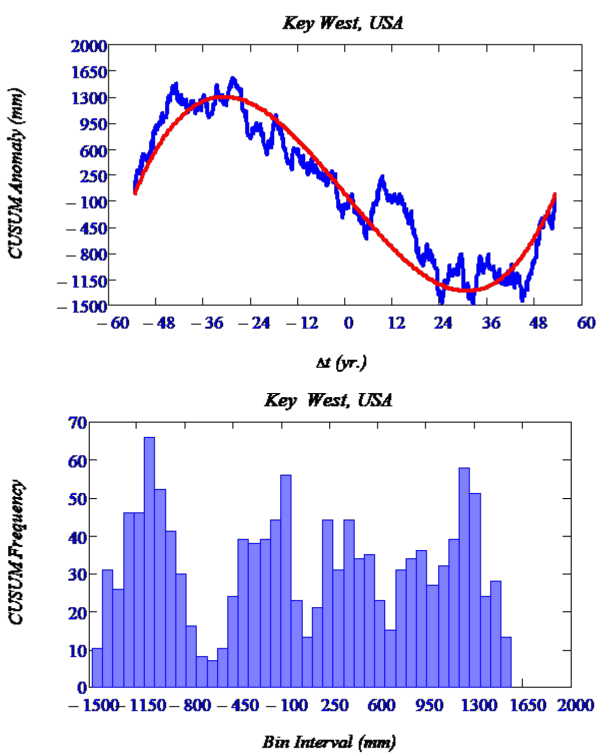

Fig. 5. Residuals and the estimated uniform acceleration's CUSUM charts at Key West, USA, TG station (top). The histogram of the residuals compartmentalizes the residuals before and after the critical points and the inflection point.

5.1 Conclusion

This study proposed and demonstrated an effective tool inspired by the CUSUM charts to identify the signature of an accelerating sea level experienced at a TG station and to verify its uniformity in addition to a significance test for its presence. The residuals of a least squares solution to a rigorous kinematic model that does not include a representation of a uniform acceleration would contain its signature. The CUSUM of these residuals were shown to enhance a heightened a cubic like plane curve of the unmodeled acceleration buried in the random noise in this study. When plotted, the residual CUSUM chart provides visually enhanced evidence for further scrutiny to explore the uniformity of the acceleration. Given that there were no such previous practices in sea level studies, there may be more to be learned through the proposed approach about the nature of sea level accelerations experienced at other globally distributed TG stations.

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