Research Article

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Low-frequency fluctuations in the yearly misclosures of the global mean sea level budget during 1900–2018

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Abstract: Sub- and super-harmonics of luni-solar forcing are proxies for the natural variations in sea levels observed at tide gauge stations with long records as demonstrated in earlier studies. This study also identified their signatures in the noisy yearly misclosures of the global mean sea level budget for the period 1900–2018. The analyses of the yearly misclosures revealed a temporal linear systematic error of 0.08 ± 0.02 mm/year, which is not explained by the budget components. The estimate is statistically significant (α = 0.05) but small in magnitude and accounts for only 11% (adjusted R^2) of the variations in the yearly misclosures. Meanwhile, the yearly misclosures have also a statistically significant constant bias as large as –12.2 ± 0.9 mm, which can be attributed to the lack of a common datum definition for the global mean sea level budget components. Modeling the low-frequency changes of luni-solar origin together with a trend and constant bias parameters reduces variability in the misclosures. Accounting for their effects explains 50% (adjusted R^2) of the fluctuations in the yearly misclosures compared to the 11% if they are not. In addition, unmodeled low-frequency variations in the yearly global budget closure assessments have the propensity of confounding the detection of a statistically significant recent uniform global sea level acceleration triggered by anthropogenic contributors.

Keywords: climate change, global mean sea level budget, luni-solar forcing

Science and philosophy are all about categorizing things better, and that often means making new and finer distinctions.

Julian Baggini 2009 *The Duck that won the lottery*.

Visiting scholar.

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1 Introduction

Sea level variations are driven by various effects and are very noisy due to seasonal, interannual, decadal, and longer variations of the ocean surface (Cazenave and Remy 2011). Sea level rise at long time scales is attributed to ocean thermal expansion and halosteric contraction, ice sheet, mountain glacier and ice cap mass balance, changes in terrestrial surface and ground water storage, and anthropogenic impoundment of waters in dams. To much lesser importance, permafrost degradation and snow and atmospheric water vapor change are also identified as major geophysical contributors to the present-day global mean sea level (GMSL) rise (Moore et al. 2011, Gregory et al. 2013, Slangen et al. 2017, Cazenave et al. 2018, WCRP Global Sea Level Budget Group 2018, Iz et al. 2018, Iz and Shum 2020a,b,c, Frederikse et al. 2020, Horwath et al. 2022).

The recent study by Frederikse et al. (2020) compiled yearly time series of GMSL budget components during 1900–2018 together with their error estimates, which are essential for proper analyses of the GMSL budget misclosures.[1] They also reported 0.04 ± 0.22 mm/year misclosure rate[2] calculated from the root sum of squares (RSSQ) of the GMSL budget components' velocities and their uncertainties. Although the reported misclosure rate is small in magnitude, its uncertainty is as large as the velocities of some of the budget components. Meanwhile, yearly GMSL misclosures exhibit periodic fluctuations at different time scales unexplained by the budget components as

1 Changes in the observed sea level should be equal to the sum of the changes attributable to density changes and water mass exchange, which is defined as the GMSL budget closure (Leuliette and Willis 2011). When this condition cannot be readily met because of the random measurement and systematic errors, the deviation from the sum is called *misclosure* in this study.

2 The 1 standard error (SE) of the cited estimate was derived from Table 1 in the study by Frederikse et al., (2020) listed for a 90% confidence interval of [–0.31, 0.41] mm/year.

it will be shown in this study. They are interannual, decadal, and multidecadal scales and multicausal due to the natural forcing such as temperature, wind and pressure, or ocean circulations, which could be conflated and/or excited externally by astronomical forcing. They are usually identified as broadband processes in the context of wind-induced decadal variability (Sturges and Hong 2001) as well as the signatures oceanic and atmospheric transport of multiyear El Niño–Southern Oscillation to the polar regions. The periodic components of the decadal sea level variations were also reported by a number of studies (Häkkinen 2000, Ünal and Ghil 1995, Jevrejeva et al. 2004).

Keeling and Whorf (1997) proposed realization of luni-solar forcing in conjunction with random beats of nearby natural and/or forced broadband oscillations of the sea level at multidecadal and decadal frequencies. Munk et al. (2002) suggested compounding of periodic lunar nodal tides and almost periodic solar radiation variations with natural variations in sea level inciting periodic oscillations of the sea level at multidecadal and decadal frequencies (super-harmonics). Their effects are also realized at interannual time scales through their sub-harmonics. Stationary long-period tides introduce vertical temperature mixing between sea surface temperature and cold bottom temperatures, thereby the source of global thermosteric sea level changes (Yndestad 2021).

A meta-analysis of the long tide gauge (TG) records by Iz (2014) revealed the compounding effect of luni-solar forcing (acting as carrier frequencies) at a global scale in TG records. Regardless of their origins, sub- and super-harmonic of periodic sea-level variations are proxies in representing natural fluctuations in the sea level effectively. Subsequent studies by Iz (2015, 2016a,b) produced further observational evidence for their presence. These periodic anomalies in the sea level propagate into the GMSL budget misclosures preponderantly through the observed GMSL time series.

Although the presence of luni-solar forcing in sea-level fluctuations has been well studied by this investigator through analyses of long TG records individually, the availability of the newly compiled records of the budget components spanning over a century offers an opportunity to verify the earlier findings. *Hence, this study aims to model and investigate fluctuations in GMSL budget misclosures for the signatures of luni-solar sub- and super-harmonics at the global scale during 1900–2018.*

In the following sections, first, the time series for the GMSL budget components compiled by Frederikse et al. (2020) are presented with their errors. The yearly time series of the budget components are used to calculate yearly GMSL budget misclosures (will be stated onward as *misclosures* for brevity) and their errors through variance propagation. Subsequently, the systematic errors in the yearly misclosures are represented by a basic kinematic model with a trend (velocity) and a uniform acceleration. This model is to serve as a baseline for assessing the explanatory power of the subsequent models that incorporate the proxy periodicities due to the compounding of luni-solar forcing with natural sea-level variations with and without the uniform acceleration. The statistics of each model solution are tabulated for comparison, and the numerical assessment of the explanatory contributions of the model parameters to the yearly misclosures is made.

2 Data on yearly variations of the GMSL budget components

The data compiled by Frederikse et al. (2020) rely on earlier work cited in their article. Figures 1–6 display the yearly variations of the GMSL budget components during 1900–2018 for a total of 119 yearly averaged values for each one of the GMSL budget components, together with their uncertainties (1 SE), which are expressed in mm of equivalent sea level during this period. The yearly time series are accessible online. The availability of the errors of the time series spanning 1900–2018 is a major contribution of their study for proper formalism in assessing GMSL budget misclosures.

The condition equations for assessing the closure/misclosure of the GMSL budget using these time series are discussed in the following section. The formulation enables the calculation of the yearly misclosures and their uncertainties through variance propagation.

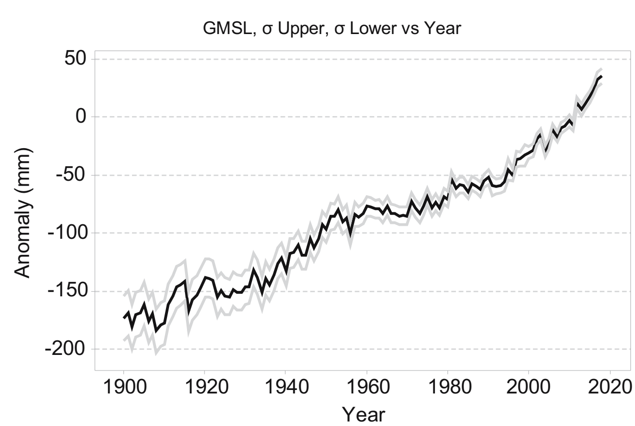

Figure 1: Yearly averaged anomalies of GMSL and their *a priori* uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

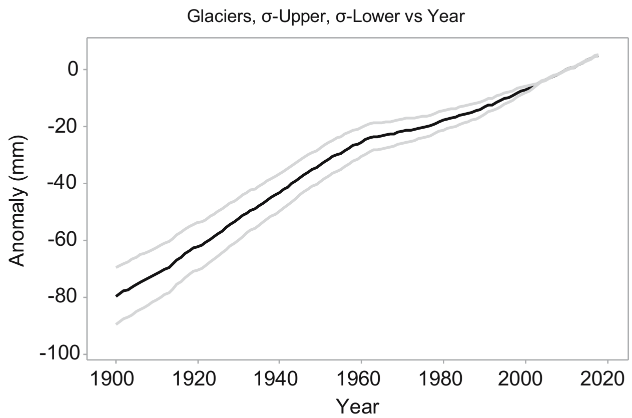

Figure 2: Yearly averaged anomalies of Glaciers component and their *a priori* uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

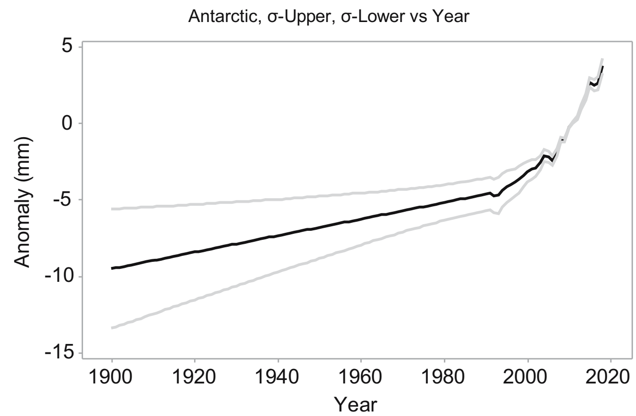

Figure 5: Yearly averaged anomalies of Antarctic component and their *a priori* uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

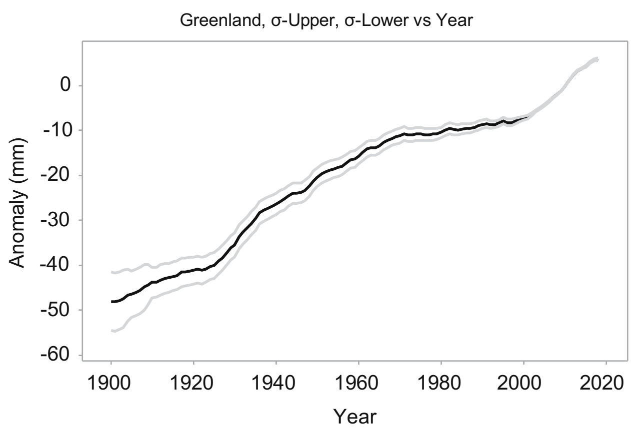

Figure 3: Yearly averaged anomalies of Greenland component and their a priori uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

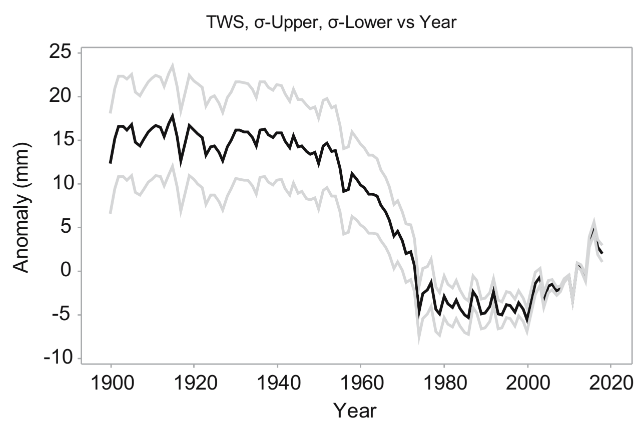

Figure 6: Yearly averaged anomalies of terrestrial water storage (TWS) component and their *a priori* uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

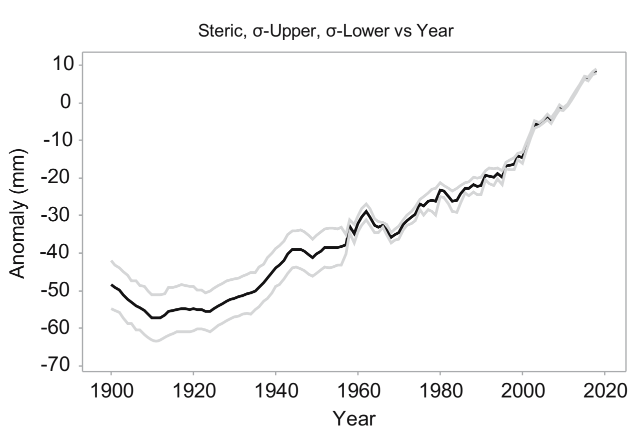

Figure 4: Yearly averaged Steric anomalies and their *a priori* uncertainties (SE) during 1900–2018 (Frederikse et al. 2020).

3 The GMSL sea-level budget and its yearly misclosure statistics

Following the narratives by WCRP Global Sea Level Budget Group (2018), Iz et al. (2019), Iz and Shum (2020a,b), the GMSL budget closure is formulated as follows:

$$\begin{aligned} &\mathrm{GMSL}(t) - \mathrm{GMSL}(t)_{\mathrm{STERIC}} - M(t)_{\mathrm{GLACIERS}} \\ &\quad - M(t)_{\mathrm{GREENLAND}} - M(t)_{ANTARCTICA} - M(t)_{\mathrm{TWS}} = 0, \end{aligned} \tag{1}$$

where $\mathrm{GMSL}(t)$ denotes time-dependent mass contributors (barystatic) to GMSL, $M(t)_{\mathrm{GLACIERS}}$ denotes the mass of glaciers, $M(\mathrm{t})_{\mathrm{GREENLAND}}$ denotes Greenland, $M(t)_{\mathrm{ANTARCTICA}}$ denotes Antarctic ice sheets, and $M(t)_{\mathrm{TWS}}$ denotes TWS. The steric component, $\mathrm{GMSL}(t)_{\mathrm{STERIC}}$, refers to the contributions of ocean thermal expansion and salinity to sea-level change (WCRP Global Sea Level Budget Group 2018).

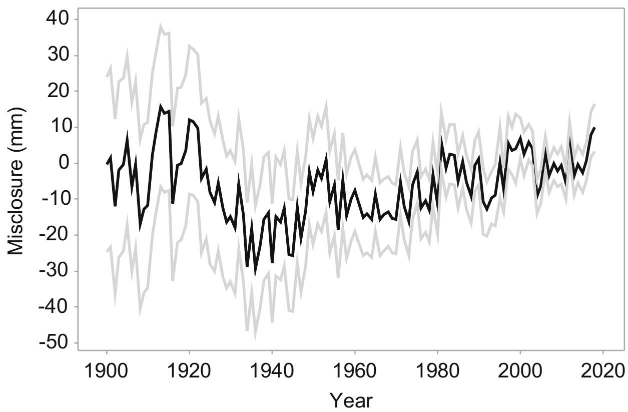

Figure 7: Yearly misclosures and their uncertaintainties (1 SE) calculated through variance propagation using equation (2). The weighted sum of squares of the yearly budget misclosures is WSSQ = 100.3 mm.

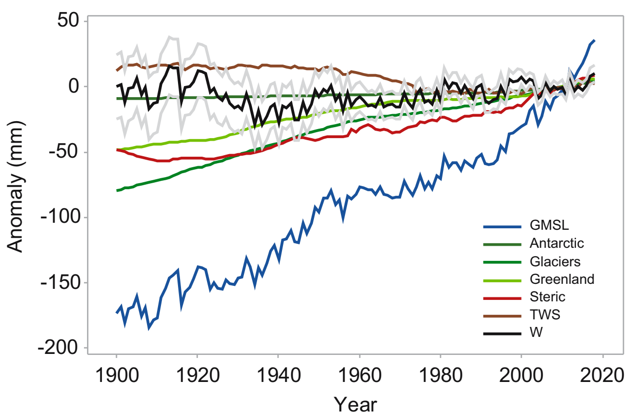

Figure 8: The yearly averaged anomalies of GMSL budget components with their 1 SE uncertainties. The yearly misclosures are shown with their uncertainties in gray color.

The GMSL budget misclosure is quantified yearly using annually and globally averaged sea-level height anomalies of each component, h^t, i.e.,

$$h^t_{\mathrm{OCEAN}} - h^t_{\mathrm{STERIC}} - h^t_{\mathrm{GLACIERS}} - h^t_{\mathrm{GREENLAND}} - h^t_{\mathrm{ANTARCTICA}} - h^t_{\mathrm{TWS}} =: W^t, \tag{2}$$

where superscript t is the epoch of the yearly averaged anomaly. The yearly misclosures are the lump sum effect of the potential systematic errors and the random noise in the yearly averaged time series of the budget components (commission errors) as well as any other unknown contributors (omission errors) shown in Figure 7. The same figure includes the standard errors of the misclosures on a yearly basis calculated from the known yearly SE of the budget components using variance propagation through

Table 1: Selected compounded luni-solar periods in years

Nodal and supe-harmonics	Nodal sub-harmonics	Solar and super-harmonics
18.6	18.6/2 = 9.3	11.1
18.6 × 2 = 37.2	18.6/3 = 6.2	11.1 × 2 = 22.2
18.6 × 3 = 55.8		
18.6 × 4 = 74.5		

equation (2)[3]. Its root weighted sum of squares[4] is 10.02 mm and the weighted mean of misclosures is $\hat{W} = 3.43 \pm 0.82$ mm. It is statistically significant at $\alpha = 0.05$ significance level. Figure 8 reveals large yearly excursions in yearly misclosures. The temporal fluctuations overlap with the contributions of either Antarctic, Glaciers, or Greenland time series or their sums. In other words, if this statistic is chosen as the criterion for closure, GMSL is not closed. Nonetheless, the current literature on this topic emphasizes using the trends of the budget components for evaluating the GMSL budget closure, which is briefly discussed in the next section.

4 The GMSL sea-level budget closure assessed using the trends of its budget components

The time derivative of the yearly budget component given by equation (2) can be expressed as follows:

$$v_{\mathrm{OCEAN}} - v_{\mathrm{STERIC}} - v_{\mathrm{GLACIERS}} - v_{\mathrm{GREENLAND}} - v_{\mathrm{ANTARCTICA}} - v_{\mathrm{TWS}} =: v^W. \tag{3}$$

In this relationship, v refers to the linear trend, constant velocity of a budget component and v^W is the misclosure rate. The budget misclosure rates will be quantified in the following sections. Recent studies WCRP Global Sea Level Budget Group (2018) and Frederikse et al. (2020) already reported some estimates on this topic. The former study's rate $v^W = 0.55 \pm 0.50$ mm/year.[5] is based on 1993–2018 time span. The latter is $v^W = 0.04 \pm 0.22$ mm/year. is for

3 The errors of the budget component are assumed to be uncorrelated.
4 WSSQ: weighted sum of squares.
5 The reported value for the misclosure 0.55 ± 0.30 mm/yearr by the WGRP (2018) in its Table 13 is computationally erroneous. It should be 0.55 ± 0.50 mm/year (Root Sum Squares, RSSQ, of the misclosure cannot be smaller than the standard error of any one of its components, suchas the standard error of the thermosteric component,

Table 2: The RSSQ of misclosure of the budget component velocities and the solution statistics for four different models are tabulated. The unit for the velocity and uniform acceleration are in mm/year and mm/year^2, respectively. The units of all other estimates are represented in mm. Adj. R^2 is represented in percent. RSSQ velocity misclosure is quoted from the study by Frederikse et al. (2020)

Models	RSSQ		Model I			Model II			Model III			Model IV		
p	$\hat{p}$	SE	$\hat{p}$	SE	VIF	$\hat{p}$	SE	VIF	$\hat{p}$	SE	VIF	$\hat{p}$	SE	VIF
W_0	−3.43	0.82	−6.51	0.84		−10.83	1.03		−8.51	0.68		−12.20	0.90	
v^W	0.04	0.22[a]	0.09	0.02	1.0	0.04	0.02	1.2	0.08	0.02	1.3	0.08	0.02	1.4
a^W						0.008	0.001	1.2				0.011	0.001	1.4
C75									−10.03	1.18	1.8	NS	NS	NS
S56									3.41	0.94	1.3	3.38	0.94	1.3
C56									7.23	1.03	1.7	NS	NS	NS
S37									−3.98	0.88	1.2	−3.51	0.84	1.1
C37									NS	NS		3.84	0.86	1.2
C22									NS	NS		2.57	0.81	1.1
S18.6									1.73	0.81	1.0	NS	NS	NS
RMSE	10.0		2.5			2.2			1.9			1.9		
Adj. R^2 %			11.2			32.8			48.8			50.5		

$\hat{p}$ Estimated parameter. SE: standard error. VIF: variance inflation factor. RMSE: root sum of square error of residuals. RSSQ: root sum of squares. Adj. R^2: adjusted R^2. NS: not significant at α = 0.05 level. Prefixes C and S refers to the coefficients of the Sine and Cosine components followed by the periods listed in Table 1 and modeled in equations (6) and (7).

the period 1900–2018 based on the same data used in this study.

The magnitude of the misclosure rate from the WCRP Global Sea Level Budget Group (2018) study is large and uncertain. The findings of Frederikse et al. (2020) GMSL budge misclosure rate is markedly improved. However, its error estimate is still as large as the magnitude of some of the velocities of the budget components.

In the following section, yearly fluctuations in the budget misclosures are modeled and estimated together with their uncertainties using weighted least squares (WLS) method (Mardia et al. 1979) to provide an alternative approach in assessing GMSL budget misclosures.

5 Model I – Yearly variations in GMSL budget misclosures with a linear trend

Given the time evolution of the misclosures, W_t, in Figure 7, a basic representation of a potential linear temporal systematic error v^W and random noise u_t^W is given as follows:

$$W_t = W_0 + v^W(t - t_0) + u_t^W. \tag{4}$$

In this expression, W_0 represents the constant datum offset, which is referenced to the middle of the series, and W_t is the yearly misclosure at an epoch t. The noise u_t^W is a stationary, temporally uncorrelated but non-homogeneous error term with zero expected value, i.e., $u_t^W \sim (0, \sigma^2_{u_t})$, $t = 1 \cdots n$, where $n = 119$ is the total number of yearly misclosures.

WLS solution statistics that account for the uncertainties of the misclosures[6] for this model are tabulated in Table 2. The residuals of the misclosures after the adjustment are shown in Figure 9. They exhibit stark unmodeled random excursions over time. The AR(1) autocorrelation coefficient of the residuals, $\rho \sim 0.23$, is low. Hence, its omission in calculating the trend model statistics is justified.

The estimated misclosure velocity (trend/bias) $\hat{v}^W$ = 0.09 ± 0.02 mm/year is twice as large of the rate reported by Frederikse et al. (2020), $\hat{v}^W$ = 0.04 ± 0.22 mm/year. Albeit being small, it is statistically significant.[7] Meanwhile, this representation explains only 11% (Adj. R^2)[8] of the variations, which shows that the yearly misclosures are noisy despite

which is 0.40 mm/year.). Similar error also exists for the misclosure evaluated for the period 1993-present in their Table 12.

6 The inverse squares of the yearly misclosure standard errors were used as weights.

7 Significance level α = 0.05 is used throughout this study.

8 R^2 shows how well fit to the data. Adjusted R^2 (Adj. R^2) adjusts R^2 for the number of terms in a model.

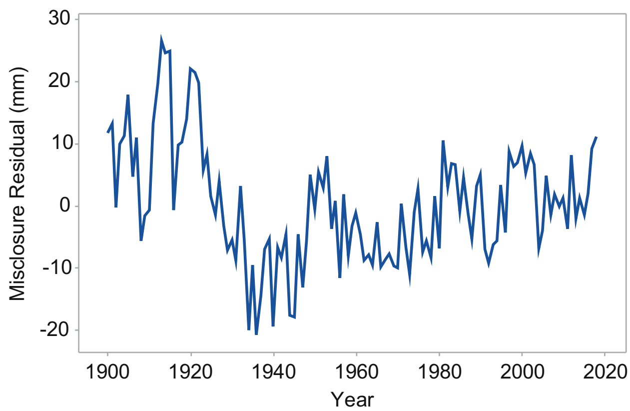

Figure 9: Misclosure residuals (mm) of the WLS solution to the trend-only model.

the small misclosure trend. In other words, the absence of a trend bias does not ensure an effective GMSL budget closure. Moreover, another issue noteworthy to consider in assessing GMSL misclosures was not addressed in earlier studies. It is the estimated misclosure constant, $\widehat{W_0} = -6.5 \pm 0.8$ mm. The estimate is statistically significant yet, and its relevance for assessing the GMSL closure is not clear. This constant error in the yearly misclosures can be attributed to the inconsistent initial epochs of the time series that are not recognized until now. Therefore, the GMSL budget is not closed as long as there exists an unaccounted, statistically significant constant bias, W_0. GMSL budget adjustment procedures, as demonstrated in İz and Shum (2020a, b), are potential solutions to go around this problem.

5.1 Model II – Yearly variations in GMSL sea-level budget misclosures with a linear trend and a uniform acceleration

The trend bias examined in the previous section is a poor representation of yearly variations of the misclosures (Adj. $R^2 = 11\%$). Although there is no visual evidence for a potential uniform acceleration in the misclosure residuals (Figure 9), claims were made by recent studies (e.g., Hogarth 2014) about its presence in GMSL anomalies during this period. Examining its presence will therefore be informative. The new model reads as follows:

$$W_t = W_0 + v^W(t - t_0) + \frac{1}{2}a^W(t - t_0)^2 + u_t^W. \quad (5)$$

In this model, the uniform acceleration parameter is defined as a^W. All the remaining parameters and the assumptions made are the same as defined in the previous section (Model I).

Another WLS solution was carried out for using this model. The solution statistics are tabulated in Table 2 under Model II. The impact of the uniform acceleration parameter is substantial. It increased the explanatory power of the model by threefold (Adj. $R^2 = 32.8\%$) compared to the Model I representation (Adj. $R^2 = 11.2\%$). The estimated uniform acceleration is also statistically significant $\hat{a}^W = 0.008 \pm 0.001$ mm/year^2 with an uncertainty considerably smaller than the one reported by Hogarth (2014), $\hat{a}^W = 0.01 \pm 0.008$ mm/year^2.

Also, the misclosure trend estimate is identical to the one reported by Frederikse et al. (2020), and its uncertainty has improved by an order of magnitude, i.e., $\hat{v}^W = 0.04 \pm 0.22$ mm/year vs $\hat{v}^W = 0.04 \pm 0.02$ mm/year. Nonetheless, the misclosure residuals still exhibit similar pronounced excursions shown in Figure 9. They are modeled and scrutinized in the following sections.

5.2 Model III – Yearly variations in of GMSL sea-level budget misclosures with a linear trend, luni-solar forcing, and their sub- and super-harmonics

Interannual, decadal, and multi-decadal fluctuations are recognized and attributed to natural variations in GMSL (e.g., Bindoff et al. 2007, Llovel et al. 2011, Esselborn et al. 2018, Dieng et al. 2021). As elucidated in Section 1, luni-solar forcing and their sub- and super-harmonics are realized as proxies representing the combined effect of natural sea-level variations (Iz 2014). If these proxies are not modeled, they will propagate into the budget misclosures through the GMSL time series. Therefore, they must be accounted for in assessing the GMSL budget closure. The following model for the GMSL budget misclosures is a kinematic representation, inclusive of periodic variations of luni-solar origin:

$$W_t = W_0 + v^W(t - t_0) + \sum_{h=1}^{2}\left[\alpha_h \cos\left(\frac{2\pi}{P_h}\right)(t - t_0) + \gamma_h \sin\left(\frac{2\pi}{P_h}\right)(t - t_0)\right] + u_t^W. \quad (6)$$

Modeling periodicities introduces additional two parameters, α_h, γ_h, for the sine and cosine of each periodicity from which the amplitudes and the phase angles of the periodic terms are calculated. The modeled periodicities were discussed in detail by Iz (2014). They are presented in Table 1.

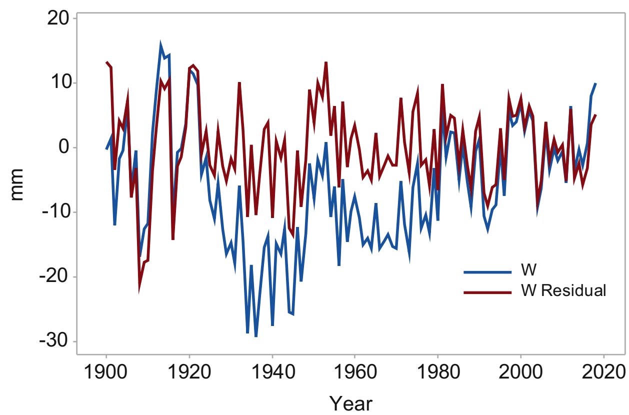

Figure 10: Misclosures and misclosure residuals are displayed. The RMS of the misclosures = 10.0 mm, reduced to 1.9 mm (the RMSE of the misclosure residuals) after modeling the linear trend and the periodic variations due to the luni-solar forcing.

The estimated parameters obtained using WLS solutions for equation (6) are tabulated in Table 2 under Model III. The listed estimates are all statistically significant at $\alpha = 0.05$ level. The inclusion of the periodic GMSL variations has improved the Adj. $R^2 = 48.8\%$ at the expense of doubling the magnitude of the velocity misclosure, $v^W = 0.08 \pm 0.02\,\text{mm/year}^2$. More importantly, all listed nodal superharmonics are statistically significant. The root mean square (RMS) of the misclosures = 10.0 mm, reduced to 1.9 mm (the root mean square error (RMSE) of the misclosure residuals) by modeling the linear trend and the periodic variations due to the luni-solar forcing (Figure 10).

The variance inflation factors (VIFs) of the estimated parameters indicate that they are well separated, i.e., uncorrelated. The random nature of the misclosure residuals is confirmed by their normal probability plot shown in Figure 11.

As stated earlier, the nonlinear progression of the GMSL rise displayed in Figure 1 also suggests a uniform acceleration during this period. Several studies such as Dangendorf et al. (2017, 2019) and Nerem et al. (2018) reported a statistically significant uniform acceleration during 1993–2018. Nonetheless, Iz and Shum (2020d) demonstrated that the signature of the claimed uniform acceleration is ambiguous since it can also be attributed to low-frequency sea-level variations, mainly caused by compounding of luni-solar forcing with natural sea-level changes and cannot be detected using short Satellite Altimetry (SA) time series. Given the availability of the series of the GMSL budget components spanning over a century offers an opportunity to resolve this ambiguity. Therefore, parameters of equation (6) are estimated together with an added uniform acceleration parameter.

5.3 Model IV – Yearly variations in GMSL sea-level budget misclosures with a constant velocity, uniform acceleration, luni-solar forcings, and their sub- and super-harmonics

The model augmented with the uniform acceleration has the same descriptions for the parameters stated in the previous section and reads as follows:

$$W_t = W_0 + v^W(t - t_0) + \frac{1}{2}a^W(t - t_0)^2 + \sum_{h=1}^{2}\left[\alpha_h \cos\left(\frac{2\pi}{P_h}\right)(t - t_0) + \gamma_h \sin\left(\frac{2\pi}{P_h}\right)(t - t_0)\right] + u_t^W. \quad (7)$$

The estimated parameters and their statistics are again obtained using WLS and listed in Table 2 under Model IV. The estimates are all statistically significant at $\alpha = 0.05$ level. The estimated uniform acceleration parameter $\hat{a}^W = 0.011 \pm 0.001\,\text{mm/year}^2$ is similar to the uniform acceleration estimated using Model II. Nonetheless, the improvement due to the newly added uniform acceleration parameter is not significant: Adj. $R^2 = 50.5\%$ compared to the Adj. $R^2 = 48.8\%$ of Model III. The RMSEs of the misclosures and their trend estimates are the same with and without a uniform acceleration parameter.[9] The inclusion of the acceleration parameter resulted in a different combination of statistically significant lunisolar sub- and super-harmonics. The nodal subharmonic of 74.5-year periodicity cannot be estimated together with the uniform sea-level acceleration (collinearity). Consequently, given the similarity of the Model III and Model VI solutions and their summary statistics, the superiority of one model over the other still cannot be established despite the availability of the long series.

6 Discussion and conclusion

This study quantified the yearly GMSL budget misclosures during 1900–2018 using different kinematic models and detected a linear temporal systematic error of 0.08 ± 0.02 mm/year, which is statistically significant but

9 The residual plots for model IV are similar to those from model III.

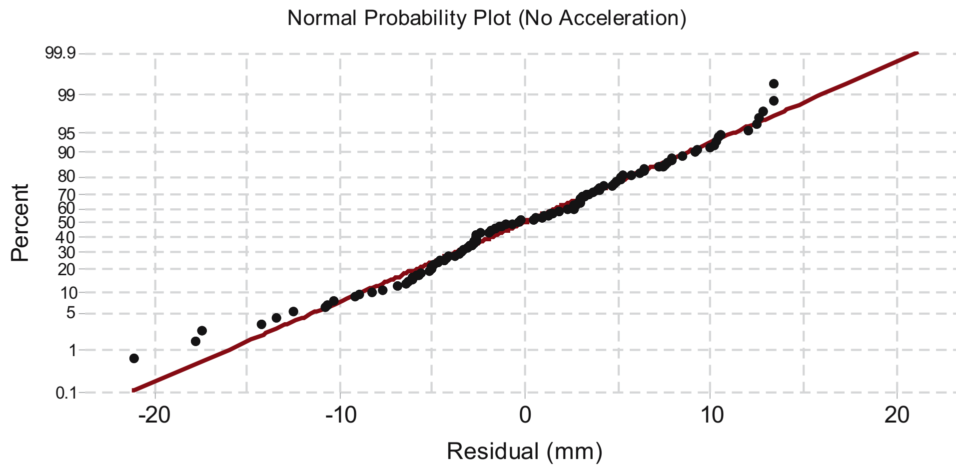

Figure 11: Misclosure residuals (mm) vs expected normal distribution (red).

negligible in size compared to the trends of the budget components. However, yearly misclosures have a statistically significant constant error of varying magnitudes estimated by the models entertained in this study. This constant error is labeled as *datum bias*, and therefore, the yearly GMSL budget cannot be claimed as closed. The physical implication of this constant bias is unbeknown to this investigator and further investigation about its origin may be needed.

More importantly, the current uncertainties of yearly misclosures (commission errors) are large for an effective yearly budget closure and were explained by the major findings of this study. The dominant systematic portion of these fluctuations are due to the periodicities induced by luni-solar forcing and their super- and sub-harmonics in the GMSL budget during 1900–2018. A similar finding was already reported by Iz (2014) in globally distributed individual TG stations with long records. Modeling the effect of the low-frequency fluctuations together with the trend and datum bias explained up to 50% (Adj. R^2) of the fluctuations in GMSL misclosures compared to the 11% in their absence. The low-frequency fluctuations have the propensity of confounding the detection of a uniform global sea-level acceleration that may have been caused by anthropogenic contributors (Iz and Shum 2020d). Taking their effects into account in GMSL budget misclosures is therefore a necessity not only for closure but also for accurate predictions of future global sea-level variations as part of climate change projections (Iz and Shum 2020c).

A by-product of this study is about the presence of a uniform GMSL acceleration during the SA era, 1993 onward, claimed by Nerem et al. (2018), whose certitude is challenged by Iz and Shum (2020d). The topic has important ramifications for understanding recent anthropogenic contributions of the global warming and its impact on sea levels and mitigation efforts. The availability of the budget data spanning 1900–2018 and, in particular, the availability of their uncertainties provided an opportunity to investigate this claim through the yearly misclosures of the GMSL budget components. Unfortunately, the models with and without a uniform acceleration (Model III and Model IV) during this period still cannot establish the presence or the absence of a global uniform acceleration during this period. On the one hand, if the extended time span of the data suggests that there is no uniform acceleration during this period (Model III), then there cannot be a uniform acceleration during SA era either since both data sets overlap. On the other hand, if the acceleration is uniform going back to 1900 as Model IV suggests, then the acceleration during the SA era is not a recent phenomenon as claimed by the proponents for its recency.

In any event, the aforementioned discussion should not be construed as a climate change skepticism but a question for further investigation. Although the estimated trend misclosures are robust for the models entertained in this study, the periodic low-frequency variations and more importantly the absence or presence of a uniform acceleration will lead to substantially different predictions of the GMSL rise (İz 2022) and is consequential for climate change mitigation measures.

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