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# **Data revisions and the statistical relation of global mean sea-level and temperature**

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# DATA REVISIONS AND THE STATISTICAL RELATION OF GLOBAL MEAN SEA-LEVEL AND TEMPERATURE

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ABSTRACT. We study the stability of the estimated statistical relation of global mean temperature and global mean sea-level with regard to data revisions. Using three different model specifications proposed in the literature, we compare coefficient estimates and forecasts using two different vintages of the annual time series. We find that two out of the three models, proposed in [1] and in [2], are very sensitive to the revisions. The magnitude of the estimated coefficient of influence as well as the implied long-term forecasts change drastically between the two data vintages considered. The model proposed in [3], on the other hand, reacts robustly to the revisions.

KEYWORDS: Sea-level, temperature, semi-empirical models, data revisions.

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## 1. INTRODUCTION AND DATA

Several studies have studied the statistical link of sea-level and temperature time series [1, 2, 3, 4, 5, 6, 7, 8, 9]. Since both temperature increase and sea-level rise are regionally varying phenomena [10], many studies have used globally aggregated temperature and sea-level time series. These time series are subject to continuous revisions and improvements, and in this study, we make the observation that these data revisions substantially influence the statistical relation of global mean temperatures and sea-level as inferred from the record. We repeat the analyses in [1], [2], and [3] using revised data downloaded in 2013 and show that both the estimated coefficients that link temperature to sea-level and the resulting long-term projections of sea-level rise are sensitive to the revisions.

Global temperature change time series are compiled by several groups, among them the NASA Goddard Institute for Space Studies (GISS) [11], the UK Meteorological Office Hadley Centre joint with the University of East Anglia Climatic Research Unit [12], and the NOAA National Climatic Data Center ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)). A commonly used time series of global sea-level changes is compiled by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Centre for Australian Weather and Climate Research [13].

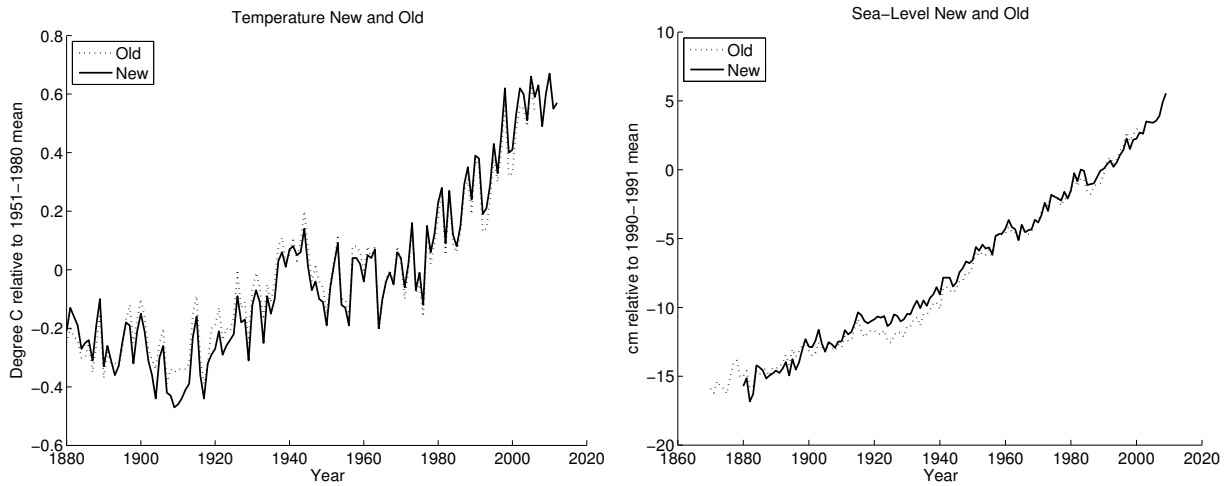


FIGURE 1. The left panel shows the temperature time series, revised (solid) and old (dotted). The right panel shows the same color coding for the global sea-level time series.

In this study, we focus (1) on the NASA-GISS global temperature time series, the evolution of which is described in the sequence of papers [14, 15, 16, 17, 11], in particular the last two vintages 2001 and 2010, and (2) on the CSIRO sea-level change time series as described in the papers [10, 18, 13], in particular the last two vintages 2006 and 2011. The old temperature vintage covered the period 1880–2006; the new vintage covers the period 1880–2012 (downloaded in November 2013). The old sea-level vintage covered the period 1870–2001; the new vintage covers the period 1880–2009. Therefore, in estimating the relationship between temperature and sea-level, when we refer to the “old” data set, we refer to the period of overlap 1880–2001; when we refer to the “new” data set, we refer to the period of overlap 1880–2009. Occasionally, we restrict the “new” data set to the old period 1880–2001 in order to understand how much difference in the estimated relationship is due to the addition of new data points and how much is due to the revision of old data points.

These time series are continuously revised for a variety of reasons described in the accompanying papers. In going from the vintage 2001 to 2010, the global temperature time series was revised to improve the adjustment for heat islands surrounding conurbations, for which satellite imagery of nighttime brightness is used [11]. In the 2001 vintage, only US imagery was used, whereas in the 2010 vintage, the satellite imagery adjustment was applied worldwide. Other changes were the integration of Antarctic temperature data compiled by the Scientific Committee on Antarctic Research [19] and of updated sea surface temperature data [20, 21]. The left panel of Figure 1 shows the time series of the 2001 vintage (old) and of the 2010 vintage (new).

The vintages 2006 (old) and 2011 (new) of the global mean sea-level time series are shown in the right panel of Figure 1. The main differences between the two vintages are the use of a larger set of

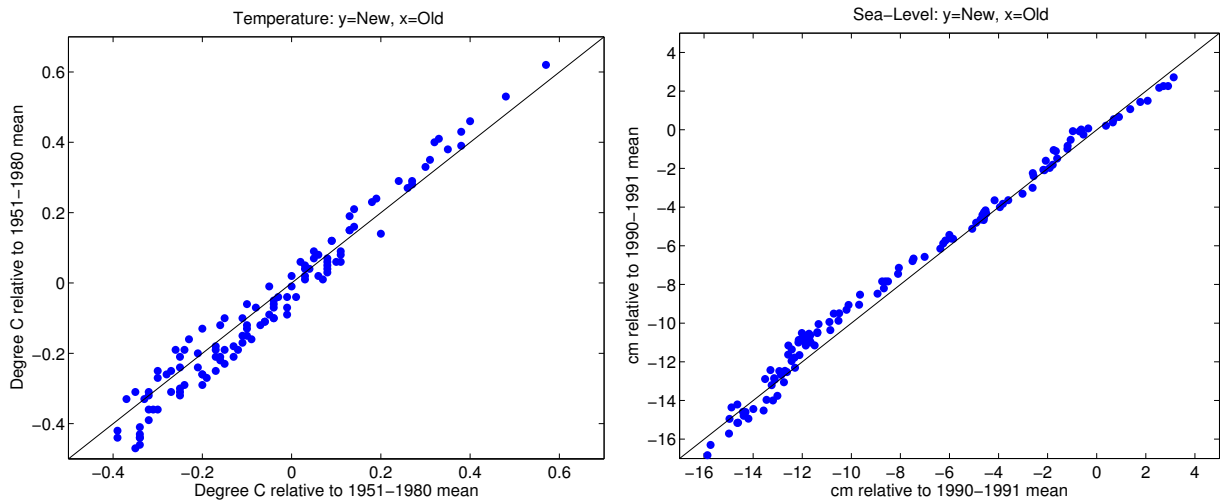


FIGURE 2. The left panel shows a scatter plot of the temperature time series revised (ordinate) versus old (abscissa). The right panel shows the same for the global sea-level time series.

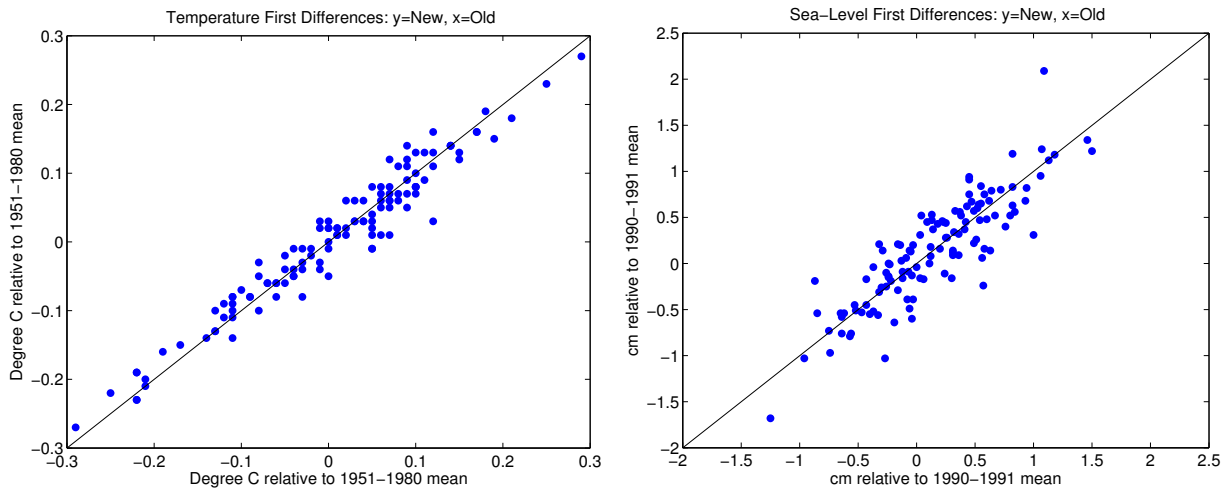


FIGURE 3. The left panel shows a scatter plot of the first differences of the temperature time series revised (ordinate) versus old (abscissa). The right panel shows the same for the global sea-level time series.

tide gauge locations and the fact that due to the availability of longer satellite altimeter data, the empirical orthogonal functions that are extracted from the satellite data and then used to project the earlier tide gauge measurements onto the employed grid cover 17 years (1993–2009) for [13] as opposed to 9 and 12 years for [10] and [18], respectively.

Figure 2 shows scatter plots of the vintages new (ordinate) versus old (abscissa) for the global mean temperature time series (left panel) and the global mean sea-level (right panel) in the time period of overlap (1880–2001). Figure 3 shows the scatter plots of the first differences. These figures show that the revisions are non-trivial changes throughout the series, and not simply updates of the most recent observations.

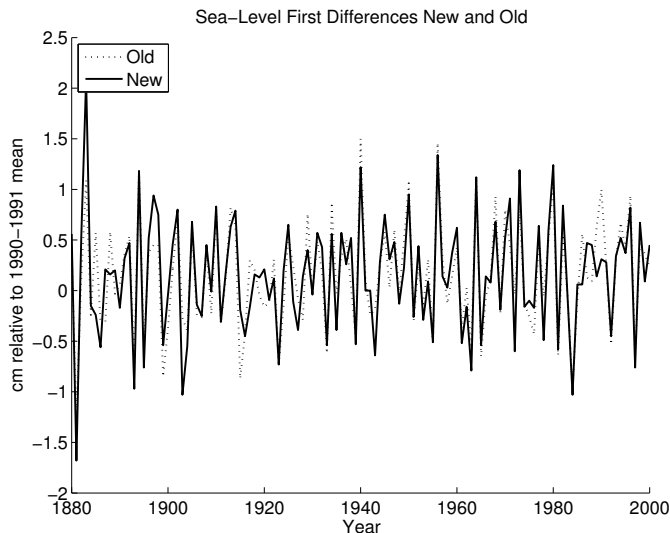


FIGURE 4. First differences of sea-level, old data (dotted) and new data (line).

## 2. METHOD AND RESULTS

In this section, we will repeat the analyses proposed in [1, 2, 3] on the new data set and compare the results to those reported from the old data set. The studies in [1] and [2] relate first differences in sea-level to the level of temperature. Figure 4 shows the first differences of old and new sea-level data. In repeating these studies, we will therefore relate the solid time series in Figure 4 to the solid time series in the left panel of Figure 1. The study in [3], on the other hand, related sea-level data to temperature level data; repeating this study means relating the solid line in the right panel of Figure 1 to the solid line in the left panel of Figure 1.

**2.1. Rahmstorf (2007) Model.** Rahmstorf [1] proposed a linear regression model for sea-level changes on temperature levels:

$$f(H_t) - f(H_{t-1}) = b(f(T_t) - f(T_0)) + \text{error}_t,$$

where  $H_t$  denotes sea-level relative to the 1990/91 mean,  $T_t$  temperature anomaly relative to 1951-1980 mean, and  $f(\cdot)$  extracts a long-term trend by singular spectrum analysis and 5-year binning. Among other assumptions in the standard linear regression model, the  $\text{error}_t$  term needs to be stationary in order to obtain valid statistical inference on the estimate of the slope parameter  $b$ . Rahmstorf [1] reported the regression slope  $\hat{b}$  of sea-level change on temperature, the correlation coefficient  $\hat{\rho}$  of  $f(H_t) - f(H_{t-1})$  and  $f(T_t) - f(T_0)$ , and the  $p$ -value of the correlation coefficient. The validity of the  $p$ -value has been questioned in [22] because the  $\text{error}_t$  term does not appear to be stationary. We report the  $p$ -value here for comparison. Table 1 reports the estimated parameters

TABLE 1. Estimates for the model of [1]. The last row with numbers in parentheses shows the estimates from using the revised data set on the old sample period.

	Regression coefficient $\hat{b}$	Correlation coefficient $\hat{\rho}$	$p$ -value
old	0.3375	0.8790	1.6e-8
new	0.1566	0.7880	4.8e-6
(new on 1880–2001)	(0.1481)	(0.7694)	(1.1e-5)

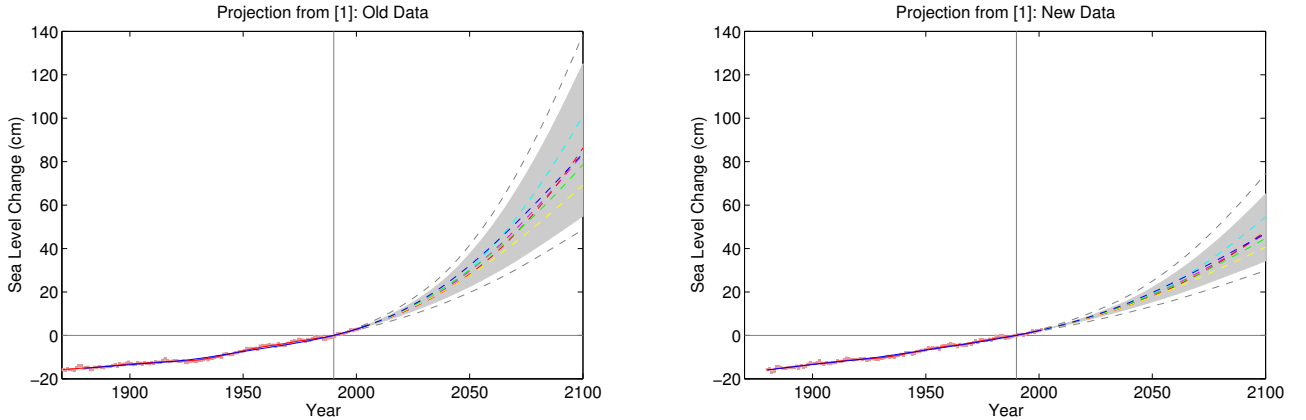


FIGURE 5. The left panel shows the projections as reported in [1]. The right panel shows the projections based on the estimates from the revised data restricted to 1880–2001, so that the forecasting period is the same in both panels, i.e., from 2001 onwards.

using the original data set and estimation method as reported in the original paper, the new data set, and the new data set restricted to the old sample period 1880–2001.

The regression coefficient estimated on the revised data is numerically about half the size of the estimate from the old data, and the correlation coefficient is about 9 percentage points lower. The consequences of these differences become very clear in the long term projections from the model. Figure 5 shows the long-term forecasts for 2002–2100 reported in [1] in the left panel and the forecast for 2002–2100 based on the estimates from the revised data restricted to 1880–2001 in the right panel. Thus, the difference in the forecasts is due only to revisions of data points for the period 1880–2001. These forecasts are shown here for comparison with the earlier literature only; stability of these relations over such a long forecast horizon seems a very strong assumption.

Since both temperature and sea-level time series have been revised, it is at this point not clear if the differences in the statistics are largely due to the changes in the one, the other, or both time series. We have estimated the model with the old temperature and new sea-level time series, and vice versa, always restricting the estimation sample to the period of overlap 1880–2001. Table 2 shows the regression and correlation coefficients for the four possible combinations. From this table,

TABLE 2. Estimation of the model proposed in [1] using all combinations of old and new time series for temperature and sea-level, restricted to the sample period 1880–2001. The first reported number in each cell is the regression coefficient  $\hat{b}$ , the second is the correlation coefficient  $\hat{\rho}$ .

Temperature	Sea-Level	
	old	new
old	$\hat{b} = 0.3375 / \hat{\rho} = 0.8790$	$\hat{b} = 0.1702 / \hat{\rho} = 0.7679$
new	$\hat{b} = 0.2867 / \hat{\rho} = 0.8576$	$\hat{b} = 0.1481 / \hat{\rho} = 0.7694$

it appears that the revision of the sea-level time series has the largest influence on the estimation of the relation.

**2.2. Grassi et al. (2013) Model.** Grassi, Hillebrand, and Ventosa-Santaulària [2] formulate a local-trend state-space model and obtain a coefficient of influence of temperature on sea-level changes that is directly comparable to the regression coefficient in [1]. The model specifies

$$\begin{aligned}
 H_t &= \mu_t^H + \varepsilon_t^H, & T_t &= \mu_t^T + \varepsilon_t^T, \\
 \mu_t^H &= \mu_{t-1}^H + \beta_{t-1}^H + c\mu_{t-1}^T, & \mu_t^T &= \mu_{t-1}^T + \beta_{t-1}^T, \\
 \beta_t^H &= \beta_{t-1}^H + \eta_t^H, & \beta_t^T &= \beta_{t-1}^T + \eta_t^T,
 \end{aligned}$$

where  $H_t$  and  $T_t$  are sea-level and temperature with long-term trends  $\mu_t^H$  and  $\mu_t^T$ , respectively. The long-term trends allow for non-stationary errors  $\beta_t^H$  and  $\beta_t^T$ , respectively, to allow for valid statistical inference on the coefficient  $c$  of interest. This specification captures the idea of a linear relation of long-term trends in sea-level differences and temperature levels, which can be seen by rewriting the first equation of the second line to

$$\mu_t^H - \mu_{t-1}^H = c\mu_{t-1}^T + \beta_{t-1}^H,$$

with a non-stationary error term  $\beta_{t-1}^H$  of lower integration order than the regressor  $\mu_{t-1}^T$ .

Table 3 reports the estimated coefficient  $\hat{c}$  of influence along with its simulation-based  $p$ -value using the original data set as reported in the original paper, the new data set, and the new data set restricted to the old sample period 1880–2001. The numerical value of the estimated coefficient of influence is reduced by about one third on the revised data, while the statistical significance increases substantially, from about 7.6 to about 1.1 percent.

Figure 6 shows the long-term projections of the sea-level rise as reported in the original paper [2] (left panel) and based on estimating the model on the revised data restricted to the old sample

TABLE 3. Estimation of the model proposed in [2] on the different data vintages. The table only reports the coefficient of influence of temperature on sea-level changes. The estimates of the variances from the model are omitted for brevity and available upon request.

	Estimated coefficient of influence $\hat{c}$	$p$ -value
old	0.4565	0.0756
new	0.3104	0.0113
(new on 1880–2001)	(0.2756)	(0.0226)

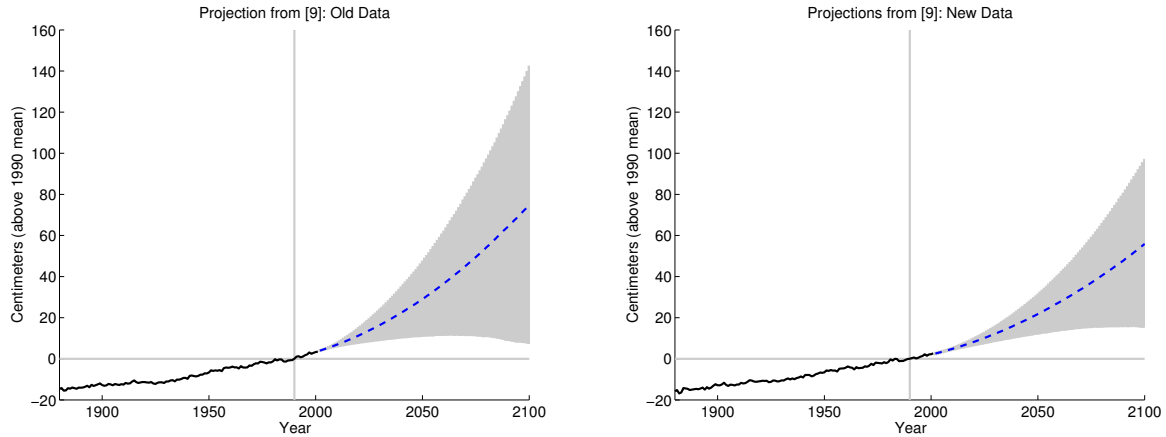


FIGURE 6. The left panel shows the projections as reported in [2]. The right panel shows the projections based on the estimates from the revised data restricted to the old sample period 1880–2001, so that the forecast is made from 2001 onwards, but using the revised data points for 1880–2001.

TABLE 4. Estimation of the coefficient of influence of temperature on sea-level in the model proposed in [2] using all combinations of old and new time series for temperature and sea-level, restricted to the sample period 1880–2001.

$\hat{c}$ Temperature	Sea-Level	
	old	new
old	0.4565	0.3374
new	0.3177	0.2756

period 1880–2001. Therefore, the differences in the forecasts are solely due to revisions of data points for the period 1880–2009, and not due to the addition of new data points.

As before, we have estimated the model with the old temperature and new sea-level time series, and vice versa, always restricting the estimation sample to the period of overlap 1880–2001. Table 4 shows the estimated coefficients of influence for the four possible combinations. In contrast to Table 2, revisions in both the temperature and the sea-level time series result in a substantial decrease in the estimated coefficient.



TABLE 5. Estimation of cointegrating relation  $z_t = H_t - \beta T_t$  in the model proposed in [3] using all combinations of old and new time series for temperature and sea-level, restricted to the sample period 1880–2001.

$\hat{\beta}$ Temperature	Sea-Level	
	old	new
old	0.3048 <small><math>t=9.57</math></small>	0.2923 <small><math>t=10.25</math></small>
new	0.2556 <small><math>t=8.68</math></small>	0.2473 <small><math>t=8.53</math></small>

**2.3. Schmith et al. (2012) Model.** Schmith, Johansen, and Thejll [3] specify a vector autoregressive model for level data of temperature  $T_t$  and sea-level  $H_t$

$$\begin{bmatrix} \Delta T_t \\ \Delta H_t \end{bmatrix} = \begin{bmatrix} \alpha_T \\ \alpha_H \end{bmatrix} z_{t-1} + \mathbf{\Gamma}_1 \begin{bmatrix} \Delta T_{t-1} \\ \Delta H_{t-1} \end{bmatrix} + \begin{bmatrix} \mu_T \\ \mu_H \end{bmatrix} + \begin{bmatrix} \varepsilon_{T,t} \\ \varepsilon_{H,t} \end{bmatrix},$$

where  $\alpha_T$  and  $\alpha_H$  are adjustment coefficients that describe how the system is reacting to the stationary disequilibrium error

$$z_t = H_t - \beta T_t.$$

The matrix  $\mathbf{\Gamma}_1$  has dimension  $2 \times 2$  and describes the short-run dynamics,  $\mu_T$  and  $\mu_H$  are linear drift terms, and  $(\varepsilon_{T,t}, \varepsilon_{H,t})$  is bivariate white noise. They find one cointegrating relationship in this model and estimate the vector error-correction formulation. In the context of studying the link between sea-level and temperature, the disequilibrium relation  $z_t$  is of primary interest, because it describes how the non-stationary time series of temperature  $T_t$  and sea-level  $H_t$  interact to form a stationary deviation  $z_t$ , which is zero in equilibrium.

Table 5 shows the estimates of  $\beta$  for the four possible combinations of old and new data on the sample period 1880–2001. The estimates are relatively more stable than in the models studied above.

**2.4. Location of Influential Data Points.** Are the differences in the estimates of the coefficient of interest using old and using new data caused by specific individual observations (outliers) or by specific periods in the new data set? In order to explore this question, we conduct the following exercise: Using the old data, we consecutively replace  $h$  observation pairs  $(T_{t-h+1:t}, H_{t-h+1:t})$  for  $t = h$  to  $T$  with the corresponding pairs from the new data set. We consider  $h = 1, \dots, 20$  years. Then we estimate the models proposed in [1] and in [2] on each of these  $T - h + 1$  pairs of temperature and sea level time series and record the estimated regression slopes  $\hat{b}$  and  $\hat{c}$ , respectively. For each  $h$ , we obtain a time series of regression coefficients stamped from  $h$  to  $T$  that show the estimated slope if a moving window of  $h$  observations is replaced with new data. Then we do the same with

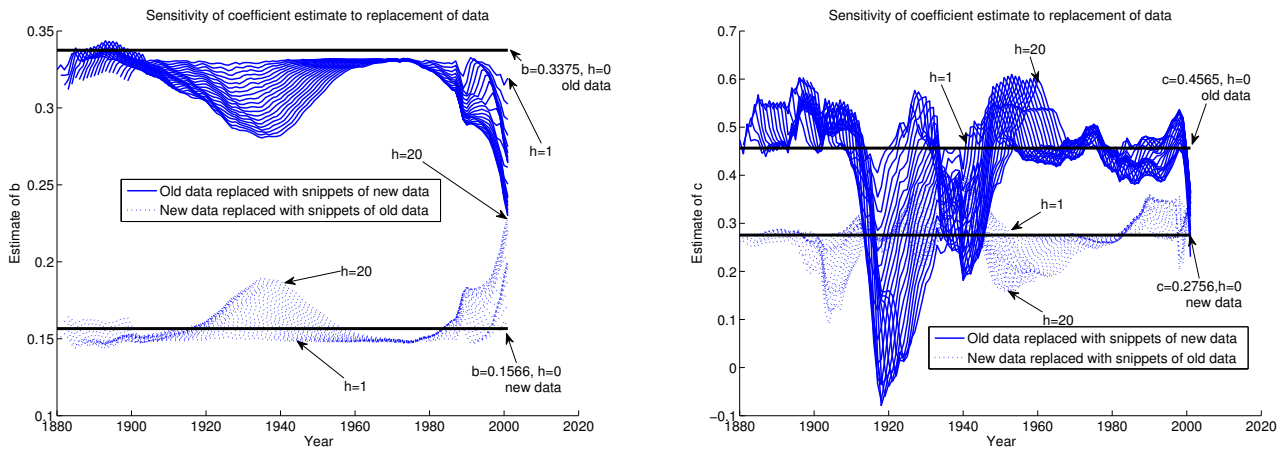


FIGURE 7. The left panel shows the estimates of the coefficient of interest in the model proposed in [1] when snippets of new data are inserted into the old data (upper family of curves) and when snippets of old data are inserted into new data (lower family of curves). The right panel shows the same for the model proposed in [2].

the new data and consecutively replace with  $h$ -snippets of old data. Figure 7 shows the results, with the model proposed in [1] in the left panel and the model proposed in [2] in the right panel.

Figure 7 shows that for both the Rahmstorf (2007) and the Grassi et al. (2013) models, the periods 1910–1950 and the last ten years of the record, 1990–2001, are the periods that influence the estimated coefficients most. In the case of the Rahmstorf (2007) model, only the exchange of the last 20 years from the old and new data results in agreeing coefficient estimates on both data sets. The Grassi et al. (2013) model is much more unstable, because it estimates the coefficient on yearly data and does not pre-average the data into 5-year bins. Here the family of curves resulting from inserting new data snippets into the old time series and from inserting old data snippets into the new time series intersect both in the 1910–1950 period and during the last ten years.

Figure 8 shows that the model proposed in Schmith et al. (2012) also reacts most strongly to the revisions in the data around the 1910s to 1950s and again in the 1990s. The range of the estimated coefficient, between approximately 0.24 and 0.31, is much narrower than in the cases of the Rahmstorf (2007) and Grassi et al. (2013) models. We conclude that among the three models considered here, this one is most robust to data revisions.

### 3. CONCLUSIONS

We have studied the ramifications of revisions of global mean temperature and global mean sea-level data on the estimated statistical relation between the two series. We find out of three alternative models proposed in the literature, two react very sensitively to the revisions, and the numerical magnitudes of both, the estimated regression coefficients and the implied forecasts, are substantially

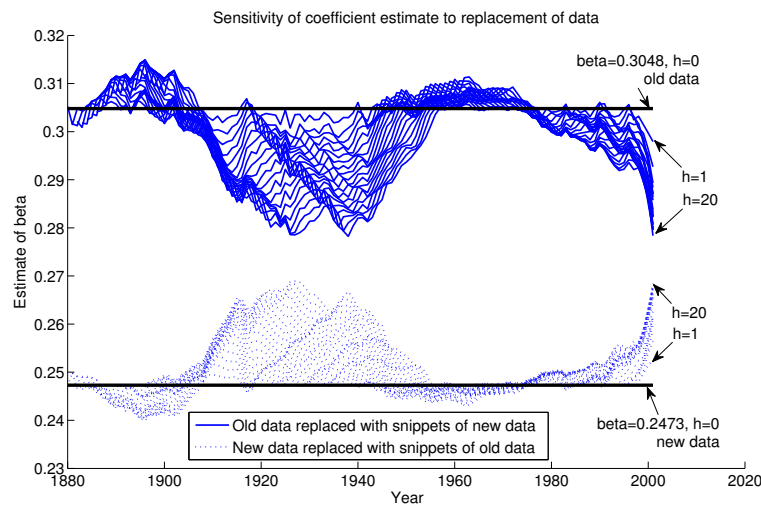


FIGURE 8. The graph shows the estimates in the coefficient of interest in the model proposed in [3] when snippets of new data are inserted into the old data (upper family of curves) and when snippets of old data are inserted into new data (lower family of curves).

reduced. Of the methods considered here, only the Schmith et al. (2012) model, which specifies a cointegrated vector-autoregression of sea-level and temperature level data, behaves stably. Exploration of the data sets inserting periods of old data into new data, and vice versa, show that the revisions of the data in the periods 1990–2001 and 1910–1950 have the largest influence on the change in the estimated relation of sea-level and temperature.

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