Response to Comments on "A Semi-Empirical Approach to Projecting Future Sea-Level Rise"

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Additional analysis performed in response to Holgate *et al.* and Schmith *et al.* shows that the semi-empirical method for projecting future sea-level rise passes the test of predicting one half of the data set based on the other half. It further shows that the conclusions are robust with respect to choices of data binning, smoothing, and detrending.

The technical comments by Holgate *et al.* (*1*) and Schmith *et al.* (*2*) provide a welcome opportunity to present further analysis of the link between sea-level rise and global warming, and to make the computer code used in the analysis available for use by other researchers (see Supporting Online Material).

Holgate *et al.* raise two issues. The first, shown in Fig. 1 in (*1*), concerns what they call a "clustering" of data in the scatter plot of temperature versus rate of sea-level rise. However, this clustering is an artifact of the authors' plotting annual data points based on a 15-year smoothed sea-level record, resulting in data points that are not independent but highly autocorrelated. This is the reason I binned the data points in my scatter plot [figure 2 in (*3*)]. This does not "further reduce the degrees of freedom," as Holgate *et al.* claim, but rather reflects the fact that there simply are not more degrees of freedom in these data after the smoothing. In fact, as the comment by Schmith *et al.* (*2*) correctly observes, it would have been more consistent to use 15-year bins. Using 15-year bins, $r = 0.9$ and $P = 0.002$ including the trend, or $r = 0.7$ and $P = 0.04$ for a detrended version of the analysis (see below). Thus, the correlation is still significant at the 99% level with trend and at the 95% level even without trend. Note that the binning affects only the look of the graph, not the statistical fit (i.e., slope and base temperature), and the particular smoothing procedure used has only a minor impact. The future sea level projections presented in (*3*) are robust to changes in these technicalities of the analysis.

The second issue that Holgate *et al.* raise is whether the semi-empirical formula proposed in (*3*) passes a simple test of predicting one half of the data set based on the other half of the data set. That this is indeed the case is demonstrated in Figs. 1 and 2. Figure 1 shows the predicted rate of sea-level rise, and of sea level itself, exactly as in figure 3 in (*3*), but using only the first half of the data set (1880 to 1940) for deriving the statistical fit. The slope found in this case is 0.42 mm/year per °C, and the base temperature is –0.42°C (relative to the period 1951 to 1980). The result shows that sea level for the period 1940 to 2000 is predicted well (to within 2 cm of observed sea level) by the semi-empirical formula, based only on the sea-level data before 1940. Figure 2 shows the same for a hindcast of sea level for the period 1880 to 1940, based only on the data after 1940 (in this case, sea level is integrated backward from the present). In each case, the error margins (dashed lines) are small enough to give useful predictions despite using only 60 years of data, and the observed sea level is well within those error margins of the method. These error margins are computed the same way as shown by the dashed gray lines in figure 4 in (*3*). The semi-empirical method thus passes this simple test very well, and its validity is thereby confirmed. The algorithms used here are the same as in (*3*). The fact that Holgate *et al.* show different results in their figure 2 is due to their using a different method, which involves detrending each half of the data separately (and likely some other differences). Comparing the graphs shows that the performance of their method is not as good as that of the method used in (*3*). The acceleration in sea-level rise between the first period (1880 to 1940) and the second period (1940 to 2000) due to global warming is captured by my semi-empirical model but not by the alternative approach proposed by Holgate *et al.*

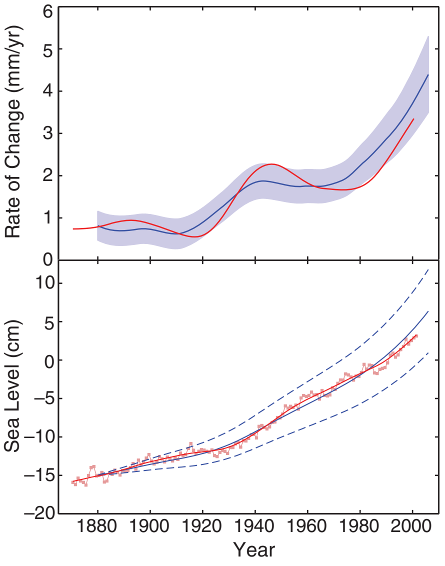

Fig. 1. (**Top**) Observed rate of sea-level rise (red) and that forecast using the simple empirical model (blue), trained using data for the period 1880 to 1940. (**Bottom**) Observed sea level (red) and that predicted using the empirical model (blue), by integrating the blue curve from the top panel forward in time. Dashed lines show the error estimate for the prediction, as in (*3*).

The comment by Schmith *et al.* (*2*) further raises the issue of the trend of the series being included in the correlation. Whether an analysis with trend or after removal of a linear (or higher order) trend is more useful depends on what one

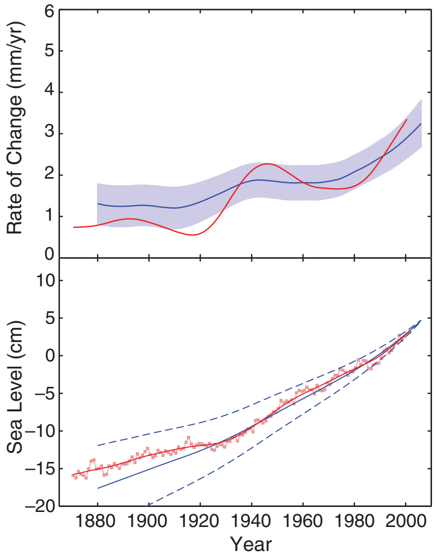

Fig. 2. (**Top**) Observed rate of sea-level rise (red) and that forecast using the simple empirical model (blue), trained using data for the period 1940 to 2000. (**Bottom**) Observed sea level (red) and that predicted using the empirical model (blue), by integrating the blue curve from the top panel backward in time. Dashed lines show the error estimate for the prediction, as in (*3*).

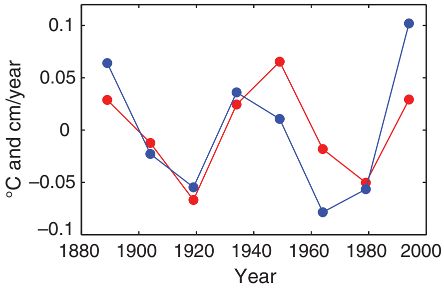

Fig. 3. Fifteen-year averages of the global mean temperature (blue, °C) and rate of sea level rise (red, cm/year), both detrended.

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is interested in. In this case, the common trend of global temperature and the rate of sea-level rise is one of the most interesting aspects of the data. If the rate of sea-level rise had not increased while temperatures warmed, the basic idea behind my analysis would have been falsified right away. Nevertheless, even the detrended series show a strong and significant correlation, with $r = 0.7$. This is evident from Fig. 3, which shows the temperature (blue) and the rate of sea-level rise (red) in their detrended versions using 15-year bins. Using the detrended data for the fit, the agreement with past observed sea level is not quite as good, the sea-level projections for the year 2100 are raised by about one-third (e.g., to 93 cm instead of 69 cm for the B1 scenario), and the statistical error estimate for these projections is increased by up to a factor of three.

Schmith *et al*. also raise the possibility of "nonsense correlations," that is, real correlations that do not have a causal basis. This can of course never be ruled out; data can only falsify but never prove a hypothesis. However, the starting point of my analysis and my paper was not a correlation found in data but rather the physical reasoning that a change in global temperature should to first order be proportional to a change in the rate of sea-level rise. The analysis shows that the data of the past 120 years are indeed consistent with this expectation, and the expected connection is statistically significant. The observational data therefore strongly support the hypothesis I put forward.

References

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2. T. Schmith, S. Johansen, P. Thejll, *Science* **317**, 1866 (2007); www.sciencemag.org/cgi/content/full/317/5846/1866c.
3. S. Rahmstorf, *Science* **315**, 368 (2007).

Supporting Online Material

www.sciencemag.org/cgi/content/full/317/5846/1866d/DC1
Computer algorithm and data files

20 February 2007; accepted 4 September 2007
10.1126/science.1141283