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DISCUSSION

Discussion of: Houston, J.R. and Dean, R.G., 2011. Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses. *Journal of Coastal Research*, 27(3), 409–417.

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ABSTRACT

RAHMSTORF, S., and VERMEER, M., 2011. Discussion of: Houston, J.R. and Dean, R.G., 2011. Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses. *Journal of Coastal Research,* 27(3), 409-417. *Journal of Coastal Research,* 27(4), 784–787. West Palm Beach (Florida), ISSN 0749-0208.

A recent article published in the *Journal of Coastal Research* analysed a number of different sea-level records and reported that they found no acceleration of sea-level rise. We show that this is due to their focusing on records that are either too short or only regional in character, and on their specific focus on acceleration since the year 1930, which represents a unique minimum in the acceleration curve. We find that global sea-level rise is accelerating in a way strongly correlated with global temperature. This correlation also explains the acceleration minimum for time periods starting around 1930; it is due to the mid-twentieth-century plateau in global temperature.

ADDITIONAL INDEX WORDS: *Ocean, sea level, climate change, global warming.*

INTRODUCTION

In a recent paper, (Houston and Dean, 2011) cast doubt on whether global sea-level rise has accelerated over the past century or so, and they questioned the link between global warming and an acceleration of sea-level rise shown in a number of recent studies (Grinsted, Moore, and Jevrejeva, 2009; Jevrejeva, Grinsted, and Moore, 2009; Rahmstorf, 2007; Vermeer and Rahmstorf, 2009). They conclude by asking "why this worldwide-temperature increase has not produced acceleration of global sea level over the past 100 years, and indeed why global sea level has possibly decelerated for at least the last 80 years" (p. 416).

However, the five main arguments presented by Houston and Dean in support of a lack of acceleration in global sea-level rise are all unconvincing:

(1) The global sea-level reconstruction of Church and White (2006) shows a small deceleration since 1930, but 1930 is a uniquely chosen start date in this respect, and this deceleration is neither statistically significant nor robust across different sea-level data sets.
(2) Many U.S. tide gauges show a deceleration; since 1930, most of them do. However, again, 1930 is a special choice, and U.S. tide gauges only provide a regional signal, not a global one.
(3) The authors' extension of the Douglas (1992) sea-level compilation shows a sea-level deceleration for 1905–2010, but this data set is not a global average but is instead highly biased to the Northern Hemisphere. It is known that the twentieth-century acceleration is largely found in the Southern Hemisphere (Merrifield, Merrifield, and Mitchum, 2009), and the only two Southern Hemisphere groups in the extended Douglas data set indeed show acceleration.
(4) Decadal trends in tide gauge compilations show large variations over the full record, and the most recent decadal trends are not unusual. However, these variations in decadal tide gauge trends are not a climate signal but rather are dominated by sampling noise due to the inadequate number of tide gauges.
(5) The satellite altimeter record shows a slight deceleration since 1993, but this time interval is far too short to draw any conclusions.

In the following we will discuss these issues in detail.

THE GLOBAL SEA-LEVEL RECORD AND ITS LINK TO TEMPERATURE

When fitting a quadratic equation to sea-level data, Houston and Dean ignore the fact that global warming has not been

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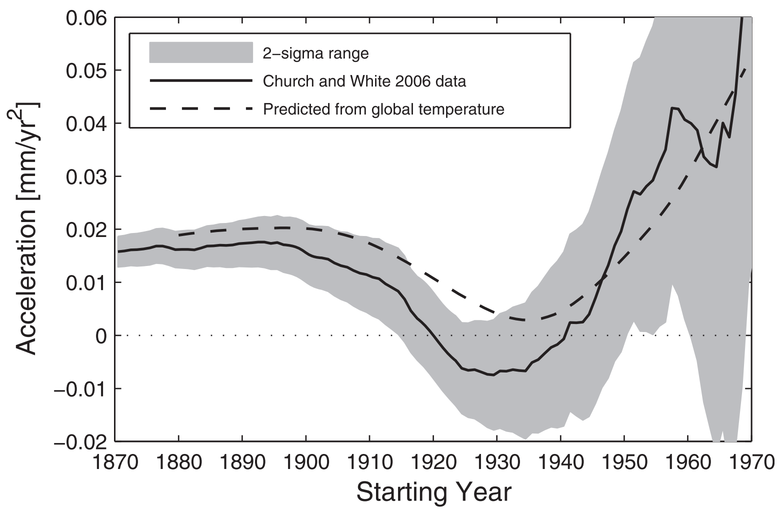

Figure 1. Acceleration of sea-level rise (*i.e.*, twice the quadratic coefficient) from different starting years up to 2001 in the global tide gauge data set of Church and White (2006; solid line), as compared to the same quantity from the sea-level hindcast of Vermeer and Rahmstorf (2009; dashed line) based on global temperature data. Note that we followed Houston and Dean in not accounting for the time-varying error bars of the tide gauge data, which is why we get slightly different numbers than those reported in Church and White (2006). We also show a conservative estimate of 2σ uncertainty in the acceleration, which accounts for an autocorrelation of 40% at lag 1 y and uses uniformly weighted data.

linear in time, nor can the sea-level history be well described by a linear increase in the rate of rise, *i.e.*, a quadratic increase in sea level itself. Instead, both follow a more complex time evolution with a high correlation between temperature and the rate of sea-level rise. Hence, Houston and Dean's method of fitting a quadratic and discussing just one number, the acceleration factor, is inadequate.

Modelling sea level as a simple function of time, $H(t)$, is not physical, because time is not the direct cause of sea-level rise. The more physical approach used in the semi-empirical models cited previously is to model sea level as function of temperature, $H(T)$. These approaches would converge only if temperature were to increase linearly in time—then semi-empirical models would give a constant acceleration of sea-level rise (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009). However, global temperature evolution over the twentieth century is not even close to that, and neither is global sea level close to parabolic behaviour.

Houston and Dean even seem to think that despite the much faster warming expected in the twenty-first century, the same acceleration value should apply to the twentieth and twenty-first centuries. They write that "it is not clear that the acceleration necessary to achieve these comparatively large projected rises in mean sea level over the course of the 21st century is evident in tide-gauge records" (p. 409). Why would tide gauge data of the twentieth century show the acceleration expected in the twenty-first century? What we may expect instead is for tide gauge data of the twentieth century to follow the temperature evolution of the twentieth century. That is indeed the case, as shown in detail below.

Houston and Dean (2011) focus mostly on acceleration for the period 1930 to today, both for their sample of U.S. tide gauges (their Table 1) and the global sea-level record of Church and White (2006) (their Figure 1), stressing the slight negative acceleration over this period. In our Figure 1, we show the acceleration for the Church and White (2006) data up to the present, but for all starting years between 1870 and 1970, not just for 1930. The figure shows a pronounced minimum in acceleration values for starting years around 1930. Houston and Dean (2011) admit that they deliberately selected this starting year because of this feature: "Since the worldwide data of Church and White (2006) … appear to have a linear rise since around 1930, we analyzed the period 1930 to 2010." Positive acceleration is found for both earlier and later starting years, as Figure 1 here shows.

Figure 1 also answers the concluding question posed by Houston and Dean, cited on the opening paragraph here. The semi-empirical models *predict* and thus explain the acceleration minimum around 1930 as a consequence of the plateau in the global temperature record in the middle of the twentieth century. Since global temperature did not rise from about 1940 to about 1980, one cannot expect any significant acceleration of sea-level rise over this period.

When correlating sea level with global temperature, nonclimatic influences on sea level can muddy the waters and are best removed to isolate the climatic effect on sea level. Glacial isostatic adjustment is routinely corrected for, and in Figure 2 we show the way in which correcting for water storage in artificial reservoirs (Chao, Wu, and Li, 2008) affects the results, following Vermeer and Rahmstorf (2009). This significantly improves the agreement between the sea-level acceleration predicted from global temperature and the acceleration actually found in the tide gauge data.

Houston and Dean rightly point out that one should likewise correct for the water mined from deep groundwater sources for irrigation purposes. However, no suitable time series of twentieth-century groundwater mining is available. Nevertheless, Vermeer and Rahmstorf (2009) performed a sensitivity

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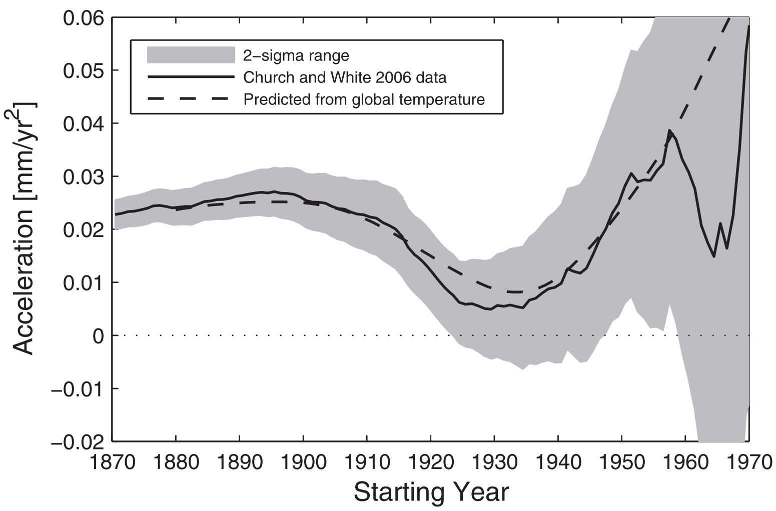

Figure 2. The same as Figure 1, but here the sea-level data are corrected for water storage in artificial reservoirs (Chao, Wu, and Li, 2008).

study of this effect, and Rahmstorf, Perrette, and Vermeer (personal communication) included the very high estimate of Wada *et al.* (2010) and assumed that water mining is proportional to global population (to extend it back in time before groundwater extraction data are available). The result is that groundwater mining only has a minor effect on semi-empirical sea-level projections: Inclusion of this effect only lowers projected future sea level by a few percent. A key strength of modelling sea level as a function of temperature is that the calibration with past data automatically tends to select for climatic effects. Nonclimatic sea-level changes do not correlate so well with temperature in the past and hence have a lesser influence on the model parameters that describe the correlation of sea level with temperature. Houston and Dean suggest that the sea-level data call into question the predictions of semi-empirical models. However, as Figures 1 and 2 show, the opposite is the case.

It should be noted that the updated global sea-level reconstruction by Church and White (2011) also shows a minimum in acceleration for starting years around 1930 (confirming this is a robust feature), but acceleration does not become negative there; it instead shows positive acceleration throughout, from any starting date up to AD 1970 (after which short-term noise dominates the calculations, and results oscillate strongly). Hence, not deceleration but acceleration is a robust feature of the global sea-level reconstructions, and sea level has responded to global warming just as suggested by semi-empirical models. Sea level in recent decades has risen *faster* than Intergovernmental Panel on Climate Change (IPCC) projections (Rahmstorf *et al.*, 2007), which are lower than those of semi-empirical models.

LOCAL VERSUS GLOBAL SEA-LEVEL DATA

In addition to the global sea-level record of Church and White (2006), Houston and Dean (2011) analyse (i) a group of U.S. tide gauge records and (ii) a small group of globally distributed long records used earlier by Douglas (1992). For the U.S. records, they find on average a deceleration since 1930 that is larger than that in the global record. For the full record lengths of each gauge, they find an average acceleration close to zero. However, the periods considered vary greatly (with starting years ranging from the 1850s to the 1940s), so simple averaging of the acceleration factors makes little sense. Also, use of only U.S. gauges does not allow any conclusions to be drawn about the acceleration of *global* sea-level rise.

It is well known that water motions between different parts of the world, *e.g.,* between Northern and Southern Hemisphere, cause regional sea-level changes unrelated to the mechanisms of global sea-level change. Houston and Dean note the analysis of Merrifield, Merrifield, and Mitchum (2009), which shows that the twentieth-century acceleration of sea-level rise is not evident in northern data but rather stems from tropical and Southern Hemisphere data.

This picture is consistent with the fact that their U.S. gauges show little acceleration, and it is also consistent with their extension of the analysis of Douglas (1992). As their Table 2 shows, the average "group acceleration" since 1905 of the eight Northern Hemisphere groups in this collection is −0.022 mm/yr^2, while for the two Southern Hemisphere groups it is +0.027 mm/yr^2. Averaging these two values, weighted by the respective ocean areas of both hemispheres, yields a positive acceleration of 0.0059 mm/yr^2. However, Houston and Dean report a *negative* acceleration for these data because they form a simple average over all groups, thus introducing a strong Northern Hemisphere bias. This illustrates that the excessive weighting of Northern Hemisphere records in the simple averaging used by Houston and Dean is sufficient to explain the deceleration they found in this data set.

SIGNAL VERSUS NOISE

In their Figure 6, Houston and Dean show decadal trends in sea-level rise over the past century that vary widely, oscillating from less than −1 to more than +5 mm/yr. What is the nature of

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these variations? When looking at an overlay of decadal trends from a range of different tide gauge reconstructions, it is clear that these variations are highly inconsistent between different data sets and thus cannot be considered true variability of global mean sea level (Rahmstorf, Perrette, and Vermeer, personal communication). Rather, they are evidently a noise problem. For example, coincident with the high 1970 peak in Figure 6 of Houston and Dean (2011), another global reconstruction (Jevrejeva *et al.*, 2008) shows a minimum with near-zero decadal rise. Also, the tide gauge reconstruction in Figure 6 of Houston and Dean (2011) shows a *negative* decadal rate centred on the year 2000, when the satellite altimeter record shows a decadal rate of rise of almost 4 mm/yr.

Christiansen, Schmith, and Theill (2010) have shown that the short-term noise in global tide gauge data compilations is almost fully attributable to inadequate spatial sampling by the limited number of coastal sites and their very uneven global distribution, getting poorer still going back in time. The principal components–based reconstruction technique of Church and White aims at, and partially succeeds in, mitigating this. It shows greatly reduced variability in decadal sea-level trends but still contains some sampling noise.

Rahmstorf, Perrette, and Vermeer (personal communication) have shown that even very little random noise in the sea-level data, with a standard deviation of only 5 mm and 40% autocorrelation for 1 y lag, is enough to cause fluctuations in decadal sea-level trends of the magnitude shown by Houston and Dean. Hence, their claim that the altimeter trend is not unusually high ("the altimeter measurements appear similar to several decadal oscillations over the past 100 years," p. 415) mistakes the sampling noise of the tide gauges for a meaningful signal. The altimeter data do not suffer from this sampling problem due to their near-global coverage.

Finally, Houston and Dean argue with the slight deceleration found in the altimeter data, a record that began only in 1993. Given the brevity of this record, it would be highly premature to draw conclusions about the sea-level response to global warming from such small short-term variations in the trend. The main feature of the altimeter data is that the trend is very linear and has much less short-term variability than seen in the tide gauge reconstructions.

CONCLUSION

In summary, we find that the deceleration in sea-level rise reported by Houston and Dean either applies to a far-too-brief time interval (since 1993), or to a unique and specially selected start date (1930), or only to regional, strongly Northern Hemisphere–biased records that are spatially or temporally averaged in an inappropriate manner. None of this supports a lack of acceleration in global sea-level rise, as compared to what is expected from global warming.

Outside a few starting years around 1930, global sea-level reconstructions robustly show a modern acceleration of sea-level rise in conjunction with global warming. A modern acceleration is also supported by data going back further in time, which show constant sea level preceding AD 1800. The tide gauge reconstruction of Jevrejeva *et al.* (2008) starting in AD 1700 finds a stable sea level from 1700 to 1800, with the largest rate of rise in the latter half of the twentieth century, and the proxy data of Kemp *et al.* (2011) show a period of stable sea level from AD 1400 to 1800, with the twentieth-century rate of rise unprecedented in at least the past 2000 y.

Moreover, when the rate of global sea-level rise is correlated to global temperature data, this correlation not only explains the lack of acceleration since 1930, it also is both highly statistically significant *and* points to a sea level that responds more strongly to global warming than predictions by climate models would indicate. This is why semi-empirical models, which use the observed sea-level data and their link to temperature, yield much higher sea-level projections than the model-based ones of the IPCC (2007).

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