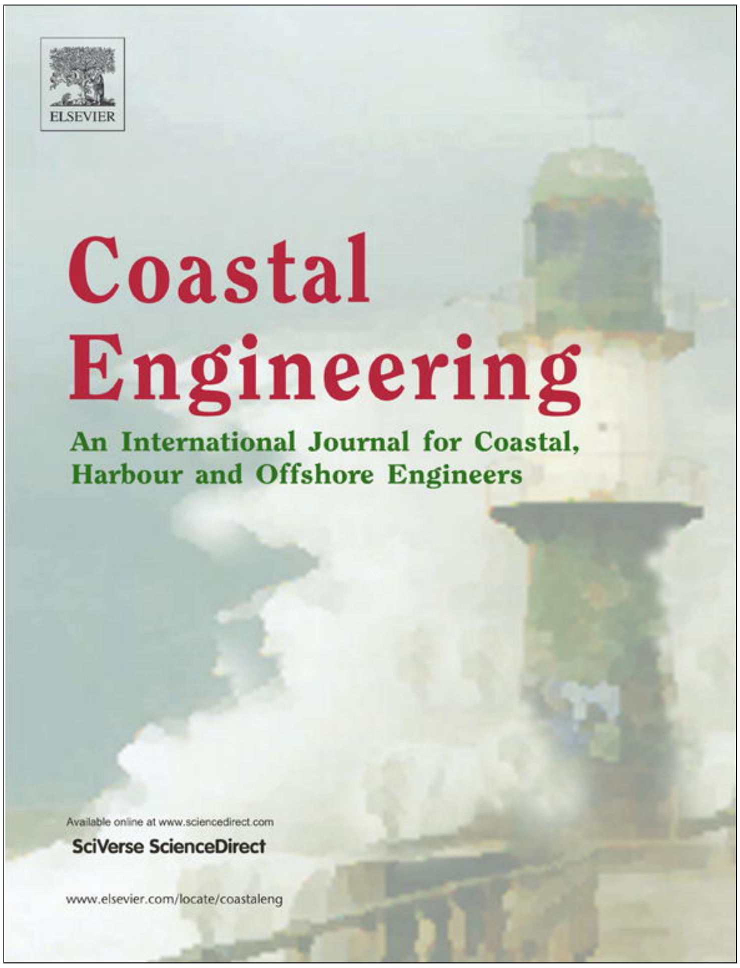
ELSEVIER
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
Available online at www.sciencedirect.com
SciVerse ScienceDirect
www.elsevier.com/locate/coastaleng

Coastal Engineering 75 (2013) 1–3

Contents lists available at SciVerse ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Discussion

Discussion of Boretti, A., 'Is there any support in the long term tide gauge data to the claims that parts of Sydney will be swamped by rising sea levels?', Coastal Engineering, 64, 161–167, June 2012

J.R. Hunter *, M.J.I. Brown

Antarctic Climate & Ecosystems Cooperative Research Centre, Private Bag 80, Hobart, Tasmania 7001, Australia
School of Physics, Monash University, Clayton, Victoria 3800, Australia

ARTICLE INFO

Article history:
Received 11 October 2012
Received in revised form 13 November 2012
Accepted 6 December 2012
Available online xxxx

Keywords:
Sea-level rise
Climate change
Climate projection

ABSTRACT

Boretti (2012) claims that sea-level records show insufficient acceleration to support the projections of sea-level rise that are used worldwide for planning and policy-making. Unfortunately, his claim is based more on flawed qualitative reasoning than on quantitative analysis.
We replicate Boretti's methodology of fitting quadratic functions to tide-gauge observations from Fremantle and Sydney, in order to estimate the sea-level acceleration. However, we also evaluate the uncertainty in these estimates (a crucial step, omitted by Boretti), and thereby show that the observed accelerations are statistically consistent with the projections of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Our finding is the same when we repeat this analysis using two data sets which have smaller uncertainties, one from satellite altimeters and the other from a sea-level reconstruction.
We therefore conclude that Boretti's claim is without foundation.

1. Introduction

Boretti (2012) claims that sea-level records show insufficient acceleration to support the projections of sea-level rise that are used worldwide for planning and policy-making. Unfortunately, he makes numerous fundamental errors. For example, he quotes no uncertainties for the accelerations which he provides, and he dismisses what he believes to be 'small' accelerations with no quantitative support. A particularly glaring error involves Boretti's Fig. 1 (lower panel), which shows a parabolic fit to the recent sea-level observations at Sydney (Fort Denison) and states that 'the sea level is not accelerating on average'; however, his calculated acceleration is positive and, if continued, would result in a 2 m sea-level rise by 2100 (much larger than the 'more likely less than …50 mm' that Boretti claims in his conclusions).

Boretti quotes sea-level rise scenarios for 2100, suggested by the Australian Government (www.ozcoasts.gov.au/climate/sd_visual.jsp), of 0.5, 0.8 and 1.1 m. The first two (0.5 and 0.8 m) were based on the upper ends of the projections of the Fourth Assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) for the B1 and A1FI emission scenarios, respectively (the world is broadly following the A1FI emission scenario at present (Le Quéré et al., 2009). The third sea-level rise scenario (1.1 m) is a 'high-end' one based on post-AR4 research and the suggestion that the AR4 projections may be underestimates. We here concentrate on the middle sea-level rise scenario, which was derived from the IPCC AR4 projections and the A1FI emission scenario.

We make two points. Firstly, the observed acceleration in sea-level over the 20th century represents a quite different issue from the projections of sea-level rise for the 21st century. It is clear that the climate is changing significantly and it is therefore unrealistic to expect the acceleration during the 20th century to be simply related to the acceleration during the 21st century. Observations from the 20th century are important, as they provide a crucial part of the information necessary for understanding the various components that contribute to sea-level rise; this is commonly referred to as 'closing the sea-level budget'. There has been significant recent progress in this field, and the budget since 1972 is now quite well constrained (Church et al., 2011). Also, Domingues et al. (2008) have shown that the thermal-expansion component of sea-level rise since 1950 is well reproduced by climate models of 20th-century sea-level that include all atmospheric forcings (in particular, they indicated the importance of stratospheric aerosol loadings from volcanic eruptions). Improved understanding of historic sea-level and its budget assists in the development of better models of the future, but we cannot expect the acceleration in the 20th century (or the lack of it) to be

* Corresponding author at: Antarctic Climate & Ecosystems Cooperative Research Centre, Private Bag 80, Hobart, Tasmania 7001, Australia. Tel.: +61 4 2709 8831; fax: +61 3 6226 2440.
E-mail address: jrh@johnroberthunter.org (J.R. Hunter).

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http://dx.doi.org/10.1016/j.coastaleng.2012.12.003

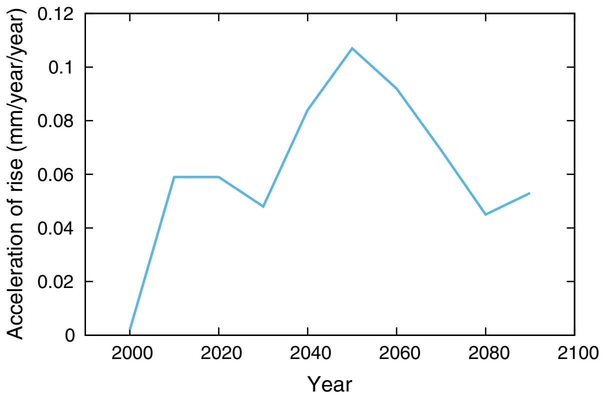

Fig. 1. Acceleration of central projection of sea level for A1FI emission scenario (IPCC AR4). The acceleration is computed by finite differences from decadal values and therefore covers the range 2000 to 2090, rather than the full range of the projections (1990 to 2100). The acceleration increases significantly over the first decades of the projection, from a relatively small value (0.002 mm yr^{-2}) at 2000. The acceleration throughout the century, and in particular at 2000, is statistically consistent with the observed accelerations shown in Table 1.

simply reproduced in the 21st. Boretti's estimations of the overall sea-level acceleration during the 20th century therefore have no direct relevance to the issue of the projections.

Secondly, 1990–2012 is the only period that we can use to compare historical observations with the 1990–2100 projections of the IPCC. Unfortunately, due to natural variability, sea-level records that are as short as this yield estimates of acceleration which have a quite large uncertainty; for the tide-gauge records from Fremantle and Fort Denison, sea level varies by ±20 mm over decadal time scales, so that accelerations based on 20-year records show variability of roughly $\pm 20\sqrt{6}/\left(10^2\right)$ or ±0.5 mm yr^{-2} (taking a simple three-point estimation of the acceleration). However, we show that observed accelerations over the past 20 years are statistically consistent with the projections from the AR4 of the IPCC (Meehl et al., 2007), and also with the constant acceleration that would be required to reach the AR4's central projection for the A1FI emission scenario at 2100. In other words, we show that observational evidence of present sea-level acceleration provides no evidence that could cast doubt on the 1990–2100 projections of the IPCC AR4.

It must therefore be emphasised that the long 20th-century records tell us nothing directly about the acceleration in sea level that is to be expected in the 21st century. It is also not appropriate to compare accelerations for the whole 20th century with projections of the sea-level rise since 1990. In this discussion, we therefore only consider sea-level observations from approximately the last 20 years.

The projections reported by the IPCC in their various assessment reports are based on process-based models of the atmosphere and ocean. These are complex and sophisticated computer programmes, developed over a long period of time in a number (about 12 at the time of the AR4) of research organisations around the world. They represent our current understanding of the observed climate system and many are closely related to the models routinely used for weather forecasting. These models provide the component of sea-level rise due to changes in ocean density and circulation, to which must be added contributions from water on land (e.g., melting glaciers and ice sheets), which are also derived from process-based models supported by observations. Therefore, the IPCC projections are in no sense simple extrapolations of the present state of sea level; they are soundly based on observations and on the processes which drive the climate.

While this discussion focuses on the present *acceleration* of sea level, it should be noted that Rahmstorf et al. (2007) showed that observations of sea level from 1990 to 2007 had a *trend* of 3.3 ± 0.4 mm yr^{-1}, which is close to the upper limit of the projections of the IPCC Third Assessment Report (TAR, the current assessment at that time); the projections of the current AR4 are very similar to those of the TAR during this period.

2. Observed and projected accelerations

Four data sets are considered: tide-gauge records from Fremantle and Fort Denison (Sydney) (downloaded from www.psmsl.org/data on 7 Sept. 2012), satellite altimeter data and the sea-level reconstruction of Church and White (2011) (the latter two data sets downloaded from www.cmar.csiro.au/sealevel/sl_data_cmar.html on 28 Sept. 2012). It should be noted that we use annually-averaged data sets, as is common practice (e.g., Woodworth et al., 2008); due to autocorrelation within a year, it is quite unnecessary to use monthly data sets to estimate trends and accelerations (as Boretti has done) over multi-decadal periods. Table 1 shows the estimated accelerations for these records over approximately the past 20 years. The accelerations were estimated by fitting quadratic functions to the sea-level records, with due regard to a priori error estimates in the cases of the satellite altimeter data and the sea-level reconstruction. The uncertainties in Table 1 were calculated on the assumption that the annually-averaged sea levels were independent. Analysis of the autocorrelation of the residuals showed that the number of degrees of freedom per year ranged from 0.6 to 1, so that the uncertainties shown may be underestimated by about 20%; this only strengthens the argument which follows. As expected for such relatively short records, the uncertainties are large (of the same order or larger than the magnitudes of the trends themselves).

In regard to the two tide gauges, our analysis was similar to Boretti's except that we additionally estimated the uncertainties in the accelerations. This step is crucially important if the observed accelerations are to be statistically compared with specific sea-level projections.

These observations are compared with the central projection of the IPCC AR4 (Meehl et al., 2007); including *scaled-up ice sheet discharge*) for an A1FI emission scenario (which the world is broadly following at present; (Le Quéré et al., 2009). We used a higher-precision version (±0.05 mm; Gregory, pers. comm.) of the data shown in tabular form in www.cmar.csiro.au/sealevel/sl_proj_21st.html. Fig. 1 shows the acceleration, estimated by comparing two adjacent first-order differences of the decadal (1990, 2000, 2010 …) projected heights. The average acceleration over 1990–2010 (the value plotted at 2000) is 0.002 mm yr^{-2}, but the acceleration rises quite rapidly to 0.04–0.11 mm yr^{-2} for the remainder of the century.

An alternative estimate of 'expected' acceleration may be obtained by calculating the constant acceleration necessary to raise sea-level from a (conservative) 2 mm yr^{-1} rate of rise in 2000 to a 2100 level which is the same as the IPCC AR4 projection described above (520 mm relative to 2000). This acceleration is 0.064 mm yr^{-2}.

The observed present accelerations of sea level shown in Table 1 are all statistically consistent with (a) the present acceleration of the central projection of the IPCC AR4 for the A1FI scenario (0.002 mm yr^{-2}), (b) the maximum acceleration during the 21st century of this IPCC projection (0.11 mm yr^{-2}), and (c) the constant acceleration (0.064 mm yr^{-2}) which would be required to raise sea level by 520 mm, starting from a 2 mm yr^{-1} rate of rise in 2000.

Table 1
Estimates of acceleration of sea-level over approximately the past 20 years. The ranges of uncertainties shown are probably underestimates (see text).

Data set	Period (inclusive)	Acceleration (mm yr^{-2}) (one standard deviation range)	
Fremantle	1990–2010	−0.60 ± 0.70	(−1.30 to 0.10)
Fort Denison (Sydney)	1990–2010	0.44 ± 0.34	(0.10 to 0.78)
Satellite altimeter	1993–2009	−0.027 ± 0.114	(−0.140 to 0.087)
Reconstruction	1990–2009	0.078 ± 0.107	(−0.028 to 0.185)

3. The final message of Boretti's paper

The final sentence is one of the most influential in any paper, and so it is instructive to deconstruct the last sentence of Boretti (2012):

> The most likely rise of sea level in the bay of Sydney by 2100 is therefore more likely less than the 50 mm measured so far over the last 100 years rather than the metre predicted by some models.

Firstly, the ‘50 mm’ comes from an earlier statement that ‘the tide gauges of Sydney show that the sea level has risen about 50 mm in 100 years in Sydney’. This presumably refers to the past 100 years (i.e., from 1910 to 2010), over which time the fitted polynomial given in Boretti's Fig. 1 (top panel) shows a rise of 78 mm and *not* 50 mm. There also is no justification provided for the phrase ‘less than’; 78 *is not* less than 50, and the sea-level record shows no evidence of a deceleration. Finally, as indicated earlier, there is no scientifically valid reason why either the trend or the acceleration of sea level should be the same in the 21st century as it was in the 20th; we are living in a changing climate.

The final sentence is just plain wrong.

4. Summary

In summary, Boretti crucially ignored the uncertainty in his estimates of sea-level acceleration. When such uncertainties are considered, observational evidence of present sea-level acceleration provides no evidence which would, at present, cast doubt on the 1990–2100 projections of the IPCC AR4, or the common and well-founded expectation that sea level could rise by at least 500 mm during the 21st century. Boretti's claims lack any robust quantitative support.

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