Global and Planetary Change 100 (2013) 263–277

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

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

Review paper

When did modern rates of sea-level rise start?

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ARTICLE INFO

Article history:
Received 13 July 2012
Accepted 26 October 2012
Available online 3 November 2012

Keywords:
Sea level
Tide gauge
Anthropocene
Holocene
Salt marsh
Microfossils

ABSTRACT

Accelerations and inflexions in recent sea-level records are known from instrumental (tide-gauge) datasets, but such records are generally too short to shed light on the question when modern rapid rates of sea-level rise commenced. Proxy sea-level records should therefore also be considered. In this review we compare recent proxy and instrumental sea-level records from the North Atlantic, Australia and New Zealand with the long-term (linear) rate of relative sea-level change that prevailed in the centuries and millennia before the 19th century. We re-evaluate dating models that underpin many of the proxy records and only consider published sea-level index points for which a reliable age can be firmly established. For seven coastal sites we determine the start of recent rapid sea-level rise by identifying the time when sea-level rise first departed from the long-term background rate. We find that within a 40 year period, centred around 1925, sea-level rise in all sites started to exceed the late Holocene background rate. This is consistent with local tide-gauge records and also with global and regional tide-gauge compilations. We conclude that proxy and instrumental sea-level datasets record a similar 20th century inflexion. Possible mismatches identified in published literature are therefore reconciled. We suggest that northern hemisphere ice melt, primarily from the Greenland Ice Sheet and small Arctic glaciers, is the main driving mechanism of early 20th century sea-level rise.

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0921-8181/$ – see front matter
http://dx.doi.org/10.1016/j.gloplacha.2012.10.020

1. Introduction

Many proxy records of sea-level change that cover recent centuries show a distinct positive inflexion in the late 1800s or the early 1900s, marking the transition from late Holocene background rates of sea-level change to the high rates that have been recorded by tide gauges and satellites during the 20th and 21st centuries (Shennan and Woodworth, 1992; Shennan and Horton, 2002; Gehrels et al., 2004; Bindoff et al., 2007; Engelhart et al., 2009; Woodworth et al., 2011a). Using evidence from proxy records, many authors have dated the inflexion, but results have been variable. The following inflexion dates have been suggested: the later half of the 19th century (Connecticut, USA; Donnelly et al., 2004), the period 1900–1920 (Nova Scotia, Canada; Gehrels et al., 2005), the start of the 20th century (southern New Zealand and Tasmania; Gehrels et al., 2008, 2012), the period 1880–1920 (northern Spain; Leorri et al., 2008), the period 1879–1915 (North Carolina, USA; Kemp et al., 2009) and the period 1865–1892 (also North Carolina, USA; Kemp et al., 2011). These possible inconsistencies raise the question whether the inflexions could be non-synchronous, which has implications for the interpretation of underlying driving mechanisms. Non-synchroneity would point at a regional cause for rapid sea-level rise, such as ocean dynamical change or thermal expansion, whereas a synchronous inflexion might signal forcing by melt of ice sheets and/or glaciers. Alternatively, the varying dates of the onset of modern rates of sea-level rise could be due to chronological limitations of the proxy records.

Sea-level records spanning several decades to centuries, whether from tide gauges or proxy information, are often parameterised in terms of a linear trend superimposed upon which is variability on interannual and decadal timescales. Relative sea-level trends arise from long term changes in the ocean and/or from vertical land movements and are the subject of great interest by study groups such as the Intergovernmental Panel on Climate Change (e.g. Bindoff et al., 2007). 'Accelerations' in sea level can take the form of a gradual change in linear trends over the period of the entire record. These accelerations are often estimated by including a quadratic term in addition to the linear trend in the parameterisation, and the mean acceleration during the record is thereby calculated by multiplying the determined quadratic coefficient by two (Douglas, 1992). Many studies of tide-gauge time series (e.g. Douglas, 1992; Maul and Martin, 1993; Church and White, 2006; Jevrejeva et al., 2006; Houston and Dean, 2011; Watson, 2011; Woodworth et al., 2011a) have focussed on century-scale accelerations as determined by quadratic regressions or low order polynomials through long datasets.

When a record exhibits an abrupt change of linear trend at some time 't', then instead of using a quadratic term it may be more appropriate to parameterise the time series as an 'inflexion', the record either side of 't' being described adequately by its own linear trend and the two trend lines constrained to have the same value of sea level at 't'. The use of an inflexion parameterisation to characterise acceleration in European tide-gauge records spanning the 19th and 20th centuries was investigated by Woodworth (1990) who focused on a possible inflexion around 1930 in the longest tide-gauge records from northern Europe. Global and regional tide-gauge compilations (such as in Fig. 1) have recorded inflexions around 1930 (Church and White, 2006; Jevrejeva et al., 2008; Woodworth et al., 2009; Church and White, 2011), and around 1850 (Jevrejeva et al., 2008). The aforementioned inflexions identified in proxy records fall roughly between these dates, creating a possible discrepancy between the instrumental and proxy records of recent sea-level change.

Comparisons between proxy and tide-gauge records raise two main questions which are addressed in this review:

(1) why does the timing and magnitude of inflexions appear to differ in proxy and instrumental records?

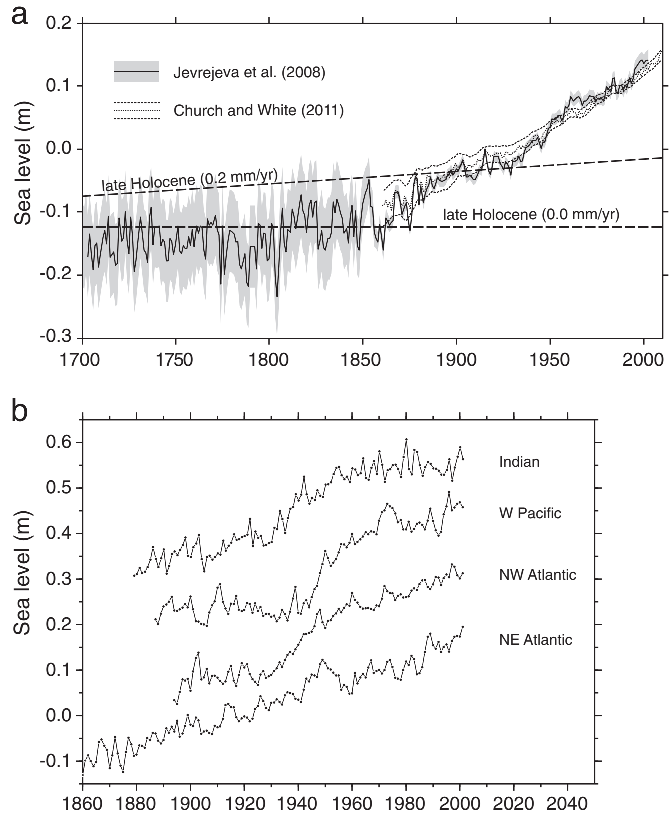

Fig. 1. a. Global tide-gauge compilations from Jevrejeva et al. (2008) and Church and White (2011). Increased error bands before 1850–1900 reflect the low number of tide-gauge records that cover the 18th and 19th centuries. The range of global late Holocene sea-level trends (0–0.2 mm/yr), as proposed by Jansen et al. (2007), is also shown. b. Compilations of tide-gauge records for four oceanic regions relevant to this study. From Milne et al. (2009), based on data from Jevrejeva et al. (2006).

(2) when did sea-level rise start departing from the long-term slow rate of sea-level rise that was persistent during much of the late Holocene?

The main aim of this paper is to reconcile the proxy and instrumental records of sea-level change during the 19th and 20th centuries. More specifically, we test the hypothesis that instrumental and proxy datasets of sea-level change are actually in agreement and both record similar times when modern rates of sea-level rise were first attained.

2. Instrumental records of sea-level change

The history of systematic sea-level observations is over three centuries long, starting in Amsterdam in 1682. What we now call automatic (or 'self-registering') tide gauges that could record the full tidal curve were developed in the 1830s, with the first often credited to Palmer (1831). These instruments took the form of a stilling well inside which was a float that was connected by a wire run over pulleys to a pen that moved up and down as the tide rose and fell, thereby drawing a tidal curve on a rotating drum of paper. The resulting continuous water-level measurements could then be expressed relative to the height of a benchmark on the nearby land.

By the end of the 19th century similar instruments had been installed at most major ports and, although sea-level measurements are often made nowadays by acoustic, pressure or radar techniques (IOC, 2006), it is important to recognise that the majority of the historical information in the archives of the Permanent Service for Mean Sea Level (PSMSL, Woodworth and Player, 2003, www.psmsl.