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Twentieth century sea-level rise inferred from tide gauge, geologically derived and thermosteric sea-level changes

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ABSTRACT

Relative sea-level (RSL) changes at thirteen sites derived from tide gauge and/or salt-marsh sediment sequences, with information for RSL changes during at least the past ~200 years, are used to infer the rates and causes of the global sea-level rise in the twentieth century (pre-satellite era) by incorporating spatially non-uniform thermosteric sea-level change and recent estimates for the melting of mountain glaciers and both polar ice sheets. The main advantage of the method adopted here is that we can avoid a model-dependence in the GIA (glacial isostatic adjustment) correction and any steady tectonic effect depending on each location can be corrected for. We first estimate the acceleration of sea-level rise in the twentieth century at each RSL observation site, and then evaluate the residuals between the sea-level acceleration and thermosteric sea-level rise. The spatially non-uniform residuals are examined to infer the rates of RSL rise due to the melting of mountain glaciers and polar ice sheets. The comparison between the residuals and the predicted rates for the melting wholly supports the estimates for the melting by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007 Report), and does not require a significant melting from the Greenland ice sheet. However, the possible equivalent sea-level rise for mountain glaciers and/or Antarctic ice sheet may be ~0.3 mm yr^{-1} larger than the preferred estimate by IPCC 2007 Report (~0.7 mm yr^{-1}), and the total one is ~1.0 mm yr^{-1}. The additional melting for ~0.3 mm yr^{-1} is due to the comparison mainly for Brest with long tide gauge records of ~200 years. Also, the present study indicates that the global mean thermosteric sea-level rise before the rapid sea-level acceleration occurred at 1990 is ~0.3 mm yr^{-1}.

1. Introduction

Many recent studies have indicated a rapid acceleration of sea-level rise after 1990 based on analyses using satellite data and subsurface temperature of the ocean (e.g., Cazenave and Nerem, 2004; Bindoff et al., 2007). The rapid acceleration, which is a crucial problem for human society in the near future, is mainly attributed to thermal expansion of the oceans (thermosteric sea-level rise) (e.g., Levitus et al., 2005) and melting of the Greenland and Antarctic ice sheets (e.g., Rignot et al., 2008a, 2008b) and mountain glaciers (e.g., Lemke et al., 2007; Ohmura, 2011), and the quantitative estimates for each contribution appear to be consistent among the studies. On the other hand, rates and causes of the sea-level rise before the rapid acceleration (in the pre-satellite era), referred to as 20th century sea-level rise here, remain controversial (e.g., Bindoff et al., 2007; Lemke et al., 2007). The main purpose of the present study is to examine the rates and causes of 20th century sea-level rise (before 1990), which would be important in discussing the recent rapid acceleration and also the future sea-level rise.

Relative sea-level (RSL) change at an arbitrary time, t, in the 20th century is spatially non-uniform, and its observation at position (θ, ϕ), colatitude θ and E-longitude ϕ, is denoted by $\zeta_{\mathrm{OB}}(\theta,\phi,t)$ here. Changes in RSL are caused by tectonic movements, $\zeta_{\mathrm{TEC}}(\theta,\phi,t)$, glacial isostatic adjustment due to the last deglaciation (GIA) (Peltier and Andrews, 1976), $\zeta_{\mathrm{GIA}}(\theta,\phi,t)$, thermosteric sea-level change, $\zeta_{\mathrm{TSL}}(\theta,\phi,t)$, and the melting of mountain glaciers and polar ice sheets, $\zeta_{\mathrm{MT}}(\theta,\phi,t)$. Also, other factors associated with positive anthropogenic terms such as groundwater mining have been indicated (e.g., Bindoff et al., 2007; Church et al., 2011), and the contributions from such and/or unknown factors are denoted by

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$\zeta_{\mathrm{OTH}}(\theta,\phi,t)$ here. These are, of course, spatially non-uniform. Then, observed RSL change, $\zeta_{\mathrm{OB}}(\theta,\phi,t)$, is given by:

$$\begin{aligned}\zeta_{\mathrm{OB}}(\theta,\phi,t) \;=\; & \zeta_{\mathrm{TEC}}(\theta,\phi,t)+\zeta_{\mathrm{GIA}}(\theta,\phi,t)+\zeta_{\mathrm{TSL}}(\theta,\phi,t)\\ & +\zeta_{\mathrm{MT}}(\theta,\phi,t)+\zeta_{\mathrm{OTH}}(\theta,\phi,t)\end{aligned} \tag{1}$$

Here we define a global sea-level rise (GSLR) in the 20th century as a volume change of seawater divided by the area of the ocean, which is related to the sum of $\zeta_{\mathrm{TSL}}(\theta,\phi,t)$, $\zeta_{\mathrm{MT}}(\theta,\phi,t)$ and $\zeta_{\mathrm{OTH}}(\theta,\phi,t)$.

Church et al. (2001), in the Third Assessment Report of the Intergovernmental Panel on Climate Change, reviewed published rates of GSLR inferred from tide gauge records by the Permanent Service for Mean Sea Level (PSMSL) (Spencer and Woodworth, 1993), and adopted as a best estimate a value of 1–2 mm yr^{-1}. The original estimates for the best estimate, in which the magnitude of tectonic movement has not been discussed quantitatively and has generally been assumed to be negligibly small compared with that for observed sea-level change, are corrected for GIA using models. The GIA correction is sensitive to both the rheological structure of the Earth and ice models describing the Late Pleistocene and Holocene melting histories of both polar ice sheets (e.g., Nakada and Lambeck, 1987). More recently, Spada and Galassi (2012) carefully selected a set of tide gauge stations (22 sites) for which GIA corrections are essentially independent of the rheological and ice models, and indicated the rate of GSLR to be 1.5 ± 0.1 mm yr^{-1}. However, their approach cannot evaluate the influence of tectonic movement for the estimate.

We consider a simple case in the relation given by Eq. (1): the magnitude of tectonic component is negligibly small ($\zeta_{\mathrm{TEC}}(\theta,\phi,t)\sim 0$), the contributions to GSLR from $\zeta_{\mathrm{TSL}}(\theta,\phi,t)$ and $\zeta_{\mathrm{OTH}}(\theta,\phi,t)$ are spatially uniform and RSL changes due to the GIA are correct (these assumptions are not adopted in the present study). Then, the residuals between $\zeta_{\mathrm{OB}}(\theta,\phi,t)$ and $\zeta_{\mathrm{GIA}}(\theta,\phi,t)$ may be used to infer the contributions to GSLR from the melting of the Antarctic and Greenland ice sheets and mountain glaciers, referred to as geographic sea-level fingerprints by Mitrovica et al. (2001) (see also questions for sea-level fingerprints by Douglas (2008)). Consequently, Mitrovica et al. (2001) inferred a melting of the Greenland ice complex with an equivalent sea-level rise (ESLR) of ~0.6 mm yr^{-1}, which is defined as a volume change of meltwater volume from the ice sheets and mountain glaciers divided by the surface of the ocean. However, such a significant melting for the pre-satellite era is inconsistent with the recent estimates for the Greenland ice sheet (e.g., Lemke et al., 2007; Rignot et al., 2008a).

On the other hand, Nakada and Inoue (2005) examined the GSLR from long tide gauge records at 7 sites with information for RSL changes during the past 140–200 years. We briefly explain their simple method without requiring the GIA correction. The relation of Eq. (1) before the onset of 20th century sea-level rise is given by:

$$\zeta_{\mathrm{OB}}(\theta,\phi,t) \;=\; \zeta_{\mathrm{TEC}}(\theta,\phi,t)+\zeta_{\mathrm{GIA}}(\theta,\phi,t) \tag{2}$$

The rates of RSL changes during the past ~200 years for the GIA are nearly time-independent (constant) for all sites. Nakada and Inoue (2005) assumed that the tectonic movement during at least the past ~200 years is steady. Of course, they involved that the steady rate (the secular trend of $\zeta_{\mathrm{TEC}}(\theta,\phi,t)$) is spatially non-uniform and depends on each location. This assumption would be reasonable except for, for example, tectonically very active regions in the Japanese Islands. The rate for the RSL rise before the onset time of 20th century sea-level rise (Eq. (2)) is denoted by $v_{19}(\theta,\phi)$ ($\partial\zeta_{\mathrm{OB}}(\theta,\phi,t)/\partial t$) here.

We next explain the secular trend of RSL change in the 20th century, $v_{20}(\theta,\phi)$, which naturally includes the rate for $v_{19}(\theta,\phi)$ (see Eq. (2)) given by:

$$v_{19}(\theta,\phi) \;=\; v_{\mathrm{TEC}}(\theta,\phi)+v_{\mathrm{GIA}}(\theta,\phi) \tag{3}$$

The terms of $v_{\mathrm{TEC}}(\theta,\phi)$ and $v_{\mathrm{GIA}}(\theta,\phi)$ correspond to the rates for $\zeta_{\mathrm{TEC}}(\theta,\phi,t)$ and $\zeta_{\mathrm{GIA}}(\theta,\phi,t)$, respectively. We can safely accept that RSL changes due to the recent melting are dominantly attributed to the

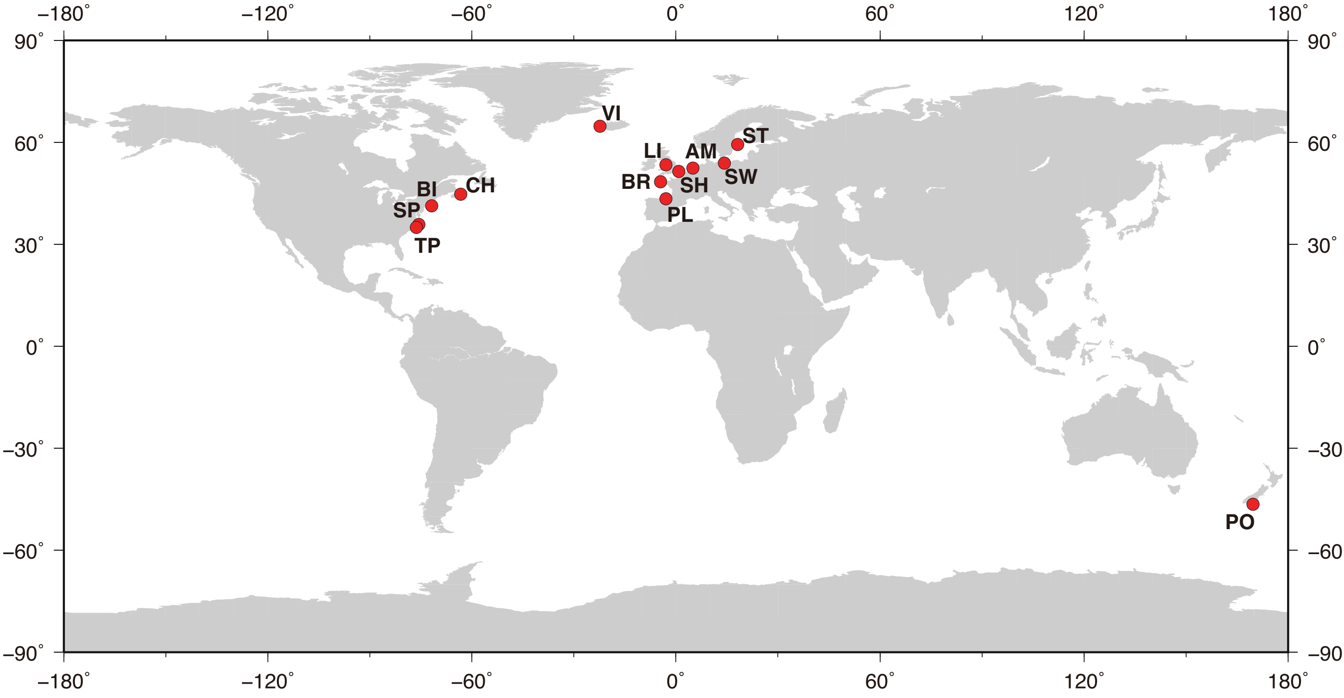

Fig. 1. Map showing sites used in this study: (1) Stockholm (ST), (2) Swinoujscie (SW), (3) Amsterdam (AM), (4) Brest (BR), (5) Plentzia estuary (PL), (6) Liverpool (LI), (7) Sheerness (SH), (8) Viòarhólmi (VI), (9) Chezzetcook (CH), (10) Barn Island (BI), (11) Sand Point (SP), (12) Tump Point (TP), (13) Pounawea (PO). Site number (1–13) and abbreviation name for each site are used in Figs. 6, 8, 10 and 11.