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Invited research article

A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios

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ABSTRACT

Sea-level change is an integrated climate system response due to changes in radiative forcing, anthropogenic land-water use and land-motion. Projecting sea-level at a global and regional scale requires a subset of projections - one for each sea-level component given a particular climate-change scenario. We construct relative sea-level projections through the 21st century for RCP 4.5, RCP 8.5 and High-end (RCP 8.5 with increased ice-sheet contribution) scenarios by aggregating spatial projections of individual sea-level components in a probabilistic manner. Most of the global oceans adhere to the projected global average sea level change within 5 cm throughout the century for all scenarios; however coastal regions experience localised effects due to the non-uniform spatial patterns of individual components. This can result in local projections that are 10′s of centimetres different from the global average by 2100. Early in the century, RSL projections are consistent across all scenarios, however from the middle of the century the patterns of RSL for RCP scenarios deviate from the High-end where the contribution from Antarctica dominates. Similarly, the uncertainty in projected sea-level is dominated by an uncertain Antarctic fate. We also explore the effect upon projections of, treating CMIP5 model ensembles as normally distributed when they might not be, correcting CMIP5 model output for internal variability using different polynomials and using different unloading patterns of ice for the Greenland and Antarctic ice sheets.

1. Introduction

Sea-level rise will affect low lying coastal settlements and ecosystems by means of gradual encroachment and short term flooding due to storms (e.g. Rowley et al., 2007; Hallegatte et al., 2013; Kopp et al., 2014). Whilst global mean sea-level (GMSL) change can be approximated by the sum of ocean expansion (steric), land-ice (Glaciers, Greenland and Antarctica) and land-hydrology components, relative sea-level (RSL) change is more complex due to the spatial variability of, local ocean processes, mass-based sea-level components and vertical land-motion (tectonic and environmental).

While published RSL projections are an aggregate of projected sea-level components, differences lie in the methods used to estimate the individual components. Spada et al. (2013) used one (General Circulation Model) GCM to output ocean processes (steric and dynamic sea level) whilst using temperature and precipitation to estimate land-ice contributions to sea level via regional climate models. Perrette et al. (2013) derived scaling relationships between individual sea-level components and global temperature to create scenario independent patterns, which could be multiplied by scenario specific global temperature projections. Slangen et al. (2014a), Kopp et al. (2014) and Grinsted et al. (2015) calculated ocean processes by averaging over multi-model ensembles of thermo-steric sea-level and dynamic sea-level from Coupled Model Inter-comparison Project Phase 5 (CMIP5, Taylor et al., 2012). Added to these ocean processes, Slangen et al. (2014a) estimated mass-changes in land-ice from model-based projections of temperature and precipitation, while Kopp et al. (2014) and Grinsted et al. (2015) multiplied the GMSL projection of land-ice sea-level components by their associated normalised spatial pattern (fingerprint) of sea-level. Land-hydrology may be treated as a global average (e.g. Kopp et al., 2014) or spatially variable term (e.g. Slangen et al., 2014a; Grinsted et al., 2015) whilst vertical land-movement is either omitted (e.g. Spada et al., 2013; Perrette et al., 2013), conservatively estimated using a glacial isostatic adjustment (GIA) model (e.g. Slangen et al., 2014a; Grinsted et al., 2015) or locally refined (e.g. Kopp et al., 2014).

A feature of Kopp et al. (2014) and Grinsted et al. (2015) was their approach to uncertainty in which they accounted for the probability of a given sea-level by sampling the probability distribution function (either Gaussian or skewed) for each component at each time. In this paper, we present RSL projections using a similar approach to Grinsted et al. (2015) and Kopp et al. (2014). We use a greater range of model outputs from CMIP5 to explore the effect of data preparation upon projected ocean processes. We show how probability density

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functions (PDFs) of individual component's GMSL projections are derived and how these are used in combination with fingerprints for each sea-level component to construct RSL projections. We then present the resulting projections through time for three scenarios, Representative Concentration Pathway (RCP) 4.5, 8.5 (Moss et al., 2010) and High-end (RCP 8.5 with high-magnitude, low-probability ice-sheet contribution) with their associated uncertainties. Next we discuss the differences between our projections and others recently published, in particular differences in uncertainty. Finally we consider the effect upon regionally projected uncertainty using alternative spatial fields for certain sea-level components.

2. Data and methods

The method used to approximate RSL is the same as that for GMSL with the incorporation of spatial variability in sea-level associated with each component. The summation we use is the same as Grinsted et al. (2015) where the time dependent global average projection for each component (e.g. Glaciers: $GLA(t)$) is multiplied by its associated fingerprint (e.g. $F_{GLA}(\theta,\phi)$) and then aggregated to give,

$$\begin{aligned} RSL(\theta,\phi,t) = {} & F_{SAL}(\theta,\phi)\cdot[STR(t)+DSL(\theta,\phi,t)] + F_{GLA}(\theta,\phi)\cdot GLA(t) \\ & + F_{GRE}(\theta,\phi)\cdot GRE(t) + F_{ANT}(\theta.\phi)\cdot ANT(t) \\ & + F_{LW}(\theta,\phi)\cdot LAN(t) + GIA(\theta,\phi)\cdot t + TECT(\theta,\phi,t) \\ & + NCLIM(\theta,\phi,t). \end{aligned} \tag{1}$$

The contributions in (1) are, the impact of self-attraction and loading (SAL) of the ocean upon itself due to the long term alteration of ocean density changes, globally averaged steric sea-level rise (STR), dynamic sea-level change (DSL), glaciers and ice-caps (GLA), Greenland ice sheet (GRE), Antarctic ice sheet (ANT), land-water storage (LAN), Glacial Isostatic Adjustment (GIA), tectonics (TECT) and non-climatic land-motion (NCLIM). The last two terms (TECT and NCLIM) represent the local effect of non-GIA and environmentally induced land motion respectively. Since these terms are difficult to quantify as global fields at present and even more difficult to forecast through the century, we omit them from our projection. The fingerprints in (1) represent the ocean surface response to the mass redistribution of a given component. For example, land-based ice masses (GLA, GRE, ANT) gravitationally attract the oceans surrounding them whilst changes in these masses alter the elastic solid earth instantaneously thus perturbing Earth's rotation (Milne and Mitrovica, 1998a). The interaction of these mechanisms results in a unique equipotential (ocean) surface for each component. The sea-level fingerprints described here have been calculated by solving the sea-level equation (Farrell and Clark, 1976), following a pseudo-spectral approach (Mitrovica and Peltier, 1991), and including changes in the Earth's rotation (Milne and Mitrovica, 1998a) and the effects of migrating coastlines (Milne and Mitrovica, 1998b). The elastic response of the solid Earth has been computed for a radially stratified and compressible Earth based on the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981). All of the sea-level fingerprints described below were computed and supplied by R. Riva (TU Delft), with the exception of GIA.

2.1. Global mean sea-level components

Each GMSL component has a time dependent median projection with uncertainty bounds defined for each scenario.

In the case of RCP 4.5 and RCP 8.5 scenarios GMSL components GLA, GRE, ANT and LAN are taken from IPCC AR5 (Church et al., 2013). We calculate STR directly using outputs from CMIP5 (Section 2.3). Each component is defined by a median and 'likely' range (17th to 83rd percentiles) sampled yearly throughout the 21st century relative to the average of 1986–2005 (Fig. S1).

The High-end scenario uses the total GMSL projection of Jevrejeva et al. (2014) at 2100 relative to 2000. Jevrejeva et al. (2014) calculated total GMSL by using projections of STR, GLA and LAN for RCP 8.5 from IPCC AR5 (Church et al., 2013) and projections of GRE and ANT from the expert elicitation of Bamber and Aspinall (2013), which have large uncertainties in their right-hand tails. Whilst the High-end scenario's median GMSL rise (0.80 m) is close to IPCC AR5 RCP 8.5 (0.74 m, Church et al., 2013), the 95th percentile (5% probability) GMSL is 1.80 m compared to 1.21 m. We extrapolate the GMSL High-end projection for each component at median, 5th and 95th percentiles (Fig. S1) using standard linear least-squares across the 21st century by assuming that the acceleration of sea-level rise is constant through the century and that the present-day rate is defined by Church et al. (2013).

2.2. Sea-level fingerprint components

The provenance of each sea-level fingerprint is as follows. F_{GLA}, F_{GRE} and F_{ANT} are from Bamber and Riva (2010), who calculated them from estimates of mass-change in each land-ice component derived from satellite gravimetry and synthetic radar aperture interferometry for the period 2000–2008. In the resulting fingerprints (Fig. S2a–c) F_{GRE} shows a RSL fall along the Atlantic coastlines of Europe and Canada and a far-field rise around South America (e.g. Mitrovica et al., 2011). F_{ANT} shows a RSL fall close to the West Antarctic ice sheet and southern tip of South America and a RSL rise everywhere else. F_{GLA} shows a small contribution to RSL in the far-field whilst a local RSL fall occurs close to glacier sources.

F_{LAN} (Fig. S2d) is calculated using projected changes in land water storage from Wada et al. (2012) who used a flux-based method to estimate the difference between groundwater extraction and recharge for various climate scenarios with transient climate forcing from three General Circulation Models (ECHAM, HadGEM1, HadGEM2).

F_{SAL} (Fig. S2e) is calculated to account for the redistribution of ocean mass from the deep ocean interior to shallow coastal regions as a result of volumetric expansion (Landerer et al., 2007). Mass-changes were estimated using projected ocean bottom pressure change from NorESM1-M and normalised (Richter et al., 2013). The fingerprint is then used to scale the local change in the sum of STR and DSL, which is an approximation that only holds if the mass redistribution used to calculate F_{SAL} is from the same emission scenario (Grinsted et al., 2015).

A critical assumption to using Eq. 1 to make RSL projections is that each fingerprint is time invariant. That is to say the spatial pattern of mass change for each component remains the same through time. This is pertinent for glaciers and ice sheets given their possible large contribution to future sea-level rise.

For glaciers, the assumption infers that the ratio of melt from one glaciated region to another will remain constant over the century. We validated this assumption by studying projected sea-level contributions from 19 glacial regions for RCP 4.5 and RCP 8.5 (Marzeion et al., 2012). We calculated the ratio of regional to global glacier contribution through time and found that ratios of 12 (RCP 4.5) and 11 (RCP 8.5) glacial regions varied by less than $\pm 1\%$ during the 21st century (Fig. S3). The ratios of other regions increase by up to 5% (e.g. Alaska). We considered the uncertainty of contributions for each glacial region (Marzeion et al., 2012) and found that those regions whose ratio exceeded $\pm 1\%$ variability had uncertainty ranges overlapping this threshold (Fig. S3). These small percentage changes allow us to assume a fixed ratio of melt and thus a single global glacial fingerprint. Some of the uncertainty postulated by this analysis is implicit in the ranges for the GLA GMSL components, which incorporated results from Marzeion et al. (2012) (Church et al., 2013).

In the case of ice-sheet variability, we consider that the pattern of future ice-mass loss will lie between present-day and uniform end-members for different scenarios (DeConto and Pollard, 2016). Tamisiea et al. (2010) showed differences in fingerprints due to these end-member states for a mass loss equivalent of 1 mm year^{-1} GMSL rise. Extrapolating RSL rates for a 100 year period shows uncertainties might be up to