



Sources of 21st century regional sea level rise

T. Howard et al.

This discussion paper is/has been under review for the journal Ocean Science (OS).
Please refer to the corresponding final paper in OS if available.

Sources of 21st century regional sea level rise along the coast of North-West Europe

T. Howard¹, A. K. Pardaens¹, J. A. Lowe¹, J. Ridley¹, R. T. W. L. Hurkmans²,
J. L. Bamber², G. Spada³, and D. Vaughan⁴

¹Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK

²Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK

³Dipartimento di Scienze di Base e Fondamenti, Urbino University “Carlo Bo”, Via Santa Chiara, 27, 61029 Urbino (PU) Italy

⁴British Antarctic Survey, Madingley Road, High Cross, Cambridge, Cambridgeshire, CB3 0ET, UK

Received: 29 November 2013 – Accepted: 3 December 2013 – Published: 17 December 2013

Correspondence to: T. Howard (tom.howard@metoffice.gov.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Changes in both global and regional mean sea level, and changes in the magnitude of extreme flood heights, are the result of a combination of several distinct contributions most, but not all, of which are associated with climate change. These contributions include effects in the solid earth, gravity field, changes in ocean mass due to ice-loss from ice sheets and glaciers, thermal expansion, alterations in ocean circulation driven by climate change and changing freshwater fluxes, and the intensity of surge tides. Due to the diverse range of models required to simulate these systems, the contributions to sea-level change have usually been discussed in isolation rather than as a fully-coupled system. Focusing on the coastline of Northwest Europe, we consider all these processes and their relative impact on 21st century regional mean sea levels and extreme flood height. As far as possible our projections of change are derived from process-based models forced by the A1B emissions scenario to provide a self-consistent comparison of the contributions. We address uncertainty by considering both a mid-range and an illustrative high-end combination of the different components.

For our mid-range ice-loss scenario we find that thermal expansion of seawater is the dominant contributor to change in sea level by 2100. However, the projected contribution to extreme sea level, due to changes in storminess alone, is significant and in places is comparable to the global mean contribution of thermal expansion. For example, under the A1B emissions scenario, by 2100, change in storminess contributes around 15 cm to the increase in projected height of the 50 yr storm surge on the west coast of the Jutland Peninsula, compared with a contribution of around 22 cm due to thermal expansion. An illustrative combination of our high-end projections suggests increases in the 50 yr return level of 86 cm at Sheerness, 95 cm at Roscoff, 106 cm at Esbjerg, and 67 cm at Bergen. The notable regional differences between these locations arise from differences in rate of vertical land movement and changes in storminess.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

In recent years, several scientific communities have put considerable effort into establishing projections of the various individual contributions to global mean sea level rise. These include: projections of thermal expansion of the oceans (e.g. Kuhlbrodt and Gregory, 2012); ice-loss from Antarctica (e.g. Vizcaíno et al., 2010), Greenland (e.g. Goelzer et al., 2013) and mountain glaciers (e.g. Giesen and Oerlemans, 2013); and from changes in the terrestrial storage of water as ground water and in reservoirs (e.g. Lempérière, 2006).

At intervals, these efforts have been usefully consolidated into “consensus” projections of global mean sea-level rise by the Intergovernmental Panel on Climate Change (IPCC; e.g., Church et al., 2013), which have guided the global debate on options for adaptation to, and mitigation of, the impacts of climate change. Rather less effort has gone into understanding the more complex processes that modify global mean sea level to give regional sea-level changes, which include vertical land movements, changes in the Earth’s gravity field, regional variations in thermal expansion, and changes in ocean circulation driven by climate change and changing freshwater fluxes. Very few studies indeed have attempted to produce projections of changes in extreme sea-level (i.e. that experienced during occasional damaging storm events), although it is well-known that the most acute impacts of sea level change on coastal communities, assets and environments can be best understood through changes in the severity and/or frequency of such extreme events (Lowe and Gregory, 2005). On a global scale these changes are dominated by changes in mean sea level (e.g. Woodworth and Blackman, 2004), but on a local scale changes in atmospheric circulation, and the consequent impact on the generation of storm surges, may also be significant.

A valuable metric in understanding these impacts is the change in height of the highest sea-level experienced during a storm over a particular return period. For example, a change in the height of the most extreme storm expected once in every 50 yr period,

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the so-called 50 yr storm, gives a good indication of the increase in flood-risk for a particular portion of coastline.

One key study (Katsman et al., 2011), examined this issue for the Netherlands coastline, and further included the potential that river discharge will exacerbate problems in coastal flood-defence. However, that study used rather diverse sources for the contributions to sea-level and storminess. Some contributions were based on process-based models tied to specific emissions scenarios, but others, specifically the contributions from ice-loss, were based on arguments about what might be plausible. In addition, that study focused on the Dutch coastline, without a consideration of how the various contributions varied across a wider geographical area. The analysis was extended to examine global variations in sea level (Slangen et al., 2012) but excluding a number of the processes mentioned above. In particular, they did not incorporate freshwater forcing, storm surge changes, or process-based model estimates of ice sheet contributions.

Other European studies, based on limited spatial areas, found that the high natural variability in sea level makes detection of trends in the extremes problematic. Haigh et al. (2010), for example, considered data from eighteen sites around the English Channel and found changes in extreme water level similar to rates of observed mean sea level change. Araújo and Pugh (2008) reached a similar conclusion for Newlyn in the UK, based on data from 1915–2005. For a recent review of past changes in factors contributing to extreme sea levels in the North Sea, see Weisse et al. (2012).

In this study, we use projections of regional sea-level change arising from 21st century ice-loss from ice sheets and glaciers (Spada et al., 2013; Howard et al., 2013), including the effects of changes to the gravity field, Earth rotation and shoreline migration. We also include improved modelling of the climate of storm surges produced in support of the UK Climate Projections, Marine and Coastal Projections 2009 (UKCP09; Lowe et al., 2009): a project to investigate the projected major contributions to 21st century change in coastal flood risk and shelf-seas hydrology around the coast of the UK. This project included both a (primarily process-based) ensemble projection of sea level

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



change and a proxy-based assessment of plausible upper limits (the so-called “H++” scenario). Their ensemble analysis gave projections of UK coastal absolute sea-level rise of 13 to 60 cm over the 21st century (5th to 95th percentile, not including vertical land movement or changes in the climate of storm surges) under the A1B emissions scenario. The corresponding figure from the upper end of their H++ scenario range was 190 cm. Here we extend the UKCP09 approach to include more of the NW European coast, and we augment the UKCP09 results with new process-based ice-melt projections.

In addition to the sources of sea level variability listed above, we include projected contributions from thermal expansion, changes in dynamic sea level associated with the freshwater flux from ice melt, changes in dynamic sea level associated with projected global warming under the A1B emissions scenario, and projected changes in relative sea level due to vertical land movements arising from ice-loss since the Last Glacial Maximum, termed glacial isostatic adjustment (GIA). We do not, however, include the contributions to extreme sea level change arising from changes in terrestrial water storage, nor changes in the climate of waves and swell.

Our aim is to provide a comparison of geographic variations and uncertainties in the different contributions to sea level. To do this we consider two scenarios for 21st century change. The first, which we describe as a “mid-range projection”, is taken from close to the middle of the uncertainty range for each process considered. The second, which we describe as a “high-end projection”, is taken from the upper end of the distribution. For contributions TE, ADSL and SRG (see Table 1 for abbreviations), these two scenarios represent the 50th and 95th percentiles respectively of an ensemble of projections to which we fitted a normal distribution. For the other contributions, we do not have access to a substantial ensemble of projections, and so we cannot specify percentiles. For these, the mid-range projection gives a best-estimate, and the high-end projection gives a measure of the upper range of possible outcomes, based on a combination of our expert judgement and analysis of process-based models. The one exception to this is the contribution from GIA, for which we present only a single modelled estimate.

Sources of 21st century regional sea level rise

T. Howard et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

2 Nomenclature

We use the abbreviations MR and HE to refer to mid-range and high-end model projections throughout. “MME” (Multi-Model Ensemble) refers to the ensemble based on some, or all, of the models that contributed data to the Climate Model Intercomparison Project Phase 3 or Phase 5 (henceforth CMIP3, CMIP5 respectively). “PPE” refers to the Perturbed Physics Ensemble of HadCM3 variants as described by Murphy et al. (2007).

In order to be unambiguous and concise regarding each of the contributions to 21st century sea-level change considered in this study, they are tabulated (Table 1) together with the abbreviations used for each.

Whilst discussing the impacts on the north-west European coast we consider the components listed above evaluated within geographical masks formed by the ocean model grid boxes nearest to the coast. Again to avoid ambiguity we tabulate (Table 2) abbreviations which we use for each component as it is evaluated on a particular coast mask.

3 Models and Methods

3.1 Contribution from TE and ADSL

For the contributions TE and ADSL, we used 11 model projections from the CMIP3 project (see, http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). This project produced model data that was used in the IPCC Fourth Assessment Report (Meehl et al., 2007; henceforth AR4). A common land mask was applied to each of the model (TE + ADSL) projections and a NW European coastally-averaged (TE + Mn_ADSL) then calculated for each model (masked region shown in Fig. 2; values very similar using masked region of half this width), where Mn_ADSL is ADSL averaged over the masked region. We also used TE data for each of the 11 models to partition the sum (TE + Mn_ADSL)

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



into its components TE and Mn_ADSL, each of which is shown in Fig. 4. This also enabled us to check our distribution of 11 TE values against the two percentiles reported in AR4.

3.2 Contribution from TIM and GCFF

5 We derived projections of two contributions, TIM and GCFF, from two time-series (named MR and HE) used in Spada et al. (2013). We partitioned each into a global mean (TIM¹) and spatially-varying component (GCFF). We selected data for the 2080–2099 period, calculating changes with respect to 1992. This model output was provided on a grid (described by Spada and Stocchi, 2007) with lower resolution than our surge
10 model grid (shown, for example, in Fig. 3). However, this lower-resolution grid does not overlap all the specific coastal sites chosen for this study, and so for each of these sites, we interpolated the low-resolution grid using values from grid-points to the east and west (for example around the British Isles). For grid points on the high-resolution grid with no low-resolution point to the east, we used the value for the nearest low-
15 resolution value to the west. This is justified by the fact that, in this region, there is only a small east-west gradient, compared to the dominant north-south gradient in the GCFF component.

3.3 Contribution from SRG

20 There is good evidence (e.g. Howard et al., 2010; Sterl et al., 2009) that changes in storm surge contribution to sea level can be added linearly to mean sea level change and so, following Lowe et al. (2009), that is the approach we took in this study.

Our approach for deriving projections of the contribution of changes in storm surge to extreme sea-level also follows that of Lowe et al. (2009). We used an ensemble of regional atmospheric climate models (RCMs) to downscale an ensemble of global

¹This is the global mean contribution due to a change in mass of the oceans, sometimes referred to as the eustatic contribution but more correctly termed the barystatic contribution.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



projections produced for the SRES A1B emissions scenario. This ensemble was generated by versions of the HadCM3 model with perturbed physical parameters, and was designed to encompass uncertainty. The surface wind and atmospheric pressure fields output by the RCMs were used to drive a barotropic surge model, CS3 (Flather et al., 1998). The domains of CS3 and the RCM are shown in Fig. 1. CS3 has been extensively validated for the present-day climate (see for example, Lowe et al., 2009).

As in Lowe et al. (2009), we present projections of the “skew surge”, which is a good measure of the impact of a surge. It is defined as the difference between the height of the highest water level predicted by the model and the nearest-in-time astronomical high-tide at the same point. A statistical generalised extreme-value model (Coles, 2001), with linear time-trend in the location and scale parameter, was fitted to the five largest independent skew surges in each year. From this, we diagnosed a maximum likelihood estimator of the trend in the fifty-year return level. Thus our approach allows for the possibility of a linear time-trend in the extremes (forced by the changing atmospheric storminess). The magnitude of this trend compared with the corresponding uncertainty gives a measure of the statistical significance.

Again, following the approach taken by Lowe et al. (2009), we treated the ensemble member projections as alternative, but equally-valid, realisations of a naturally variable future skew surge storm-climate. Under this assumption, it is reasonable to take the mean trend in the ensemble as a representative central projection, and the standard deviation of the ensemble as a measure of spread. Assuming that the 11 trends in the extremes are normally distributed, we could then estimate the 95th percentile of the trend, independently at each location. This assumption is reasonable, even though we do not expect the *extremes themselves* to be normally distributed. We acknowledge that the approach is limited by the fact that we disregard the spatial dependence in the trends, but argue that it is still reasonable because we make no claims about the joint probability of the spatial patterns.

4 Results

4.1 Contribution from TE and ADSL

Patterns of combined TE + ADSL for 11 members of the CMIP3 multi-member ensemble (MME) are shown in Fig. 2, along with the coast mask used to evaluate the local spatial mean. The projections of TE reported in AR4 for 2100, were 13 cm (5th percentile) and 32 cm (95th percentile), giving a mean of 22.5 ± 5.8 cm, where the uncertainty is expressed as a standard deviation assuming a normal distribution. The corresponding value from our 11-member ensemble is 21.4 ± 5.5 cm. For this contribution, the agreement is very good, and so it makes little difference whether we adjust our estimates to take account of the range quoted in AR4 or not; however, we have made this adjustment in order to take advantage of the additional information used in AR4 (the range quoted in AR4 comes from more than 11 models). This ensured that our approach, applied to the NW European coastline, was consistent with the methodology used previously (Lowe et al., 2009). The adjustment consists of replacing the 11-member mean and variance of TE (21.4 cm and 30.25 cm²) with the corresponding values from AR4 (22.5 cm and 33.64 cm²). We also made a consistent adjustment to the mean and variance of the sum (TE + Mn_ADSL), whilst preserving the covariance as given by the 11 ensemble members.

A direct comparison with CMIP5 results is not possible due to the different approach to emissions in AR5 compared to AR4, however we note that both mean and the spread of (TE + Mn_ADSL) are comparable to the values for the NW European region given in AR5 under RCP4.5 (Church et al., 2013; their Fig. 13.16).

4.2 Contribution from TIM and GCFE

Patterns of these contributions are not shown here because they are similar to those presented previously (Spada et al., 2013). The TIM contributions are 20 cm (mid-range) and 50 cm (high-end).

OSD

10, 2433–2459, 2013

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.3 Contribution from SRG

The projected component of extreme water level changes due only to changes in storm surge climate is shown in Fig. 3. We note that the pattern is broadly consistent with the expected increase in the frequency and/or intensity of westerly or south-westerly winds.

5 This is addressed further in the discussion section below.

5 Comparison and addition of contributions

The distribution of values, shown in Fig. 4, allows us to explore the relative significance of the various contributions to 21st century extreme sea level change around NW Europe.

10 The contributions shown in Fig. 4 come from very different types of model and in general their error covariances are not known (the exception is TE and Mn_ADSSL, see below). Furthermore the HE TIM member is selected as an illustrative high-end realisation with an unquantified probability of exceedance. Nevertheless, previous studies (e.g. Sterl et al., 2009; Howard et al., 2010) have shown that it is reasonable to combine

15 surge changes additively with mean sea level change. Similarly Howard et al. (2013) show that for their model IDSL and ADSL changes appear to be additive. Therefore we present an illustrative addition of HE contributions to the change in the height of the 50 yr storm, for seven locations around NW Europe in Fig. 5. The locations are Aberdeen, Sheerness, Cork Harbour, Roscoff, 's-Gravenhage (Den Haag), Esbjerg and Bergen. Again the abbreviations used for the contributions are those of tables 1 and 2.

20 Note that the HE contribution from (TE + Mn_ADSSL) is *not* simply the sum of the HE TE and HE Mn_ADSSL contributions shown in Fig. 4 because in the case of these two contributions only we *do* know about their covariance and we can select a representative HE value from the distribution of their sum.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



6 Discussion

Under our mid-range projection we found that TE and TIM are the largest contributors to 21st century extreme sea level change around NW Europe (Figs. 4 and 5). However, the largest uncertainties arise from TIM, and TIM made the largest contribution to the HE projection. Although the uncertainty was also large in Mn_ADSL, we found both contribution and uncertainty to be very small for Mn_IDSL (MR: 1.4 cm; HE: 3 cm). The SRG contribution is important in some locations, though within the limitations of our SRG modelling approach, it appeared to be relatively well-constrained (see Sect. 6.1). Spatial variations due to SRG and GIA are both considerable.

Nicholls et al. (2011) tabulate estimates for century-scale rates of global mean sea-level rise from a range of methods including semi-empirical models. We have not quoted projections from such models here, but rather we note the IPCC AR5 (Church et al., 2013) view that there is low agreement in semi-empirical model projections and no consensus in the scientific community about their reliability. In Table 3 we compare high-end projections from our study with two other studies addressing sea level change around the coast of NW Europe. In order to make a like-for-like comparison we exclude contributions from SRG and GIA in Table 3 because these contributions were not addressed by one of the studies.

Lowe et al. (2009) provide a mostly-process-based projection² of sea-level rise for the coast of the UK (with which our TE, GIA, ADSL and SRG contributions are all consistent). However Lowe et al. (2009) also offer a proxy-based projection for vulnerability testing, their so-called “H++” scenario range. It is informative to compare this scenario with our results (Table 3), although the H++ range was intended to look at plausible upper limits based on proxy data and it should be borne in mind that recent observations and model projections do not provide any evidence to suggest that such high levels of sea level rise will occur within the 21st century. Church et al. (2013), acknowledging that the potential additional contribution to global mean sea-level rise from the

²their projection of ice sheet behaviour was not process-based

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

collapse of marine-based sectors of the Antarctic Ice Sheet cannot be precisely quantified, judge that there is “medium confidence that it would not exceed several tenths of a metre of sea level rise during the 21st century”.

Katsman et al. (2011) used a semi-empirical approach to develop a plausible scenario of high-end 21st century sea level rise for both the global mean and for the coast of the Netherlands under the A1FI emissions scenario. Owing to the different approach and different emissions scenario, our results are not directly comparable but comparison for the global and regional total is possible (Table 3). The differences between the Katsman figures and this study are mostly due to the larger projected contribution from the Antarctic ice sheet in the “severe” scenario used in Katsman et al. (2011).

Our TE and Mn_ADSL contributions are taken from the CMIP3 models and have been discussed elsewhere (e.g. Landerer et al., 2007; Lowe and Gregory, 2006; Suzuki et al., 2005). Our TIM and Mn_GCFF are based on work described in Spada et al. (2013). Our Mn_IDSL contribution is discussed extensively by Howard et al. (2013). Consequently, we focus here on the SRG contribution for NW Europe.

6.1 Changes in surges

Following Lowe et al. (2009) we assessed the local statistical significance of the SRG contribution by comparing the PPE mean with the PPE spread. We found the SRG contribution was positive and locally statistically significant in this sense at Aberdeen, Cork Harbour, Roscoff, Esbjerg and Bergen (P value less than 0.05, one-sided test).

The changes in TE and ADSL (Fig. 2) were based on the CMIP3 MME, whereas the surge changes were based on the more limited PPE. Despite this, even under the limited range of changes in storminess emerging from the PPE, we find surge changes are a significant contributor in some locations. Surge changes are critically dependent on changes in atmospheric storminess and it should be borne in mind that previous work has shown that the range of storminess changes emerging from the PPE in our region of concern are smaller than those emerging from the CMIP3 MME (Lowe et al., 2009). As a consequence, the surge changes could be more important than implied

by Fig. 5 under a more comprehensive multi-model assessment (cf. Lowe et al., 2009 chapter 4, their discussion of the “H++” approach).

A general pattern of a projected increase in storm surge extremes in the eastern North Sea, particularly on the west-facing coast of the Jutland peninsula (Fig. 3) but a much smaller signal on the east coast of the UK, can be seen in projections made by a number of previous studies (based on emissions scenarios including A1B, A2 and B2) e.g. Gaslikova et al. (2013), Debernard and Røed (2008), Woth (2006), Lowe and Gregory (2005, in particular their projection for the B2 scenario). These previous studies, however, used only single realisations or small ensembles, typically combined with a comparison of two 30 yr time slices representing the projection and the present day respectively. Such an approach is susceptible to aliasing information from natural multi-decadal variations in storminess over the region (see for example Jenkins et al., 2008, in particular their Fig. 1.14). Some recent studies (e.g. Sterl et al., 2009; Lowe et al., 2009) have addressed this issue by using larger model ensembles and/or considering the linear change in storm surge characteristics over the full period of the simulation, typically 150 yr. We use both approaches here. Consistent with Sterl et al. (2009) we find no significant increase in storm surge characteristics on the Dutch coast. As noted by Sterl et al. this in turn is consistent with an increase in westerly or south-westerly winds, which do not tend to produce severe surges on the Dutch coast.

6.2 Surge change relationship with wind changes.

Sterl et al. (2009) projected a small increase in maximum wind speeds over the southern North Sea over the 21st century, noting that since this was due to winds from the south-west it may not lead to a significant increase in surge heights along the Dutch coast. Our model results support this conclusion for the Dutch coast; for example, we find a small, statistically insignificant increase in surge amplitude at ‘s-Gravenhage. We also note that the larger (and in some areas statistically significant) trends in the ensemble-mean surge projections are mostly on west or south-west facing coasts, broadly consistent with an increase in the westerly or south-westerly component of

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



wind. However, there is no strong signal of winter mean windspeed change in our PPE (see for example Brown et al., 2009, particularly their Fig. 10 referring to the UK or their Fig. 13a which refers to the entire RCM domain). In validating their driving climate models Sterl et al. (2009) and Howard et al. (2010) consider the annual maximum daily mean wind speed at 5° E 55° N. We looked at our model relationship between this quantity and the changing surge levels at Esbjerg, where some of the largest changes are projected. We find a statistically significant but weak correlation between modelled annual maximum daily mean wind speed at 5° E 55° N and the modelled annual maximum skew surge at Esbjerg (Pearson's $r = 0.2$, P value less than 0.001 over the 150 yr of model simulation, using data from all eleven members of the PPE) and a weak correlation between the *century-scale change* in the 50 yr return level of daily mean wind speed at 5° E 55° N (11 values, one from each PPE ensemble member) and the *century-scale change* in the 50 yr return level of skew surge at Esbjerg (11 values, one from each PPE ensemble member; $r = 0.37$, P value 0.26). Our ensemble mean projected century-scale change in the 50 yr return level of daily mean wind speed at 5° E 55° N is of the order of 10 cm per second over the 21st century (90 % CI of [-16, 37] centimetres per second per century). Although this is *consistent* with the increase in surge amplitude at 's-Gravenhage, in view of the weak correlation it is of limited utility in *explaining* the increase. Many other factors need to be considered: wind direction, duration, spatial extent and storm track, for example. Such an analysis is beyond the scope of the present work. Gaslikova et al. (2013) report somewhat similar patterns of projected storm surge change to ours under the A1B emissions scenario and their changes appear to be related to their reported increase in both the annual 99th percentile of windspeed and the frequency of occurrence of westerly or south-westerly winds with speeds greater than 17.2 ms^{-1} , both change assessments being based on the 30 yr time slice approach. DeWinter et al. (2013) consider projections of 12 members of the CMIP5 ensemble and they also find an indication of annual extreme winds over the North Sea coming more often from western directions.

Sources of 21st century regional sea level rise

T. Howard et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

7 Conclusions

In this study, we compared projected mid-range and high-end 21st century contributions to extreme sea-level change around north-west Europe. These contributions arise from changes in atmospheric storminess, terrestrial ice melt from ice sheets and glaciers, thermal expansion of the oceans, changes in dynamic sea level associated with the projected ice loss, and with projected climate change, and effects of glacial isostatic adjustment associated with loss of ice since the Last Glacial Maximum. As far as possible we have used projections based on the SRES A1B emissions scenario to provide a self-consistent, process-based model-derived set of projections of mean sea level rise and changes in extreme surge levels expressed as the change in the height of the 50 yr flood. In regard to sea-level rise, the A1B scenario is broadly similar to representative concentration pathway RCP6.0, used in the most recent IPCC Assessment (Church et al., 2013).

We find that the largest sources of uncertainty are in the contribution from dynamic sea level changes associated with the direct warming effects of radiative forcing, and the global mean contribution of ice-loss. Our approach does have some limitations; for example, our analysis of the changing distribution of surges is based on a perturbed-physics ensemble generated by a single model, rather than a multi-model ensemble. Nevertheless, we find that the change in the statistical distribution of surges (associated with changes in their atmospheric forcing only) contributes significantly to the spatial variations in the projected changes of the 50 yr flood height, and in some locations may make a very significant contribution. For example, our central estimate of this contribution to the rise in the 21st century extreme sea level on the west coast of the Jutland Peninsula is 15 cm, which can be compared with a central estimate of around 22 cm from global mean thermal expansion.

Acknowledgements. This work was supported by funding from the ice2sea programme from the European Union 7th Framework Programme, grant number 226375. Ice2sea contribution number #164. We acknowledge the significant contribution made by Kevin Horsburgh and his colleagues at the National Oceanography Centre.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



References

- Araujo, I. B. and Pugh, D. T.: Sea levels at Newlyn 1915–2005: analysis of trends for future flooding risks, *J. Coastal Res.*, 24, 203–212, doi:10.2112/06-0785.1, 2008.
- Brown, S., Boorman, P., McDonald, R., and Murphy, J.: Use and interpretation of surface wind projections from the 11-member Met Office Regional Climate Model ensemble, UKCP09 Technical Note. Met Office Hadley Centre, Exeter, UK, available at: <http://ukclimateprojections.defra.gov.uk> (last access: 12 December 2013), 2009.
- Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea level change, in: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, in press, 2013.
- Coles, S.: *An introduction to statistical modeling of extreme values*, Springer, 208 pp., 2001.
- Debernard, J. B. and Roed, L. P.: Future wind, wave and storm surge climate in the Northern Seas: a revisit, *Tellus A*, 60, 427–438, doi:10.1111/j.1600-0870.2008.00312.x, 2008.
- de Winter, R. C., Sterl, A., and Ruessink, B. G.: Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs, *J. Geophys. Res.-Atmos.*, 118, 1601–1612, doi:10.1002/jgrd.50147, 2013.
- Flather, R. A., Smith, J. A., Richards, J. D., Bell, C., and Blackman, D. L.: Direct estimates of extreme storm surge elevations from a 40 yr numerical model simulations and from observations, *The Global Atmosphere and Ocean System*, 6, 165–176, 1998.
- Gaslikova, L., Grabemann, I., and Groll, N.: Changes in North Sea storm surge conditions for four transient future climate realizations, *Nat. Hazards*, 66, 1501–1518, doi:10.1007/s11069-012-0279-1, 2013.
- Giesen, R. H. and Oerlemans, J.: Climate-model induced differences in the 21st century global and regional glacier contributions to sea-level rise, *Clim. Dynam.*, 41, 1–18, 2013.
- Goelzer, H., Huybrechts, P., Fürst, J. J., Nick, F. M., Andersen, M. L., Edwards, T. L., Fettweis, X., Payne, A. J., and Shannon, S. R.: Sensitivity of Greenland ice sheet projections to model formulations, *J. Glaciol.*, 59, 733–749, 2013.

OSD

10, 2433–2459, 2013

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Haigh, I., Nicholls, R., and Wells, N.: Assessing changes in extreme sea levels: application to the English Channel, 1900–2006, *Cont. Shelf. Res.*, 30, 1042–1055, doi:10.1016/j.csr.2010.02.002, 2010.

Howard, T., Lowe, J., and Horsburgh, K.: Interpreting century-scale changes in Southern North Sea storm surge climate derived from coupled model simulations, *J. Climate*, 23, 6234–6247, doi:10.1175/2010jcli3520.1, 2010.

Howard, T., Ridley, J., Pardaens, A. K., Hurkmans, R. T. W. L., Payne, A. J., Giesen, R. H., Lowe, J. A., Bamber, J. L., Edwards, T. L., and Oerlemans, J.: The land-ice contribution to 21st century dynamic sea level rise, *Ocean Sci. Discuss.*, submitted, 2013.

Jenkins, G. J., Perry, M. C., and Prior, M. J.: The climate of the UK and recent trends. Met Office Hadley Centre, Exeter, UK, available at: <http://ukclimateprojections.defra.gov.uk> (last access: 12 December 2013), 2008.

Katsman, C. A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., Kopp, R. E., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H. P., Ridley, J., von Storch, H., Vaughan, D. G., Vellinga, P., Vermeersen, L. L. A., van de Wal, R. S. W., and Weisse, R.: Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta-the Netherlands as an example, *Climatic Change*, 109, 617–645, doi:10.1007/s10584-011-0037-5, 2011.

Kuhlbrodt, T. and Gregory, J. M.: Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change, *Geophys. Res. Lett.*, 39, L18608, doi:10.1029/2012GL052952, 2012.

Landerer, F. W., Jungclauss, J. H., and Marotzke, J.: Regional Dynamic and Steric Sea Level Change in Response to the IPCC-A1B Scenario, *J. Phys. Oceanogr.*, 37, 296–312, doi:10.1175/JPO3013.1, 2007.

Lempérière, F.: The role of dams in the XXI century: achieving a sustainable development target, *International Journal on Hydropower and Dams*, 13, 99–108, 2006.

Lowe, J. A. and Gregory, J. M.: The effects of climate change on storm surges around the UK, *Philos. T. R. Soc.*, 363, 1313–1328, doi:10.1098/rsta.2005.1570, 2005.

Lowe, J. A. and Gregory, J. M.: Understanding projections of sea level rise in a Hadley Centre coupled climate model. *J. Geophys. Res.*, 111, C11014, doi:10.1029/2005JC003421, 2006.

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake J, Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., and Bradley, S.: UK Climate Projections science report: Marine and coastal projections, Met Office Hadley Cen-

tre, Exeter, UK, available at: <http://ukclimateprojections.defra.gov.uk> (last access: 12 December 2013), 2009.

- Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z.: Global climate projections, in: *Climate change 2007: The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen Z, Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, London, 2007.
- Murphy, J. M., Booth, B. B. B., Collins, M., Harris, G. R., Sexton, D. M. H., and Webb, M. J.: A methodology for probabilistic predictions of regional climate change from perturbed physics ensembles, *Philos. T. R. Soc. A*, 365, 1993–2028, doi:10.1098/rsta.2007.2077, 2007.
- Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., De Gusmao, D., Hinkel, J., and Tol, R. S. J.: Sea-level rise and its possible impacts given a “beyond 4 °C world” in the twenty-first century, *Philos. T. R. Soc. A*, 369, 161–181, doi:10.1098/rsta.2010.0291, 2011.
- Peltier, W. R.: Global glacial isostasy and the surface of the ice-age earth: The ice-5G (VM2) model and grace, *Annu. Rev. Earth Pl. Sc.*, 32, 111–149, doi:10.1146/annurev.earth.32.082503.144359, 2004.
- Slangen, A. B. A., Katsman, C. A., van de Wal, R. S. W., Vermeersen, L. L. A., and Riva, R. E. M.: Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, *Clim. Dynam.*, 38, 1191–1209, doi:10.1007/s00382-011-1057-6, 2012.
- Spada, G. and Stocchi, P.: SELEN: a Fortran 90 program for solving the “sea-level equation”, *Comput. Geosci.*, 33, 538–562, doi:10.1016/j.cageo.2006.08.006, 2007.
- Spada, G., Bamber, J. L., and Huurkmans, R.: The gravitationally-consistent fingerprint of future terrestrial ice loss, *Geophys. Res. Lett.*, 40, 482–486, doi:10.1029/2012GL053000, 2013.
- Sterl, A., van den Brink, H., de Vries, H., Haarsma, R., and van Meijgaard, E.: An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate, *Ocean Sci.*, 5, 369–378, doi:10.5194/os-5-369-2009, 2009.
- Suzuki, T., Hasumi, H., Sakamoto, T. T., Nishimura, T., Abe-Ouchi, A., Segawa, T., Okada, N., Oka, A., and Emori, S.: Projection of future sea level and its variability in a high-resolution climate model: Ocean processes and Greenland and Antarctic ice-melt contributions, *Geophys. Res. Lett.*, 32, L19706, doi:10.1029/2005GL023677, 2005.

OSD

10, 2433–2459, 2013

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Vizcaíno, M., Mikolajewicz, U., Jungclaus, J., and Schurgers, G.: Climate modification by future ice sheet changes and consequences for ice sheet mass balance, *Clim. Dynam.*, 34, 301–324, 2010.

5 Weisse, R., von Storch, H., Niemeier, H. D., and Knaack, H.: Changing North Sea storm surge climate: an increasing hazard?, *Ocean Coast. Manage.*, 68, 58–68, doi:10.1016/j.ocecoaman.2011.09.005, 2012.

Woodworth, P. L. and Blackman, D. L.: Evidence for systematic changes in extreme high waters since the mid-1970s, *J. Climate*, 17, 1190–1197, doi:10.1175/1520-0442(2004)017<1190:efscie>2.0.co;2, 2004.

10 Woth, K., Weisse, R., and von Storch, H.: Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, *Ocean Dynam.*, 56, 3–15 doi:10.1007/s10236-005-0024-3, 2006.

OSD

10, 2433–2459, 2013

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Summary of the contributions to 21st century sea-level change included in this study.

Abbreviation	Description	Source
TE	Global mean thermal expansion of the ocean	Developed herein following Lowe et al. (2009)
TIM	Global mean Terrestrial Ice Melt from offline ice models	Howard et al. (2013)
GCOFF	Gravitationally-consistent fingerprint of projected future ice melt from offline ice models (fast elastic lithosphere response) expressed as departures from the global mean	SELEN, Spada and Stocchi (2007)
GIA	Ongoing vertical land movement, due to glacial isostatic adjustment (slow viscous lithosphere response)	ICE-5G(VM2) Peltier (2004)
IDSL (DSL due to ice)	Regional changes in dynamic sea level associated with the freshwater forcing from ice-loss determined in offline models	HadCM3, Howard et al. (2013) and refs therein
ADSL (DSL directly due to A1B)	Regional changes in dynamic sea level for A1B emissions scenario, excluding the effects of ice-loss determined in offline models	Developed herein following Lowe et al. (2009)
SRG	Local 21st-century change in 50 yr return level of storm (skew) surge associated with changes in atmospheric storminess under the A1B scenario	HadCM3 PPE downscaled with CS3, Lowe et al. (2009) and references therein

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 2. Definitions and abbreviations used for those components which are evaluated on a local coastal mask.

Abbreviation	Description
Mn_AD_SL	ADSL averaged over the NW Europe coastal mask shown in Fig. 2.
Mn_IDSL	IDSL averaged over the NW Europe coastal mask shown in Fig. 2.
Mn_GCFF	GCFF averaged over the NW Europe coastal mask shown in Fig. 2.
Max_GCFF	Maximum of GCFF over the NW Europe coastal mask shown in Fig. 2.
Mn_SR_G	SRG averaged over the high-res. coastal mask shown in Fig. 3.
Max_SR_G	Maximum of SRG over the high-resolution coastal mask shown in Fig. 3.

Sources of 21st century regional sea level rise

T. Howard et al.

Table 3. High-end 21st century sea level change figures taken from Lowe et al. (2009), Katsman et al. (2011) and this study. The Lowe et al. (2009) figures are the top of the range of their “H++” scenario, with “Local” referring to the coast of the UK. The Katsman et al. (2011) figures are the top of the range of their high end scenario, with “Local” referring to the coast of the Netherlands. For this study the “Local” figure refers to ‘s-Gravenhage. Figures for Lowe et al. (2009) and for this study exclude both GIA and SRG for consistency with the Katsman et al. (2011) projection.

Lowe et al. “H++”	Global	2.5 m
	Local (UK)	1.9 m
Katsman et al. A1FI	Global	1.15 m
	Local (Netherlands)	1.05 m
This study A1B, HE	Global	0.82 m
	Local (‘s-Gravenhage)	0.84 m

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.



Fig. 1. Domain of the storm surge model, CS3 (shaded). The outer frame indicates the domain of the regional atmospheric climate model.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

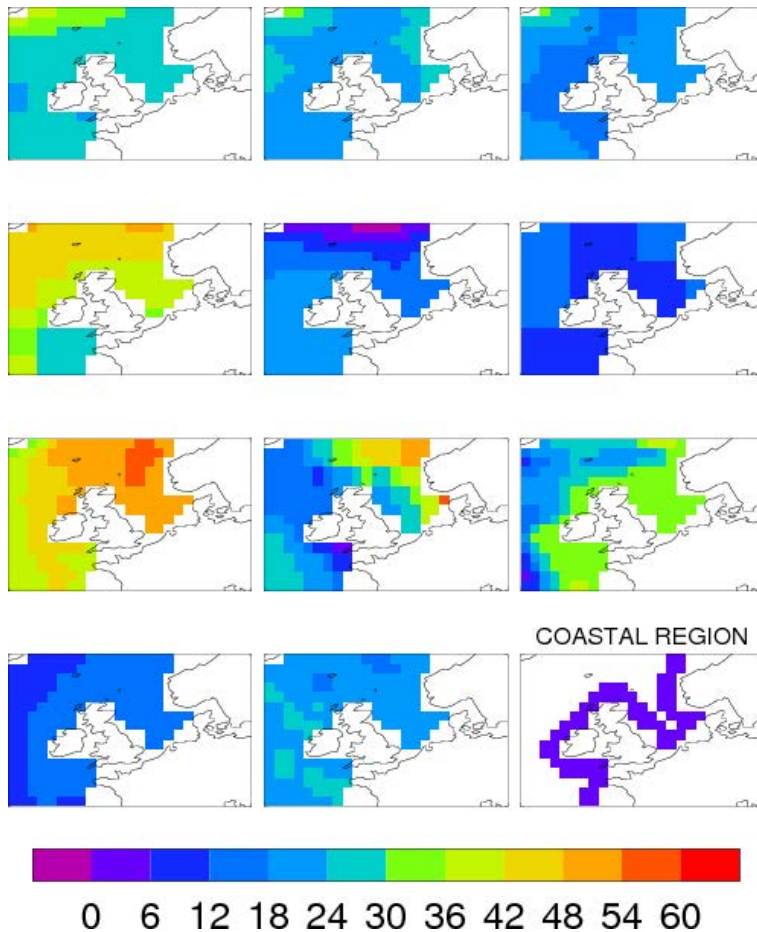


Fig. 2. (TE + ADSL) in centimetres for the NW European region derived from 11 CMIP3 models. Projections are for the SRES A1B scenario and for the period 2080–2099 relative to 1980–1999. The lower right frame shows the mask used to extract Mn_ADSL.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Sources of 21st century regional sea level rise

T. Howard et al.

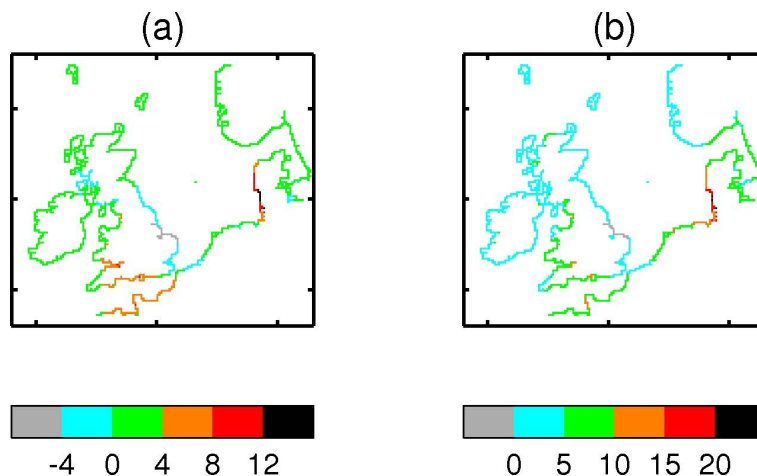


Fig. 3. Projected contribution in centimetres of the change in storm surge climate to 21st century change in the 50yr return storm for **(a)** Central estimate **(b)** 95th percentile. Both are given in terms of the skew surge above present-day astronomical high tide, and represents the contribution due to atmospheric storminess changes only.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

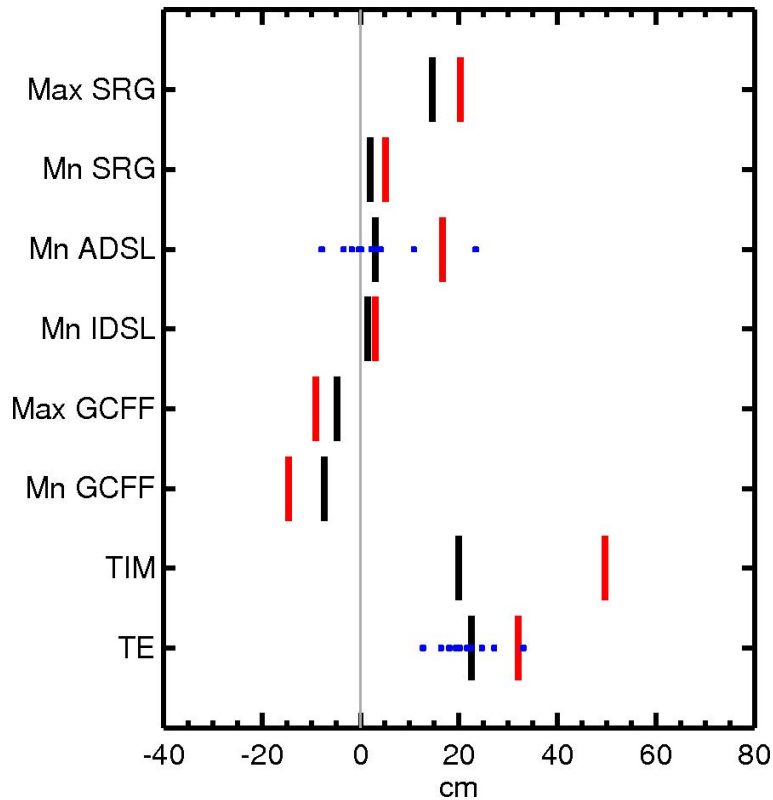


Fig. 4. Comparison of components of sea level change around NW Europe, showing the 21st century change in 50 yr storm height (centimetres). Black bars indicates the mid-range, and red, the high-end scenarios. Blue dots show the individual ensemble members where these are available. The abbreviations used in the figure are those given in tables 1 and 2.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



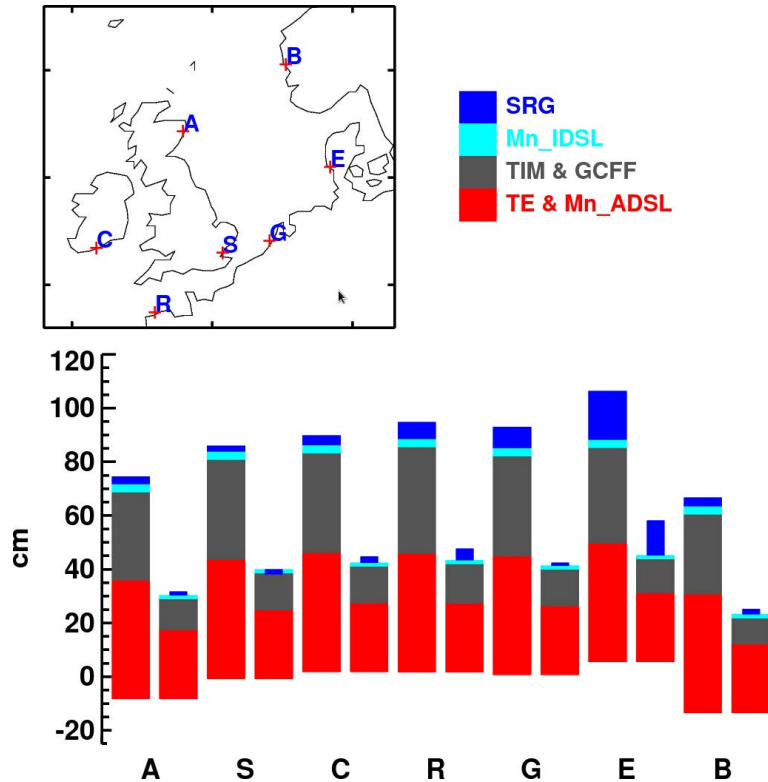


Fig. 5. Illustrative addition of high-end and mid-range projections of contributions to changes in the height of the 50 yr storms in 2100 for seven locations around NW Europe. The locations are Aberdeen, (A); Sheerness, (S); Cork Harbour (C); Roscoff, (R); 's-Gravenhage (Den Haag, G); Esbjerg (E) and Bergen (B). For each location, the larger (left-hand) bar shows the high-end estimate, and the smaller (right-hand) bar shows the mid-range estimate. The projected contribution from GIA is shown as an offset to the zero of each bar. The mid-range SRG projection at Sheerness is negative, and so that this can be seen, the mid-range SRG projections are shown as half-width bars. Further details in main text.

Sources of 21st century regional sea level rise

T. Howard et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

