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#### **Title**

Sources of 21<sup>st</sup> century regional sea level rise along the coast of North-West Europe.

#### **Authors**

Tom Howard, Anne K Pardaens, Jonathan L Bamber, Jeff Ridley, Giorgio Spada, Ruud TWL Hurkmans, Jason A Lowe, David Vaughan.

#### **Affiliations**

Tom Howard, Anne K Pardaens, Jason A Lowe, Jeff Ridley  
Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, United Kingdom.  
e-mail: tom.howard@metoffice.gov.uk Tel: +44(0)1392 886678 Fax:  
+44(0)870 900 5050

Ruud Hurkmans, Jonathan Bamber  
Bristol Glaciology Centre, School of Geographical Sciences, University of  
Bristol, University Road, Bristol, BS8 1SS, UK.

Giorgio Spada  
Dipartimento di Scienze di Base e Fondamenti, Urbino University "Carlo Bo",  
Via Santa Chiara, 27, I-61029 Urbino (PU) ITALY

David Vaughan  
British Antarctic Survey, Madingley Road, High Cross, Cambridge,  
Cambridgeshire, CB3 0ET, United Kingdom

## 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 storm surges. 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 in one self-consistent assessment. Focusing on the coastline of North-West Europe, we consider all the processes mentioned above and their relative impact on 21<sup>st</sup> century regional mean sea levels and the 50-year return 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 North-West European sea level by 2100. However, the projected contribution to extreme sea level, due to changes in storminess alone, is in some places significant and 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-year 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-year return level of 86 cm at Sheerness, 95 cm at Roscoff, 106 cm at Esbjerg, and 67cm at Bergen. The notable regional differences between these locations arise primarily from differences in the rates of vertical land movement and changes in storminess.

## Keywords

Extreme sea level. Sea level change. Storm surge. European coastline. Model projection. Process-based.

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Comment [TPH2]: A001

Comment [TPH3]: A002

Comment [TPH4]: A003

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## 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, Ligtenberg et al., 2013), Greenland (e.g. Goelzer et al., 2013, Nick et al., 2013, Shannon 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).

Comment [TPH6]: A008

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 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 and changing freshwater fluxes driven by climate change. 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 potential 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 surge expected once in every 50-year period, the so-called 50-year storm surge, 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. Their study used various 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 extrapolation of short time series of observations. In addition, that study focused on the Dutch coastline, without a consideration of how the various contributions varied across a wider geographical area. A more recent study (Slangen et al 2012) but excluded a number of the processes mentioned

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1 above. In particular, they did not incorporate freshwater forcing, storm surge  
2 changes, or process-based model estimates of ice sheet contributions.

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3  
4 Other European studies, based on limited spatial areas, found that the high  
5 natural variability in water level makes detection of trends in the extremes  
6 problematic. Haigh et al. (2010), for example, considered data from eighteen  
7 sites around the English Channel and found changes in extreme water level  
8 similar to rates of observed mean sea level change over the 20<sup>th</sup> century.  
9 Araújo and Pugh (2008) reached a similar conclusion for Newlyn in the UK,  
10 based on data from 1915-2005. For a recent review of past changes in factors  
11 contributing to extreme sea levels in the North Sea, see Weisse et al (2012).

Comment [TPH10]: A012

12  
13 In this study, we use projections of regional sea-level change arising from 21<sup>st</sup>  
14 century ice-loss from ice sheets and glaciers (Spada et al., 2013, Howard et al.  
15 2014), including the effects of changes to the gravity field and Earth rotation.  
16 We also include modelled changes in the climate of storm surges produced in  
17 support of the UK Climate Projections, Marine and Coastal Projections 2009  
18 (UKCP09; Lowe et al., 2009): a project to investigate the projected major  
19 contributions to 21<sup>st</sup> century change in coastal flood risk and shelf-seas  
20 hydrology around the coast of the United Kingdom. The UKCP09 project  
21 included both a (primarily process-based) ensemble projection of sea level  
22 change and a proxy-based assessment of plausible upper limits (the so-called  
23 “H++” scenario). Their ensemble analysis gave projections of UK coastal  
24 geocentric sea-level rise of 13 to 60 cm over the 21<sup>st</sup> century (5<sup>th</sup> to 95<sup>th</sup>  
25 percentile, not including vertical land movement or changes in the climate of  
26 storm surges) under the A1B emissions scenario. The corresponding figure  
27 from the ‘upper end’ of their H++ scenario range was 190 cm. Here we extend  
28 the UKCP09 approach to include more of the North-West (NW) European  
29 coast, and we augment the UKCP09 results with new process-based ice-melt  
30 projections.

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31  
32 In addition to the sources of sea level variability listed above, we include  
33 projected contributions from thermal expansion, changes in dynamic sea level  
34 associated with the freshwater flux from ice melt, changes in dynamic sea  
35 level associated with projected global warming under the A1B emissions  
36 scenario, and projected changes in relative sea level due to vertical land  
37 movements arising from ice-loss since the Last Glacial Maximum, termed  
38 glacial isostatic adjustment (GIA).

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39  
40 Our aim is to provide a comparison of geographic variations and uncertainties  
41 in the different contributions to North-West European sea level. To do this we  
42 consider two scenarios for 21<sup>st</sup> century change. The first, which we describe  
43 as a “mid-range projection”, is taken from close to the middle of the  
44 uncertainty range for each process considered. The second, which we  
45 describe as a “high-end projection”, is taken from the upper end of the  
46 distribution. For contributions **TE**, **ADSL** and **SRG** (**TE**: Global mean thermal  
47 expansion of the ocean, **ADSL**: Regional changes in dynamic sea level for  
48 A1B emissions scenario, excluding the effects of ice-loss determined in offline  
49 models; **SRG**: Local 21st-century change in 50-year return level of storm  
50 (skew) surge associated with changes in atmospheric storminess under the

A1B scenario; see table 1 for summary of all such abbreviations), these two scenarios represent the 50<sup>th</sup> and 95<sup>th</sup> percentiles respectively of an ensemble of projections to which we fitted a normal distribution (see section 3.3). 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 representative estimate, and the high-end projection gives an illustrative measure of the upper end of the 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.

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Comment [TPH14]: A016

Some of the factors *not* included in this study, but which may contribute to changes in extreme sea level, include changes in terrestrial water storage (e.g. Lettenmaier and Milly, 2009), changes in the climate of waves and swell (e.g. Lowe et al., 2009), changes in the tidal constituents or tidal range (e.g. Muddersbach et al, 2013, Woodworth, 2010, Müller et al., 2011, Pickering et al., 2012) and changes in the seasonal cycle (e.g. Wahl et al. 2014).

Comment [TPH15]: B004 and B007

## 2 Nomenclature

We use the abbreviations MR and HE to refer to the representative mid-range and illustrative 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" (see section 3.3) 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 21<sup>st</sup> 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 NW 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](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).

1 We used eleven of the CMIP3 models. These were selected from the full set  
2 of CMIP3 models on the basis that DSL projections under the A1B scenario  
3 and the accompanying parallel sections of simulations with fixed greenhouse  
4 gas concentration were both available to us (together with global thermal  
5 expansion). Using this subset of models therefore allowed a common  
6 approach to be taken in removing model drift in the DSL pattern changes.

Comment [TPH16]: A027 and A026

7  
8 A common land mask was applied to each of the model (**TE + ADSL**)  
9 projections and a NW European coastally-averaged (**TE + Mn\_ADSL**) then  
10 calculated for each model (the masked region is shown in Fig. 2; the values  
11 are very similar when using a masked region of half this width), where  
12 **Mn\_ADSL** is **ADSL** averaged over the masked region. We also used **TE** data  
13 for each of the 11 models to partition the sum (**TE + Mn\_ADSL**) into its  
14 components **TE** and **Mn\_ADSL**. ~~each of which is shown in Fig. 4.~~ This also  
15 enabled us to check our distribution of 11 **TE** values against the two  
16 percentiles reported in AR4, and to make a basic comparison with the  
17 corresponding values in AR5 (see section 4.1).

Comment [TPH17]: A022

### 19 3.2 Contribution from **TIM** and **GCFF**

20  
21 We derived projections of two contributions, **TIM** and **GCFF**, from two time-  
22 series (MR and HE) which are the same as those used in Spada et al. (2013).  
23 We partitioned each into a global mean (**TIM**<sup>1</sup>) and spatially-varying  
24 component (**GCFF**). We selected data for the 2080-2099 period, calculating  
25 changes with respect to 1992 (see Howard et al., 2014 for further details).  
26 This model output was provided on a grid (described by Spada and Stocchi,  
27 2007) with lower resolution than our surge model grid (shown, for example, in  
28 Fig. 3). However, this lower-resolution grid does not overlap all the specific  
29 coastal sites chosen for this study, and so for each of these sites, we  
30 interpolated the low-resolution grid using values from grid-points to the east  
31 and west (for example around the British Isles). For grid points on the high-  
32 resolution grid with no low-resolution point to the east, we used the value for  
33 the nearest low-resolution value to the west. This is justified by the fact that, in  
34 this region, there is only a small east-west gradient, compared to the dominant  
35 north-south gradient in the **GCFF** component.

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### 37 3.3 Contribution from **SRG**

38  
39 There is good evidence (e.g. Howard et al, 2010; Sterl et al. 2009) that  
40 changes in storm surge contribution to sea level can be added linearly to  
41 mean sea level change and so, following Lowe et al. (2009), that is the  
42 approach we took in this study.

43  
44 Our approach for deriving projections of the contribution of changes in storm  
45 surge to extreme sea-level also follows that of Lowe et al. (2009). The  
46 approach is based on a perturbed atmospheric physics ensemble (PPE) of the  
47 HadCM3 global climate model, downscaled by a matching ensemble of

<sup>1</sup> This 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.

1 perturbed HadCM3 variants in atmospheric regional climate model (RCM)  
2 format.

3  
4 We acknowledge that the uncertainty range of our PPE will not in general  
5 encompass the structural uncertainty of the MME that we were able to use for  
6 the **TE** and **ADSL** contributions. Nevertheless, the range of climate sensitivity  
7 exhibited by the PPE is comparable to that of the MME (Collins et al, 2011).

Comment [TPH20]: A025

8  
9 The surface wind and atmospheric pressure fields output by the RCMs were  
10 used to drive a barotropic surge model, CS3 (Flather et al., 1998), in  
11 combined surge-and-tide mode. A parallel simulation in tide-only mode allows  
12 extraction of the non-tidal surge residual or the skew surge. Changing  
13 bathymetry due to increasing mean sea level is not included in the surge  
14 model but is added linearly in a separate step (this does not include changing  
15 coastline due, for example, to newly inundated areas; the land/sea mask does  
16 not change). The model integration ran from 1850 to 2100. The domains of  
17 CS3 and the RCM are shown in Fig. 1. CS3 has been extensively validated  
18 for the present-day climate (see for example, Lowe et al., 2009).

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19  
20 As in Lowe et al. (2009), we present projections of the “skew surge”, which is  
21 a good measure of the impact of a surge. It is defined as the difference  
22 between the height of the highest water level predicted by the model and the  
23 nearest-in-time astronomical high-tide at the same point. A statistical  
24 generalised extreme-value model (Coles, 2001), with linear time-trend in the  
25 location and scale parameter, was fitted to the five largest independent skew  
26 surges in each year (see for example Tawn, 1992; Coles, 2001). From this,  
27 we diagnosed a maximum likelihood estimator of the trend in the fifty-year  
28 return level. Thus our approach allows for the possibility of a linear time-trend  
29 in the extremes (forced by the changing atmospheric storminess). The  
30 magnitude of this trend compared with the corresponding uncertainty gives a  
31 measure of the statistical significance.

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32  
33 Again, following the approach taken by Lowe et al (2009), we treated the  
34 ensemble member projections as alternative, but equally-valid, realisations of  
35 a naturally variable future storm surge climate. Under this assumption, it is  
36 reasonable to take the mean trend in the ensemble as a representative central  
37 projection, and the standard deviation of the ensemble as a measure of  
38 spread. Assuming that the 11 trends in the extremes are normally distributed,  
39 we could then estimate the 95<sup>th</sup> percentile of the trend, independently at each  
40 location. This assumption is reasonable, even though we do not expect the  
41 extremes themselves to be normally distributed. We acknowledge that the  
42 approach is limited by the fact that we disregard the spatial dependence in the  
43 trends, but argue that it is still reasonable because we make no claims about  
44 the joint probability of the spatial patterns.

Comment [TPH24]: A017

## 46 4 Results

### 48 4.1 Contribution from **TE** and **ADSL**



Patterns of combined **TE + ADSL** for 11 members of the CMIP3 MME are shown in Fig. 2, along with the coast mask used to evaluate the local spatial mean (i.e. a spatial mean representative of the NW European coast). The range of projections of **TE** reported in AR4 for A1B and for 2090-2099 relative to 1980-1999, were 13 cm (5<sup>th</sup> percentile) and 32 cm (95<sup>th</sup> percentile), giving a mean of  $22.5 \pm 5.8$  cm, where the uncertainty is expressed as a standard deviation assuming a normal distribution. The corresponding value from our 11-member ensemble is  $21.4 \pm 5.5$  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 **TE** 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  $30.25 \text{ cm}^2$ ) with the corresponding values from AR4 (22.5 cm and  $33.64 \text{ cm}^2$ ). 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. For each of the 11 members, the partitioning of the sum (**TE + Mn\_ADSL**) into its components **TE** and **Mn\_ADSL** is shown by the dotted points in Fig. 4.

Comment [t25]: B014

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., in press; their figure 13.16).

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## 4.2 Contribution from **TIM** and **GCFF**

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).

## 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. This is addressed further in the discussion section below.

## 5 Comparison and Addition of Contributions

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



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\_ADSL**, 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 surge changes additively with mean sea level change. Similarly Howard et al. (2014) 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-year storm surge, for seven locations around NW Europe in Fig. 5. The locations are Aberdeen, Sheerness, Cork Harbour, Roscoff, Den Haag, Esbjerg and Bergen. Again the abbreviations used for the contributions are those of tables 1 and 2. Note that the HE contribution from (**TE + Mn\_ADSL**) is *not* simply the sum of the HE **TE** and HE **Mn\_ADSL** 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 HE value directly from the distribution of their sum.

## 6 Discussion

Under our representative mid-range projection we found that **TE** and **TIM** are the largest contributors to 21<sup>st</sup> century extreme sea level change around NW Europe (Fig. 4, Fig. 5). However, the largest uncertainties arise from **TIM**, and **TIM** made the largest contribution to the illustrative high-end projection. The uncertainty due to **Mn\_ADSL** was also large. Within the limitations of our method (i.e. the use of only one model formulation with two different meltwater forcings), 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 section 6.1). Spatial variations due to **SRG** and **GIA** are both considerable.

In table 3 we compare illustrative 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 addressed differently in the three studies. The IPCC AR5 (Church et al., 2013) note that there is low agreement within semi-empirical model projections and no consensus in the scientific community about their reliability. Thus we have not quoted projections from such models here. However for a summary of such projections in comparison to process-based projections the reader may see for example Nicholls et al. (2011).

Comment [TPH28]: B016

Comment [TPH29]: A030 and A031

1 Lowe et al. (2009) provide a mostly-process-based projection<sup>2</sup> of sea-level  
2 rise for the coast of the UK (with which our **TE**, **GIA**, **ADSL** and **SRG**  
3 contributions are all consistent). However Lowe et al. (2009) also offer a  
4 (partly proxy-based) projection for vulnerability testing, their so-called “H++”  
5 scenario range. It is informative to compare this scenario with our results  
6 (table 3), although the H++ range was intended to look at plausible upper  
7 limits based partly on proxy data and it should be borne in mind that recent  
8 observations and model projections do not provide any evidence to suggest  
9 that such high levels of sea level rise will occur within the 21<sup>st</sup> century.  
10 Church et al. (2013), acknowledging that the potential additional contribution  
11 to global mean sea-level rise from the collapse of marine-based sectors of the  
12 Antarctic Ice Sheet cannot be precisely quantified, judge that there is “medium  
13 confidence that it would not exceed several tenths of a metre of sea level rise  
14 during the 21st century”.

15  
16 Katsman et al. (2011) developed a plausible scenario of high-end 21<sup>st</sup> century  
17 sea level rise for both the global mean and for the coast of the Netherlands  
18 under the A1FI emissions scenario. Owing to the different approach and  
19 different emissions scenario, our results are not directly comparable but  
20 comparison for the global and regional total is possible (table 3). The  
21 differences between the Katsman figures and this study are mostly due to the  
22 larger projected contribution from the Antarctic ice sheet in the ‘severe’  
23 scenario used in Katsman et al (2011). However it is also noticeable that the  
24 local sea level rise is greater than the global mean in our study, but smaller in  
25 the other two. The main reason for this is the smaller contribution from the  
26 Greenland ice sheet in our projections (see Howard et al., 2014). (The  
27 fingerprint of Greenland melt is characterised by less-than-global-mean  
28 increases around NW Europe).

29  
30 Our **TE** and **Mn\_ADSSL** contributions are taken from the CMIP3 models and  
31 have been discussed elsewhere (e.g. Pardeens et al., 2011; Landerer et al.,  
32 2007; Lowe and Gregory, 2006; Suzuki et al., 2005). Our **TIM** and **Mn\_GCFF**  
33 are based on work described in Spada et al. (2013). Our **Mn\_IDSL**  
34 contribution is discussed extensively by Howard et al. (2014). Consequently,  
35 we focus here on the **SRG** contribution for NW Europe.

## 36 37 6.1 Changes in surges 38

39 Following Lowe et al. (2009) we assessed the local statistical significance of  
40 the **SRG** contribution by comparing the PPE mean with the PPE spread. We  
41 considered a range of geographically distributed locations (shown in Fig 5).  
42 We found the **SRG** contribution was positive and locally statistically significant  
43 in this sense at Aberdeen, Cork Harbour, Roscoff, Esbjerg and Bergen (P-  
44 value less than 0.05, one-sided test).

45  
46 The changes in **TE** and **ADSL** (Fig. 2) were based on the CMIP3 MME,  
47 whereas the surge changes were based on the more limited PPE. Despite this,

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<sup>2</sup> their projection of ice sheet behaviour was not process-based

1 even under the limited range of changes in storminess emerging from the  
2 PPE, we find surge changes are a significant contributor in some locations.  
3 Surge changes are critically dependent on changes in atmospheric storminess  
4 and it should be borne in mind that previous work has shown that the range of  
5 storminess changes emerging from the PPE in our region of concern are  
6 smaller than those emerging from the CMIP3 MME (Lowe et al, 2009). As a  
7 consequence, the surge changes could be more important than implied by Fig.  
8 5 under a more comprehensive multi-model assessment (c/f Lowe et al. 2009  
9 chapter 4, their discussion of the “H++” approach).

10  
11 A general pattern of a projected increase in storm surge extremes in the  
12 eastern North Sea, particularly on the west-facing coast of the Jutland  
13 peninsula (Fig. 3) but a much smaller signal on the east coast of the UK, can  
14 be seen in projections made by a number of previous studies (based on  
15 emissions scenarios including A1B, A2 and B2), e.g. Gaslikova et al. (2013),  
16 Debernard and Røed (2008), Woth (2006) , Lowe and Gregory (2005, in  
17 particular their projection for the B2 scenario). These previous studies,  
18 however, used only single realisations or small ensembles, typically combined  
19 with a comparison of two 30-year time slices representing the projection and  
20 the present day respectively. Such an approach is susceptible to aliasing  
21 information from natural multi-decadal variations in storminess over the region  
22 (see for example Jenkins et al., 2008, in particular their figure 1.14). Some  
23 recent studies (e.g. Sterl et al 2009, Lowe et al. 2009) have addressed this  
24 issue by using larger model ensembles and/or considering the linear change  
25 in storm surge characteristics over the full period of the simulation, typically  
26 150 years. We use both approaches here. Consistent with Sterl et al. (2009)  
27 we find no significant increase in storm surge characteristics on the Dutch  
28 coast. As noted by Sterl et al. this in turn is not inconsistent with an increase  
29 in westerly or south-westerly winds, which do not tend to produce severe  
30 surges on that coast.

Comment [t30]: B018

## 31 32 33 6.2 Surge change relationship with wind changes.

34  
35 Sterl et al. (2009) projected a small increase in maximum wind speeds over  
36 the southern North Sea over the 21<sup>st</sup> century, noting that since this was due to  
37 winds from the south-west it may not lead to a significant increase in surge  
38 heights along the Dutch coast. Our model results support this conclusion for  
39 the Dutch coast; for example, we find a small, statistically insignificant  
40 increase in surge amplitude at Den Haag. We also note that the larger (and in  
41 some areas statistically significant) trends in the ensemble-mean surge  
42 projections are mostly on west or south-west facing coasts, broadly consistent  
43 with an increase in the westerly or south-westerly component of wind.  
44 However, there is no strong signal of winter mean windspeed change in our  
45 PPE (see for example Brown et al. 2009, particularly their fig 10 referring to  
46 the UK or their fig 13(a) which refers to the entire RCM domain). In validating  
47 their driving climate models Sterl et al. (2009) and Howard et al. (2010)  
48 consider the annual maximum daily mean wind speed at 5°E 55°N. We looked  
49 at our model relationship between this quantity and the changing surge levels  
50 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 years of model simulation, using data from all eleven members of the PPE) and a weak correlation between the *century-scale change* in the 50-year 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-year 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-year return level of daily mean wind speed at 5°E 55°N is of the order of 10 cm per second over the 21<sup>st</sup> century (90% confidence interval of [-16, 37] centimetres per second per century). Although this is *consistent* with the increase in surge amplitude at Den Haag, 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 99<sup>th</sup> percentile of windspeed and the frequency of occurrence of westerly or south-westerly winds with speeds greater than 17.2 m/s, both change assessments being based on the 30-year 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.

## 7 Conclusions

In this study, we compared representative mid-range and illustrative high-end projections of 21<sup>st</sup> century contributions to extreme sea-level change around NW 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-year flood. In regard to sea-level rise, the A1B scenario is broadly similar to both representative concentration pathways RCP4.5 and RCP6.0, which differ only in the latter half of the 21<sup>st</sup> century.

We find that the largest sources of uncertainty within these single-emission-scenario simulations 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

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distribution of surges (associated with changes in their atmospheric forcing only) contributes significantly to the spatial variations in the projected changes of the 50-year flood height, and in some locations may make a significant contribution, particularly along parts of the European mainland coast not considered by Lowe et al. (2009). For example, our central estimate of this contribution to the rise in the 21<sup>st</sup> 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.

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Ocean Dynamics 56:3–15 DOI 10.1007/s10236-005-0024-3

1

Abbreviation	Description	Source
<b>TE</b>	Global mean thermal expansion of the ocean	Developed herein following Lowe et al. (2009)
<b>TIM</b>	Global mean Terrestrial Ice Melt from offline ice models	Howard et al. (2014)
<b>GCFF</b>	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)
<b>GIA</b>	Ongoing vertical land movement, due to glacial isostatic adjustment (slow viscous lithosphere response)	ICE-5G(VM2) Peltier (2004)
<b>IDSL (DSL due to ice)</b>	Regional changes in dynamic sea level associated with the freshwater forcing from ice-loss determined in offline models	HadCM3, Howard et al. (2014) and refs therein
<b>ADSL (DSL directly due to A1B)</b>	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)
<b>SRG</b>	Local 21 <sup>st</sup> -century change in 50-year 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

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*Table 1: Summary of the contributions to 21<sup>st</sup> century sea-level change included in this study.*

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Abbreviation	Description
<b>Mn_ADSL</b>	<b>ADSL</b> averaged over the NW Europe coastal mask shown in Fig. 2
<b>Mn_IDSL</b>	<b>IDSL</b> averaged over the NW Europe coastal mask shown in Fig. 2
<b>Mn_GCFF</b>	<b>GCFF</b> averaged over the NW Europe coastal mask shown in Fig. 2
<b>Max_GCFF</b>	Maximum of <b>GCFF</b> over the NW Europe coastal mask shown in Fig. 2
<b>Mn_SRG</b>	<b>SRG</b> averaged over the high-res. coastal mask shown in Fig. 3
<b>Max_SRG</b>	Maximum of <b>SRG</b> over the high-resolution coastal mask shown in Fig. 3

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3

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

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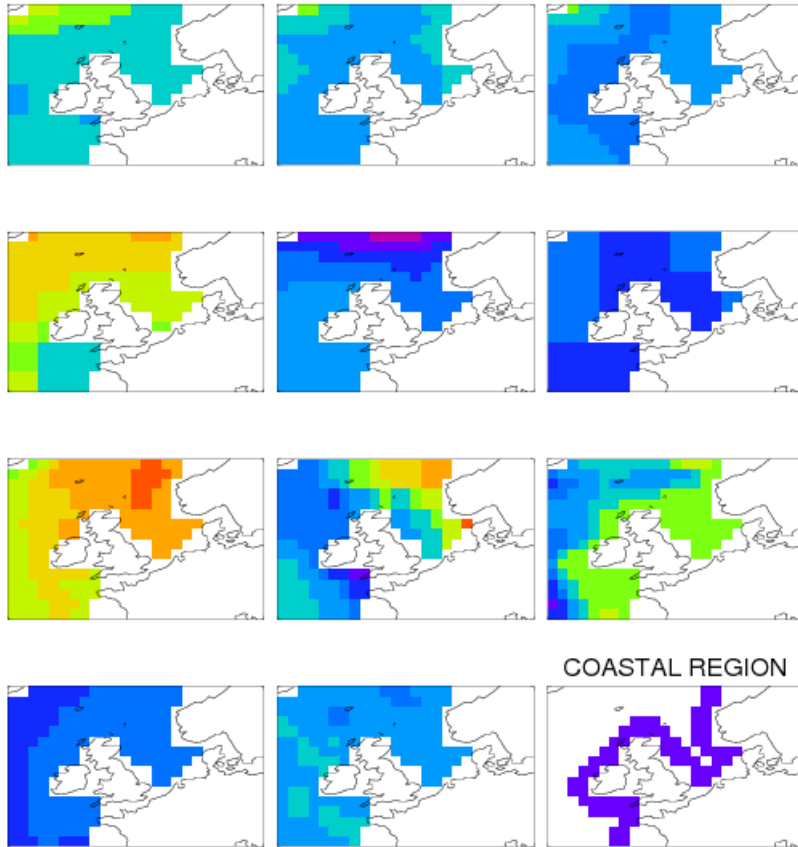
7

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 (Den Haag)	0.84 m

Table 3. High-end 21<sup>st</sup> century sea level change figures taken from Lowe et al. (2009), Katsman et al. (2011) and this study. The Lowe et al. figures are the top of the range of their "H++" scenario, with "Local" referring to the coast of the UK. The Katsman 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 Den Haag. Figures for Lowe et al. and for this study exclude both **GIA** and **SRG** because these were not treated in the same way in each study..



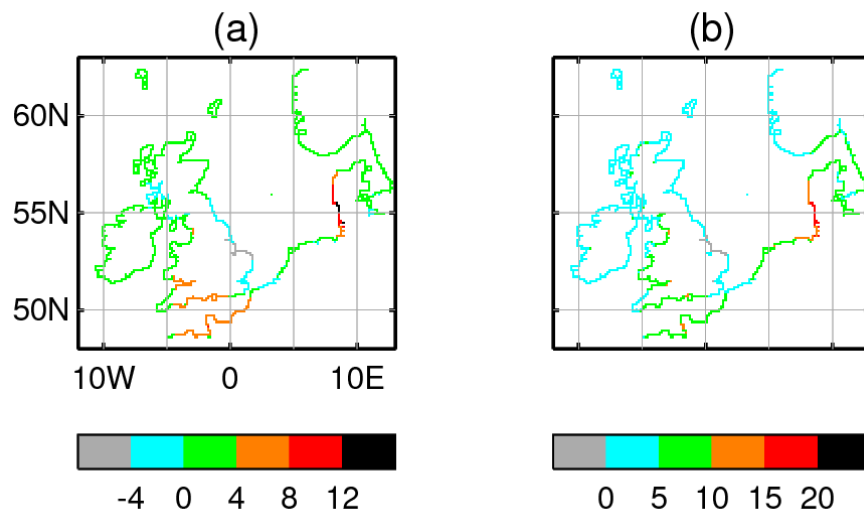
Figure 1. Domain of the storm surge model, CS3 (shaded). The outer frame indicates the domain of the regional atmospheric climate model.



0 6 12 18 24 30 36 42 48 54 60

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**.

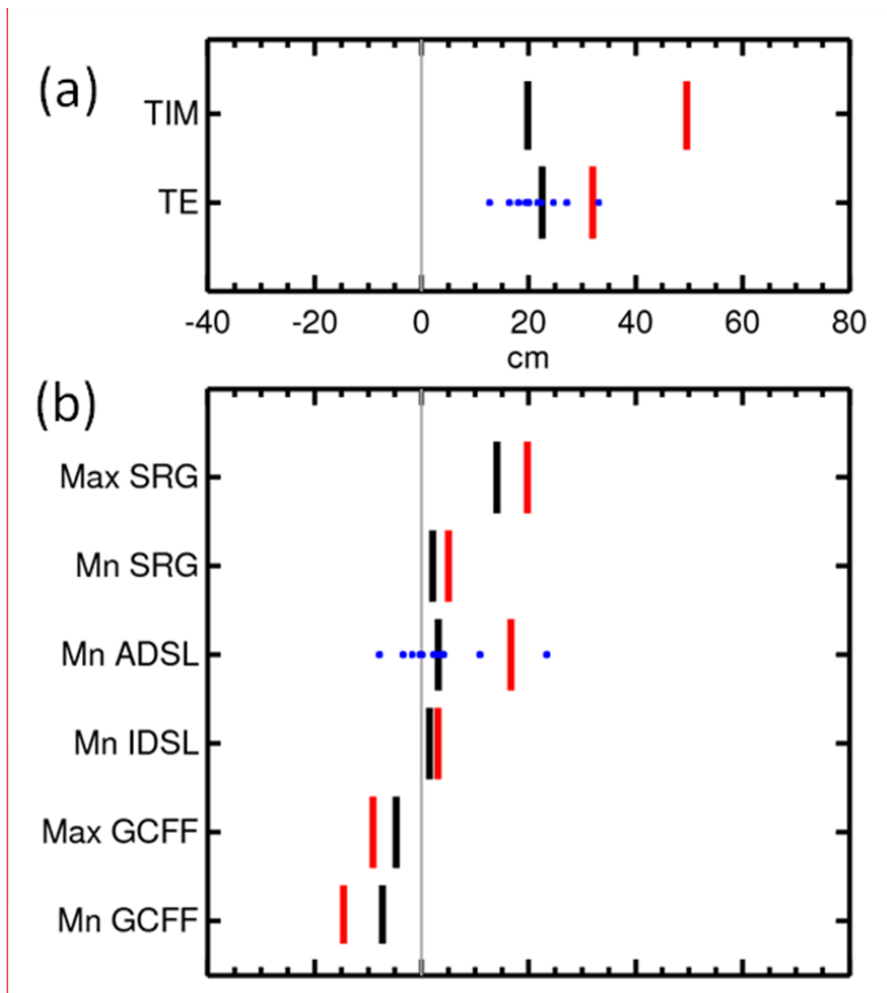




**Comment [TPH32]:** A037 Lat/Lon lines and axis labels added

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

1



**Comment [TPH33]:** A038. Figure now split into global and local contributions.

Fig. 4: Comparison of contributions to the 21<sup>st</sup> century change in 50-year storm surge height around NW Europe (centimetres). (a) Global mean contributions. (b) local contributions. Black bars indicate the representative mid-range, and red, the illustrative high-end contributions. 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.

1

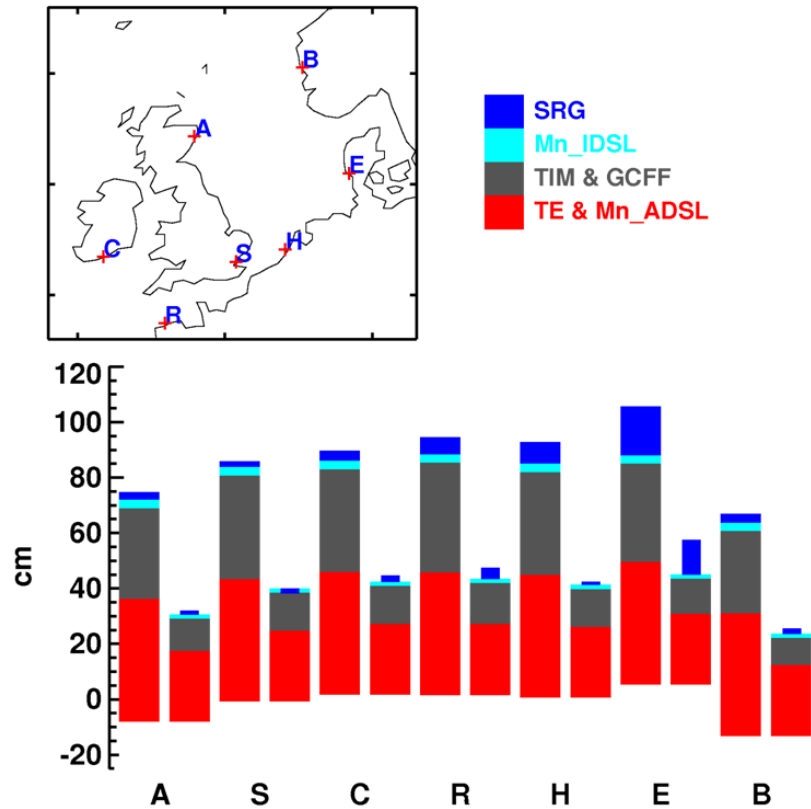


Fig. 5. Addition of illustrative high-end (and representative mid-range) projections of contributions to 21st-century change in the height of the 50-year storm surge for seven locations around NW Europe. The locations are Aberdeen, (A); Sheerness, (S); Cork Harbour (C); Roscoff, (R); Den Haag, (H); Esbjerg (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 are given in the main text.

Comment [t34]: B021

Comment [t35]: B019

Comment [t36]: B022