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Constructing scenarios of regional sea level change using global temperature pathways

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Abstract

The effects of sea level change become increasingly relevant for the Dutch coast. Therefore we construct two scenarios for regional sea-level change in the 21st century. They are designed to follow two temperature pathways, in which global mean temperature rises moderately ('G', +1.5 K in 2085) or more substantially ('W', +3.5 K in 2085). Contributions from all major processes leading to sea level rise are included (ocean expansion, glacier melt, ice-sheet changes, and landwater changes), except glacial isostatic adjustment and surface elevation changes. As input we use data from 42 coupled global climate models that contributed to CMIP5. The approach is consistent with the recent fifth assessment Report of IPCC, but provides an alternative viewpoint based on global temperature changes rather than RCPs. This makes them rather accessible and readily applicable to policy makers and the general public. We find a likely range for the G-scenario of +25–60 cm in 2085, and +45–80 cm for the W-scenario. These numbers have been rounded to 5 cm precision, to emphasise to any end-user of these scenarios that estimated lower and upper limits themselves are uncertain.

S Online supplementary data available from stacks.iop.org/erl/9/115007/mmedia

Keywords: regional sea level projections, temperature pathways, North Sea area

1. Introduction

Global and regional sea level rise are amongst the most important indicators and consequences of the fact that our planet gradually warms. Global sea level has risen by about 20 cm over the past century, and the recent fifth assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5, hereinafter AR5) clearly shows that moderate to substantial further (and more rapid) rises can be expected in the coming decades to centuries (Rignot *et al* 2011, Church *et al* 2013). While uncertainties in future projections are considerable, it is by now clear that vast coastal areas may potentially be under threat, even if the rate of sea level rise will not accelerate. Impacts of sea level rise are obviously most pronounced for low lying coastal areas. The Netherlands are a classic example, where great effort has been and still is spent in protecting the land, which largely resides below current mean sea level, from the impacts of sea level rise. Present-day observed sea-level rise is on the order of 2–3 mm per year. Because of its direct relevance to national safety, local and regional governments require up to date information and accurate regional projections of future sea level rise.

1.1. A set of scenarios for the future climate of the Netherlands (KNMI'14)

The aim of this paper is to present a set sea-level scenarios for the North Sea. These scenarios are part of a larger set of climate scenarios issued by the Royal Netherlands Meteorological Institute (KNMI) for a range of atmospheric climate variables (temperature, precipitation, visibility etc), and are intended to provide consistent and plausible outlooks of the future climate in the Netherlands (van den Hurk *et al* 2006, 2014a). Global-mean temperature change (dTglob) is used as a steering variable. By this we mean that instead of

Table 1. Steering values of global-mean temperature change (with respect to 1986–2005 average) that are used in the KNMI'14 sea-level change scenarios.

Scenario/year	2050	2085	2100
G-scenario	+1.0 °C	+1.5 °C	+1.6 °C
W-scenario	+2.0 °C	+3.5 °C	+4.0 °C

creating future climate projections on the basis of various representative concentration pathways (RCPs) (Meinshausen *et al* 2011) as is done for example in AR5, we use global temperature pathways for discriminating between the different scenarios. There are two main reasons for using dTglob instead of RCPs. The first is the fact that sea level change, as well as many atmospheric climate variables, scales well with global temperature change (van den Hurk *et al* 2014b). Secondly, it is thought that dTglob is a variable more easily understood by the general public than the concept of RCPs.

Two distinct temperature pathways are chosen, corresponding to a moderate warming scenario (G) and a warmer scenario (W). Table 1 lists the values for three key years, relative to the reference period 1986–2005. For intermediate years, dTglob is linearly interpolated. The scenarios are therefore not very extreme in their choice of the dTglob; the G-scenario overlaps with RCP4.5 and W with RCP8.5.

1.2. Processes included in the KNMI'14 scenarios

Many different physical processes contribute to global and regional sea-level change (Church *et al* 2010, Dangendorf *et al* 2014a). Primary contributors to present-day and future sea level change are the expansion of the ocean due to warming and the reduction of the amount of water stored on land, mostly in the form of ice and snow (Church and White 2011, Church *et al* 2011, 2013). All contributing processes manifest themselves as a superposition of a slowly varying (trend)-signal and faster fluctuating components. These fluctuations imply that the exact future state cannot be predicted at long lead times. However, also the slowly varying (trend) signal is subject to considerable uncertainty, both because different models produce different results ('ensemble spread') and because of model inaccuracies, incomplete physics and methodological uncertainties (Hu and Deser 2013). The scenarios developed here aim to describe the slowly varying (climate) component. We now detail the processes included in KNMI'14 (Mathematical details in supplementary material appendix B).

1.2.1. Ocean expansion and circulation changes. The ocean may expand as a result of changes in ocean temperature and salinity. Changes in the ocean circulation (i.e., dynamics) also influence the sea level regionally. The ocean has a large heat capacity, and during warmer periods enormous amounts of heat are absorbed. These are advected horizontally as well as downward into the deep ocean, to be gradually released during cooler climatic periods. For this reason the oceans store a considerable amount of heat of the past climate, and its response to global warming is generally nonlinear. The ocean circulation changes, such as the response of the meridional overturning circulation and the ocean gyres, introduce more complexity to the problem, related to density changes resulting from temperature and salinity changes.

1.2.2. Glaciers and small ice caps. This term considers changes in surface mass balance (SMB) and dynamics of the glaciers and small ice caps. Included here are all glaciers worldwide, including those on Greenland and Antarctica that are not connected to the main ice sheets. Glaciers respond more rapidly to climate change compared to the ice sheets, so their short-term influence on the global and regional sea-level change is expected to be considerable. The total possible contribution from all present-day glaciers however, is modest (likely between 31 and 53 cm) compared to the large ice sheets (Arendt *et al* 2012, Huss and Farinotti 2012, Marzeion *et al* 2012, Grinsted 2013, Radic *et al* 2014). Important parameters influencing the mass balance of a local glacier are the regional climate (temperature and precipitation), as well as its orientation and altitude. Despite such subtleties, the total contribution from all glaciers together can be parameterized approximately in terms of global mean temperature change (van de Wal and Wild 2001, Slangen and van de Wal 2011). Regionalization is subsequently achieved by a process called dynamic fingerprinting, explained in section 2.3.

1.2.3. Large ice sheets. This term considers changes of the largest ice sheets on the planet, those of Greenland (GIS) and Antarctica (AIS). AIS contains by far the most ice. If it would melt completely, it would raise global mean sea level by more than 60 m. The GIS is much smaller and holds an equivalent of ~6 m of global sea level. Ice sheets will respond to climate change in two different ways. First there will be changes in their SMB, which is the sum of snowfall, summer melt of snow and ice resulting in liquid run-off from the ice sheet. Regional climate models forced by atmosphere-ocean global climate models (AOGCMs) are used to find suitable parameterizations of SMB in terms of dTglob (Fettweis *et al* 2013). Secondly, the ice sheets may also show a rapid dynamical response (DYN). The DYN-term describes possible changes in iceberg calving and basal melt of tidewater glaciers by warmer ocean water. Although the latter process does not contribute to sea-level rise *per se*, it is associated with ice flow from grounded glaciers to the floating ice shelves which does contribute to accelerated sea-level rise. Other mechanisms, such as marine ice sheet instability (Joughin and Alley 2011) may play a role. However, to date there is no consensus on the magnitude and time scale of the changes (Truffer and Fahnestock 2007, Vaughan and Arthern 2007, Little *et al* 2013), which translates in substantial uncertainty bands (Horton *et al* 2014, de Vries and van de Wal 2014).

1.2.4. Land water change. This term collects changes in the amount of water stored in the form of lakes and rivers, wetlands, as well as the seasonal snowpack at high altitudes and latitudes. Estimates of contributions attributable more directly to human activity, such as groundwater mining, dam building, and increased runoff due to changes in land use, are also included (Wada *et al* 2012).

1.2.5. Atmospheric pressure. Changes in the atmospheric pressure are reflected directly in sea level as for each mbar of pressure drop the local sea level increases 1 cm (the inverse barometer effect). Changes in the moisture content of the atmosphere may lead to additional modifications. In the global mean this term is near zero, but locally it can be a substantial contributor to sea level change (Slangen *et al* 2014).

1.2.6. Surface elevation. Changes of the earth surface elevation are not taken into account. These follow from glacial isostatic adjustment (GIA, the response of the earth crust to past ice sheet coverage) and other processes leading to subsidence (e.g., peat compactification). Thus, the scenarios described here are in essence scenarios of absolute sea-level rise. However, more instantaneous elastic deformations and gravitational changes resulting from future land ice melt are included (see section 2.3). GIA-induced sea-level trends are spatially non-uniform. Along the Dutch coast values are between −0.02 and +0.4 mm yr^{-1} (Peltier 2004).

2. Data and methodology

The data used in this study comprises of output from 42 AOGCMs that contributed to CMIP5 (Taylor *et al* 2012) and forced using representative concentration pathways RCP4.5 and RCP8.5. This data also formed the basis of much of the AR5 sea-level chapter. For the historic period, we use PSMSL tide-gauge data (www.psmsl.org) from six stations along the Dutch coast. Satellite altimetry data (1993–2013) is used from AVISO. Both tide-gauge and altimetry data have been GIA-corrected using ICE-5 G (Peltier 2004). Details are given in supplementary material A. To guarantee consistency the parameterized processes for ice-sheet and glacier contributions are computed following methods of AR5 (details in supplementary material B). For the DYN-AIS term a higher upper-bound is used to account for the uncertain and skewed shaped of the likely distribution (Katsman *et al* 2011).

2.1. Steering towards global temperature pathways

Sea level scenarios are constructed for two temperature pathways. This is achieved by using a temperature regression approach, which bears some similarities to the approach taken in Perrette *et al* (2013). We illustrate the technique for the global-mean ocean (steric/dynamic) contribution, but it is also used, to ensure consistency, for the contributions that are parameterized using dTglob (glaciers, ice sheet SMB).

For any given year, the first step is to compute 30 year central averages of the ocean contribution and dTglob for each of the 42 models. This yields 42 change values for each variable (symbols in figure 1). The ocean contributions are

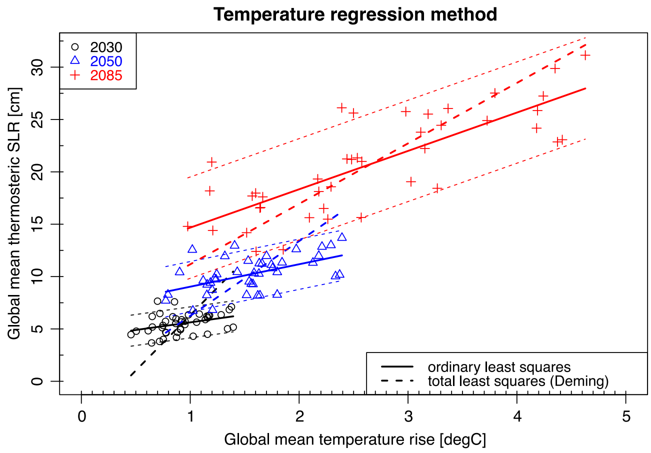

Figure 1. Illustration of the temperature regression approach for the global-mean steric/dynamic contribution to sea-level change. The symbols show 30 year model averages centred on the stated year. Linear regressions (full lines) and 90% confidence band (thinly dashed) are also indicated. Total least squares regression lines are shown as thick dashed lines.

then regressed on the global temperature changes. The central values for the ocean-contribution for the given year are estimated as the values predicted by the regression. A likely range is computed as the 90% confidence band around the predictions, assuming that the scatter is not strongly dependent on dTglob. The procedure is repeated for each year from 2000–2100. Figure 1 illustrates this for the global mean ocean contribution.

In using regression to estimate change coefficients it is silently assumed, as almost everyone does, that the regression model $y = a + bx$ is the appropriate one. Actually, it depends on whether x or y is assumed to have errors. If all uncertainty is in x or if both x and y have uncertainties then the ordinary least squares (OLS) method is biased. Whether the statistical model used here (OLS) is the correct one, nobody knows. However, we expect the uncertainty in dTglob to be much smaller than that of the ocean thermosteric expansion, as ocean models are notorious for their biases and different responses to changing forcing boundary conditions. For completeness, however, we have investigated the effect of using a total least squares regression (TLS) instead of OLS. The result is shown as the dashed lines in figure 1. A couple of things become clear upon comparing the two methods. First of all, the two methods indeed yield different solutions. However, differences are not excessively large in the predicted values; up to 2.5 to 3 cm (e.g. at dTglob = 3.5 for the 2085 line). Secondly, the TLS method gives rise to systematically larger regression slopes, thereby yielding larger W-scenario values, but slightly lower G-(=moderate)-scenario values. This is obvious since part of the variability in inter-model dTglob is interpreted as model uncertainty, whereas in OLS this would be exact. Thirdly, the differences between TLS and OLS appear to decrease at later years, when the variance becomes larger due to, for example, the different climate sensitivities of the AOGCMs. Given these arguments it seems reasonable to stay with OLS.

By carrying out the regression procedure for each year, the method is able to partly capture the nonlinear relation between the ocean steric-dynamic contribution and global temperature change. This becomes manifest in the gradual increase of the regression slope in figure 1 for different sight years. If the relation was dominated by nonlinearity, a widening of the residuals would be clearly visible at larger values of dTglob. This behaviour is not strongly visible in figure 1, but will lead to a slight overestimation (underestimation) of the uncertainty range for low (high) dTglob.

Some of the process contributions are parameterised in terms of dTglob (glacier contribution, and those from the SMB changes of the ice sheets). Formally these parameterizations allow arbitrary temperature pathways to be examined. Unfortunately, however, this does not hold for the ocean data. Our aim is to use a consistent approach through all components. For this reason, we have decided to adopt the same approach to the glacier and ice sheet SMB contributions as to how we determined the ocean steric/dynamic response fields.

2.2. Distribution sampling

At a given lead time each contribution produces a distribution of possible outcomes. Not all processes can be modelled simultaneously in a fully interacting way by a single global climate model or earth system model. Therefore, we have incomplete knowledge of possible covariances and correlations between the individual terms. To resolve this, the different contributions are combined using a sampling approach (supplementary material A.2). This approach is similar to AR5 and retains the correlations between global temperature and the ocean thermal expansion fields. A likely range is determined from a high and low percentile of the sampled distribution. Note that the range of total sea level change is not equal to the sum of the individual ranges. The median can be approximated reasonably accurately as the sum of the individual medians:

$$m_{\mathrm{tot}}(t) \approx \sum_i m_i(t), \qquad (1)$$

where $m_i(t)$ is the median from process i in period t, and the sum runs over all contributing processes. Other percentiles can be approximated as

$$q_{\mathrm{tot}}(t) \approx m_{\mathrm{tot}}(t) + \operatorname{sgn}(\alpha_q)\sqrt{\sum_i \left[q_i(t) - m_i(t)\right]^2}, \qquad (2)$$

where $q_i(t)$ denotes the qth percentile of the distribution of process i and α_q is the quantile function of the normal distribution. Equations (1) and (2) are exact for gaussian distributions, but in our scenarios give results within 5 cm of the direct estimate. Figure 2 illustrates this for synthetic data of three distributions.

2.3. Regional response fingerprints

Regional sea-level estimates are obtained from the global estimates by taking into account the fact that the meltwater from for example the glaciers will not distribute evenly over the oceans due to the elastic deformation of the solid Earth and gravitational and rotational changes induced by the accompanying change in mass distribution (Milne *et al* 2009, Katsman *et al* 2011). As a result, a shrinking land ice mass yields a distinct pattern of local sea level rise referred to as its 'fingerprint' (Mitrovica *et al* 2001). The gravitational, elastic and rotational effects are accounted for by multiplying each of the global mean contributions from ice melt from glaciers and ice sheets by their relative fingerprint ratios, which are taken from Katsman *et al* (2011) and Slangen *et al* (2014).

The glacier fingerprint in the Netherlands is around 75% of the global mean and decreases over the 21st century to 70% due to the changes in the locations of the dominant glacier sources. The Antarctic contribution reaching the North Sea exceeds the global mean (110%–120%), while, in contrast, the contribution from GIS is only around 20%. However due to its proximity there is a sharp gradient of the GIS fingerprint over the North East Atlantic. Since the KNMI'14 scenarios are tailored to the Dutch coast, we use the fingerprint values closest to the North Sea coast. Finally, the landwater fingerprint is about 75% of the global mean.

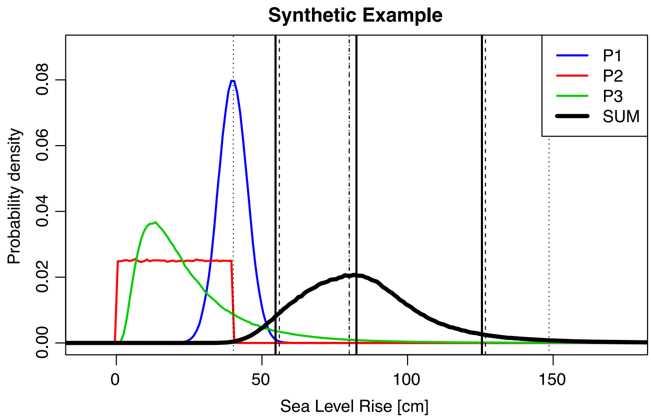

Figure 2. Synthetic example, in which three contributions to sea-level rise with different underlying distributions (Gaussian (P1), uniform (P2) and log-normal (P3)) are summed. The P05, P50 and P95 percentiles of the sum are also shown (full vertical lines). Two approximations of these quantiles are also shown, one based on the sum of individual quantiles (dotted lines), the other (dashed lines) on using equation (2).

3. Results

3.1. Two scenarios for the North Sea

Figure 3 shows our key-result for the North Sea region (defined as the sea within the rectangular box bounded by 3.5° W–7.5° E and 51–60° N). Observations are included as 5 year (+ sybols) and 30 year running averages (black line) of 6 tide-gauge stations along the Dutch coast (see supplementary material A). Also shown (green *x*) is the 5 year running average satellite altimetry over the North Sea, obtained from AVISO.

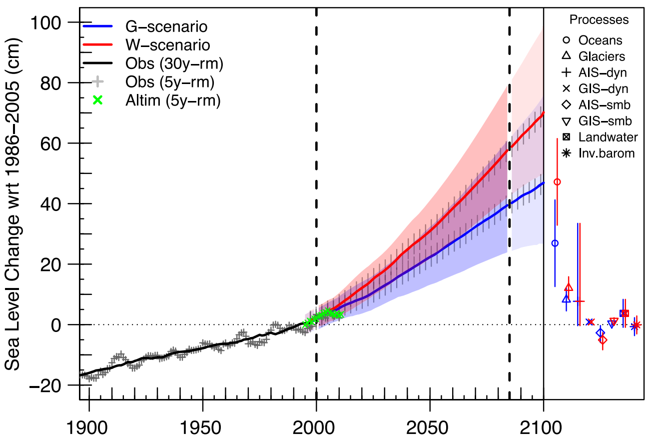

Figure 3. Scenarios for sea-level rise along the North Sea coast. The vertical axis denotes 30 year running mean sea-level change in cm, relative to 1986–2005. For years before 2000 and beyond 2085, the mean was taken over an increasingly smaller window and is drawn in a different shading. Estimates of natural variability at 5 year time-scale (see text for details) is included in the range and shown as vertical dashes. The black line denotes the 30 year running mean through tide-gauge observations along the Dutch coast, grey + symbols the 5 year running means (see text for details). The green *x* symbols show 5 year running means from satellite altimetry over the North Sea, with respect to 1993–1997 mean. The right margin shows the ranges from the different processes in 2100.

Unsurprisingly, sea levels along the Dutch coast increase in both scenarios, with the W (warm) scenario giving +45–80 cm in 2085 for dTglob = +3.5 K and the moderate scenario (G, +1.5 K in 2085) +25–60 cm. We state these numbers rounded to 5 cm precision, to emphasise that, despite all efforts in the computation, even the lower and upper limit are intrinsically uncertain. The nonlinear shape of the curves reveals that the rate of sea-level change increases in both scenarios. Needless to say is that sea levels will keep rising long after possible future stabilization of temperature rise.

The largest contribution is from the ocean expansion. Second largest are glaciers and small ice-caps. Especially near the end of the 21st century, the likely range strongly widens in both scenarios. This widening is partly caused by the relatively large model-uncertainty in the ocean component, but also by the large possible range of the rapid dynamic component of the Antarctic ice sheet (AIS-dyn), as can be seen from the process contributions in the right margin of figure 3. This component is estimated to be strongly asymmetric around the median (symbol), reflecting the large uncertainty in the upper-bound. The only negative contribution to global sea-level relates to the SMB changes of Antarctica. Precipitation increase and hence increasing accumulation is the main driver behind this. Changes in GIS have relatively little impact near the Dutch coast.

The grey + symbols show the 5 year running averaged observations. Clearly there is considerable natural variability around the 30 year running mean. The start of the 21st century is characterized by values lower than the average trend, which is reflected both in the tide-gauge and altimeter record, for reasons to be investigated further. The shaded scenario bands include a rough estimate of the internal variability and are

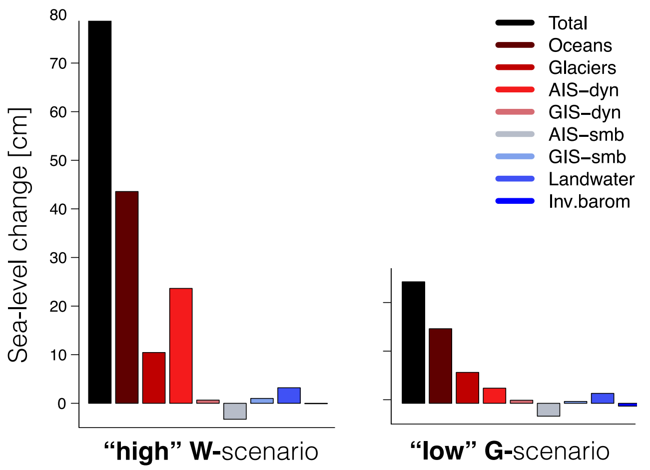

Figure 4. Contributions (cm) to the high W-scenario (left) and the low G-scenario (right) in 2085.

also shown as vertical dashes. This term is computed here simply as the variance of the 5 year running average deviations from the 30 year running mean, and is seen to fit well with the typical fluctuations in the observational record.

Internal variability of sea level occurs on a variety of time scales, from short to very long (Church *et al* 2010, Dangendorf *et al* 2014b). This makes it more difficult to detect possible accelerations in regional sea-level rise. Studying 5 year running deviations is just one way to discuss qualitatively the role of internal variability. The shortest time scales are removed by considering 5 year running means. By subtracting these from the 30 year running means, we remove the trend, as well as most of the variability on time-scales beyond 30 year (these should be visible in the black line, but are small). The scenario bands have approximately enough spread to cover variation from natural fluctuations. If, on the other hand, we would have constructed the scenarios by averaging over a larger basin (for example the North Atlantic, or even the entire globe), the spread would have been reduced considerably. Such scenarios would not be suited to describe the natural fluctuations in the North Sea.

3.2. Low-end and high-end scenarios

The right margin in figure 3 shows that all components are accompanied by considerable uncertainties. Therefore, it is instructive to compare these for total rises near the lower and upper limit of the estimated ranges. Figure 4 shows such a comparison. It displays the process contributions in 2085 for a high W-scenario (values within 2.5 cm of the upper limit of the W-scenario) and a low G-scenario (values within 2.5 cm of the lower limit). The low G-scenario has markedly smaller contributions from all components, but most noticeably from the steric/dynamic (ocean) component and from AIS-dyn, reflecting the large uncertainty in the latter given it is parameterised independent of dTglob (supplementary material B.3).

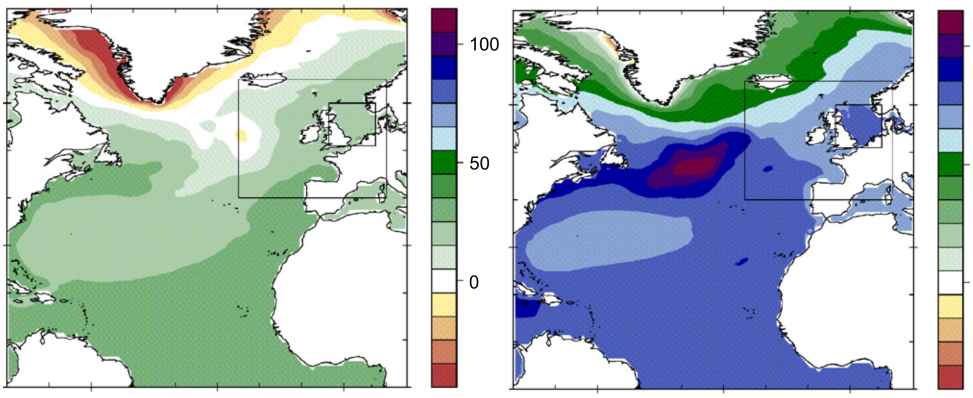

Figure 5. Lower value of sea level change (P05) of the G-scenario (left) and and upper value (P95) of the W-scenario in 2085. Numbers indicate cm of change w.r.t. 1986–2005.

3.3. Gridded scenario patterns

In addition to the time-series for the specific target areas, scenarios have been constructed for each geographical location separately. This has been done only for the target sight years of 2050 and 2085 and using a smaller sample-size. The results take the form of gridded maps, which can be used to examine the spatial robustness of the local scenarios discussed previously.

Figure 5 shows the low-G and high-W scenarios in 2085 for the North Atlantic, confirming that the scenarios not only differ in magnitude but also regionally. There is a clear South-East to North-West gradient in the scenario values, mostly related to the GIS-fingerprint. These distinct spatial gradients in the patterns have been a major motivation to use the North Sea scenario values as the ones most relevant to the Netherlands. However, despite the better agreement with the observations, there are good reasons to not zoom into a too small region of the globe. Perhaps the most important caveat is the regional pattern of expansion related to changes in ocean dynamics. At present the confidence in the ability of climate models to simulate these changes correctly is low, due to their coarse resolution. Well known biases in ocean circulation in the northeast Atlantic are a too zonal North Atlantic Current, which in the observations is steered by the Mid Atlantic ridge, a feature only simulated by ocean models at roughly 0.25°resolution or higher. This bias causes the subpolar gyre to extend too far to the east, resulting in too large sea-surface height (SSH) gradients in the northeastern basin. This may affect the simulated dynamical response when the subpolar gyre is projected to weaken. Also, the connection between shelf sea (North Sea) and deep ocean is not well resolved in climate models. Gradients in SSH between shelf sea and deep ocean may exist, associated with slope currents, but these features are absent in coarse resolution climate models.

4. Conclusion and discussion

In this paper a set of sea-level scenarios have been developed for the North Sea, in which global temperature change is used as a steering variable (KNMI'14). The two scenarios (G and W) follow different temperature 'pathways', in which global temperature increases only moderately (G), or more strongly (W). Uncertainty is included by expressing the scenarios as ranges. Each range is given by the 5%–95% percentile range obtained from a distribution of sea-level projections for the 21st century (Note that in AR5 this is defined as the likely range). The scenarios have been tailored to the North Sea region, but the methodology is straightforwardly implemented for any other area. As an example we discuss a gridded W-scenario for the North Atlantic (figure 5).

The KNMI'14 scenarios are consistent with IPCC AR5 (Church *et al* 2013), but provide for a different viewpoint, because of the use of temperature pathways rather than RCPs. For the North Sea area the results are broadly similar to the global mean estimates. When comparing individual contributions, however, there are minor differences, related for instance to the relative proximity of the Greenland ice sheet. The W-scenario (figure 3) shows large overlap with RCP8.5-based sea-level change estimates, the G-scenario is more similar to RCP4.5 and RCP6.0 scenarios. Because of the choice of our temperature pathways, RCP2.6 scenarios fall below our two scenarios. Similarly there are differences between the KNMI'14 scenarios presented here and those previously issued as KNMI'06 (van den Hurk *et al* 2006). Apart from more thorough treatment of the uncertainties, KNMI'14 uses the fingerprinted, local responses for some of the contributions, whereas KNMI'06 used global-mean values. Also the ocean steric/dynamic component is larger in KNMI'14. Although we generally have low confidence in the accuracy of the AOGCMs in correctly representing the changes in the North Sea (see discussion at the end of section 3.3), we feel justified in retaining the North Sea as the main target region because it matches the variability in the observed record along the North Sea coast reasonably well. If a larger domain would have been taken (the large square in figure 5), the variability is found to be considerably smaller (not shown).

A question that comes up naturally when constructing a set of climate scenarios is at what time-horizon the magnitude of the mean changes becomes larger than the natural

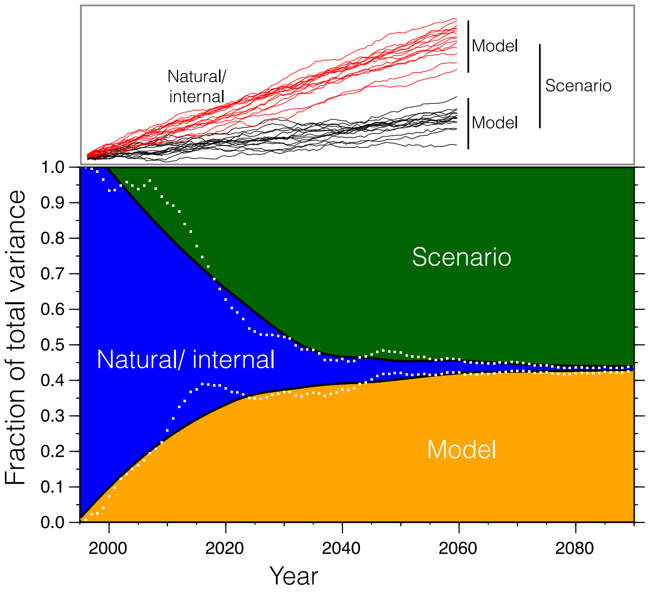

Figure 6. Top: schematic representation of the three-way variance partitioning (see text for explanation). Bottom: relative contributions to the total variance in projected sea level (North Sea). The black lines are a spline fit through the white dotted lines (unsmoothed) results.

variability. Another issue relates to the time-horizon at which the different scenarios become significantly different. As can be seen in figure 3, the two temperature-dependent scenarios retain overlapping uncertainty bands all the way up to 2100. Furthermore, the estimates of natural variability (vertical bars in figure 3) show that initially the spread is dominated by internal variability. To get some insight into this issue we write the total variance as a sum of three contributions

$$\sigma_{\rm tot}^2 = \sigma_N^2 + \sigma_M + \sigma_S^2 \qquad (3)$$

with N the natural or internal variability, M the model uncertainty and S the scenario spread (Hawkins and Sutton 2009). A schematic picture is given in figure 6 (top). For the present paper the natural variability (N) is estimated as the ensemble-mean of the variance of the 5 year running deviation from the individual predictions (i.e., the 'wiggliness' around the straight lines). The model uncertainty (M) is estimated as the variance of the scenario bands, averaged over the different scenarios. Finally the scenario uncertainty (S) is the variance between the scenario-central estimates. Figure 6 (bottom) shows how the relative importance of these three terms changes over time for the sea-level scenarios for the North Sea coast. Initially most of the variance is attributed to the internal variability (blue), consistent with figure 3. However, the other two terms become rapidly more important. Yet, model uncertainty and natural variability will still make up for more than half the total variance up to 2030. Beyond that, the scenarios become more discriminating, although model uncertainty will remain a large contributor to the total uncertainty until the end of the 21st century.

To reduce the model uncertainty demands a better understanding of the two components that display the largest uncertainties: those of the ocean (steric/dynamic) and especially in the long run, the changes of the Antarctic ice sheet.

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