A model study of factors influencing projected changes in regional sea level over the twenty-first century

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Abstract In addition to projected increases in global mean sea level over the 21st century, model simulations suggest there will also be changes in the regional distribution of sea level relative to the global mean. There is a considerable spread in the projected patterns of these changes by current models, as shown by the recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4). This spread has not reduced from that given by the Third Assessment models. Comparison with projections by ensembles of models based on a single structure supports an earlier suggestion that models of similar formulation give more similar patterns of sea level change. Analysing an AR4 ensemble of model projections under a business-as-usual scenario shows that steric changes (associated with subsurface ocean density changes) largely dominate the sea level pattern changes. The relative importance of subsurface temperature or salinity changes in contributing to this differs from region to region and, to an extent, from model-to-model. In general, thermosteric changes give the spatial variations in the Southern Ocean, halosteric changes dominate in the Arctic and strong compensation between thermosteric and halosteric changes characterises the Atlantic. The magnitude of sea level and component changes in the Atlantic appear to be linked to the amount of Atlantic meridional overturning circulation (MOC) weakening. When the MOC weakening is substantial, the Atlantic thermosteric patterns of change arise from a dominant role of ocean advective heat flux changes.

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1 Introduction

Projected increases in sea level under business-as-usual (BAU) greenhouse gas scenarios for the 21st century have serious implications for society and ecosystems. The coastal population is also projected to increase, compounding the potential impact of sea level rise on communities and assets. In addition to the direct threat of flooding, particularly in low lying regions with limited adaptive capacity, the coastal ecosystems and resources they provide are also vulnerable. The projected global sea level increases are a result of the thermal expansion of the ocean as temperatures increase, together with increasing inflow of water from land-based ice melt. There are also potentially more direct anthropogenic contributions to sea level, for example arising from changes in reservoir storage. The recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report ('AR4'; Meehl et al. (2007)) gives a range of 0.18–0.59 m for global sea level rise between the 1980–1999 and 2090–2099 periods. This is primarily based on projections by an ensemble of current coupled climate models, run for a number of plausible BAU socio-economic scenarios, with simple climate model results used to scale to alternative scenarios. Land–ice melt contributions were derived from

model surface temperature projections and mass balance sensitivity estimates.

Local sea level generally differs from the global-mean, under the influence of ocean circulation together with regional variations in ocean density and atmospheric pressure (the 'inverted barometer' effect). Climate model projections for the 21st century suggest that as well as global mean sea level changes, the large-scale spatial pattern is also liable to change, potentially having a significant effect on local sea level rise. Projected atmospheric surface pressure changes should comprise a relatively small component of influence on the large-scale regional sea level changes represented in general circulation models, given the projected magnitudes of pressure change (Lowe and Gregory 2006). A further influence on regional sea level comes from changes in the gravitational attraction of ocean water to the ice sheets (e.g. Mitrovica et al. 2009) as these ice masses are reduced under the influence of global warming. This effect would become increasingly significant for rapid net ice sheet melt, for example a collapse of the West Antarctic Ice Sheet. For recent decades, observed regional sea level rates of change vary from location to location: the 1993–2003 altimeter measurements show local rates that can reach about five times the global mean rate (Bindoff et al. 2007). These recent regional variations are thought to primarily reflect an influence of decadal variations rather than a long term trend.

In general, climate models show limited agreement between projected 21st century changes in regional sea level relative to each model's own global mean (Gregory et al. 2001; Church et al. 2001; Meehl et al. 2007). This increases overall uncertainty in projected local sea level rise. Some progress has been made towards understanding the projected regional changes and model spread in these. In an assessment of a range of models, Gregory et al. (2001) suggested that those which were more structurally similar tended to produce more similar patterns of regional sea level change. For a single model (run under an idealised greenhouse gas increase scenario), Lowe and Gregory (2006) analysed the pattern of projected changes in terms of components, such as the expansion/contraction given by temperature or salinity changes of the water column. They found that changes in surface heat, freshwater and wind stress all played a role in the regional changes relative to the global mean, with the effects of these on ocean density (rather than on the barotropic circulation) being generally dominant.

Several studies have suggested links between regional sea level changes and a projected weakening of the Atlantic meridional overturning circulation (MOC). A reduction in the Atlantic meridional gradient of sea level has been associated with a collapse of the MOC in model sensitivity studies (Levermann et al. 2005; Vellinga and Wood 2007).

A more localised pattern of change in the north-west Atlantic, consisting of a meridional dipole or tripole, has been associated with projected 21st century changes in the North Atlantic Current, which is a component of the MOC (e.g. Bryan 1996; Gregory et al. 2001; Suzuki et al. 2005; Landerer et al. 2007b). The absence of such a dipole pattern was also noted in a future projection where the MOC did not weaken (Gregory et al. 2001). Yin et al. (2009) compared projected North Atlantic sea level pattern changes in their model with those in a MOC weakening sensitivity study and concluded, on the basis of their similarity and a mechanistic analysis, that MOC changes were primarily responsible.

In the northern mid-latitude Pacific, some model studies have shown a projected north–south dipole pattern of change in sea level in the opposite sense to that in the Atlantic, indicating an increase in sea level gradient and consistent with an increase in the strength of the Kuroshio current (Suzuki et al. 2005; Landerer et al. 2007b). A northward shift of the boundary between North Pacific subtropical and subpolar gyres may also contribute to the regional pattern of sea level change there under global warming (e.g. Sato et al. 2006).

Model studies have generally shown smaller than global mean increases in sea level in the cold Southern Ocean waters. This has been linked to the relatively small expansion of colder waters here for a given addition of heat (e.g. Russell et al. 2000; Lowe and Gregory 2006), together with export of heat from, and possibly reduced heat import to, this region. This southern region of relatively small increase in sea level forms a dipole with a band of larger-than-global-mean sea level increase at its northern flank. This south–north dipole has been associated with changes in the Antarctic Circumpolar Current (e.g. Gregory et al. 2001; Suzuki et al. 2005; Landerer et al. 2007b). Arctic sea level projections tend to be greater than the global mean (e.g. Meehl et al. 2007), and it has been suggested that this is associated with freshening of this region (e.g. Bryan 1996; Russell et al. 2000; Landerer et al. 2007b).

Despite progress that has been made on understanding projected changes in sea level regional distribution relative to the global mean, primarily from analyses of individual models, there remains a substantial range in these local projections relative to the global mean. In this study, we use a common framework analysis, primarily of an AR4 ensemble of models, to understand factors contributing to this range. We analyse the relationship of projected changes in sea level to aspects of the model behaviour, particularly the model steric changes and the roles of temperature and salinity changes in this. For the Atlantic, we analyse links between the sea level component changes and the MOC.

This paper is organised as follows. Section 2 discusses the model ensembles which were used for our study. Section 3 shows the projections of regional sea level change for the most recent multi-model ensemble (AR4) and looks at aspects of their relationship to the simulated sea level distribution prior to introducing trends in anthropogenic greenhouse gases. Section 4 discusses the spread of the regional projections in this ensemble relative to an earlier generation ensemble and to ensembles of models formed from varying parameters in a single model structure. The relationship of the regional sea level changes to the steric component changes (and temperature and salinity parts of this) are discussed in Sect. 5, with a more detailed focus on the Atlantic/Arctic and adjoining Southern Ocean region. Section 6 focuses on the relationship of the Atlantic sea level and steric component changes to MOC changes and to the underlying temperature and salinity distributions of the water column. The paper ends with a summary and discussion in Sect. 7.

2 Climate model ensembles

2.1 Multi-model IPCC-related ensembles

We have primarily considered projections of regional distribution of sea level relative to the global mean as given by a coupled ocean-atmosphere model ensemble used by AR4. We have also compared some aspects of these projections to those from the IPCC Third assessment report ('TAR', Church et al. 2001) ensemble. The individual models in the TAR and AR4 ensembles were developed by different modelling groups and generally differ in their structure (e.g. model resolution, parametrizations of physical processes which take place at the sub-gridscale etc.). The AR4 models are taken from the third Climate Model Intercomparison Project (CMIP3) and are also known as CMIP3 models. The future projections of these 'multi-model ensembles' cover a range of uncertainty associated with their dissimilarity in model formulation. The AR4 models are a generally newer and more advanced generation of models (e.g. in terms of resolution, complexity) than was used for the TAR. Our main analysis uses a slightly different subset of the AR4 models (the thirteen member AR4_13 ensemble) than was used for analysis of regional sea level projections in AR4 (the sixteen member AR4_IPCC ensemble). In general coupled climate models undergo some drift in climate, even without trends in external forcing agents, as they approach a state where the surface fluxes provided by the atmosphere model are in balance with the ocean state. The AR4_13 ensemble was selected on the basis of our having concurrent control simulation data (for which concentrations of greenhouse gas and other radiative forcing agents are fixed) to the 21st century projected changes, as well as the necessary sub-surface temperature and salinity data for our analyses. The concurrent control simulations enable a common approach to removal of model drifts in order to obtain climate trends related to changes in external forcings. Documentation of the AR4 models is available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory (http://www-pcmdi. llnl.gov). Some features of the climate models (e.g. ocean model resolution, use of free surface or rigid lid ocean model boundary condition) are compared in Table 8.1 of AR4.

The AR4_13 and AR4_IPCC ensembles (which consist of one simulation for each model) use the special report on emissions scenarios (SRES) A1B future scenario, following on from historical (C20) simulations starting in the mid 19th century, which in turn were initialised from the control simulations. Under the A1B scenario, CO_2 concentrations increase to 720 ppm by 2100 and additional radiative agents increase the overall radiative forcing to approximately that equivalent to a CO_2 increase of 835 ppm (Meehl et al. 2007). Not all of the radiative forcing agents, however, are specified by the SRES scenarios and the AR4 models differ somewhat in these. The TAR ensemble consists of simulations run under the IS92a scenario or an approximation to that. The forcing change over the 21st century is similar for the SRES A1B and IS92a scenarios, with estimated increases of 4.76 W/m^2 for IS92a and 5.00 W/m^2 for A1B (TAR Appendix II.3, Table I.3.11), although integrated over the century the A1B forcing is greater due to its timeseries profile (TAR, their Fig. 9.13a). In terms of the influence of the two scenarios on sea level, the central estimates of global-mean thermal expansion for the 21st century are similar for the TAR and AR4 A1B ensembles.

For the AR4_13 ensemble, we calculate the 21st century change in regional sea level between the time mean 1980–1999 and 2080–2099 periods. Model drift is estimated using trends in the parallel section of the control (CTL) simulation. The change in sea level over the section of control simulation that runs parallel to the projections (between the control simulation 20 year time periods 'T1' and 'T2') is thus subtracted from the change in sea level over the projection timeperiod: $[(A1B_{2080\text{-}2099} - C20_{1980\text{-}1999}) - (\text{CTL}_{T2} - \text{CTL}_{T1})]$. When determining the significance of sea level changes relative to unforced variability, we removed the higher frequency changes in the control simulation before calculating CTL_{T2} and CTL_{T1}.

The sea level diagnostics should not include the influence of atmospheric pressure changes, but as noted earlier this effect should be relatively small. In some models, a 'rigid-lid' ocean surface boundary condition is used, where

addition or subtraction of surface freshwater fluxes does not affect the ocean volume. In such models sea surface height gradients can be inferred from the equation of motion (as discussed by Gregory et al. (2001)) and sea surface height relative to the global mean can be diagnosed. Other models have a "free surface" boundary condition where sea surface height and the volume of the ocean are naturally linked. Sea surface height changes provided by the modelling groups and used in this study will thus have been diagnosed in a number of ways. In regions of sea ice, there may be some differences between models in what the sea surface height diagnostic represents. For some models this will include the water equivalent of the sea ice while for others it may not. Regions of sea ice are small in terms of global ocean area, but such differences in diagnostic definition would have an effect on, for example, gradients of sea level change at the Arctic boundaries as sea ice melts under global warming. In this paper we focus primarily on the steric components of regional sea level change, which are calculated in the same way for all models.

For the TAR ensemble, the change in sea level is calculated from the final model decade relative to the decade 100 years earlier, as in the TAR sea level analysis (Church et al. (2001), their figure 11.13 and their Table 9.1 for future scenario details and references), so model drift is not removed. As we are primarily interested in comparing the large-scale patterns of regional sea level change between models, we have conservatively re-gridded the projected changes to a common grid for much of this analysis. We have generally used a low resolution model grid for this, of resolution 5° longitude by 4° latitude, although for the spread of projected changes in ensembles (spatial correlations, standard deviations) we follow the AR4 report and use a 1° by 1° grid. Regional sea level changes in the models show large-scale patterns across the global oceans and these changes, which we focus on in this study, can be compared at low resolution. Smaller scale changes will be represented in more detail in the higher resolution models and an analysis of local coastal changes, for example, would need to carefully consider the effects of averaging over a coarse resolution grid.

2.2 Perturbed parameter QUMP models

Ensembles linked to the Quantifying Uncertainty in Model Projections (QUMP) project of the Met Office Hadley Centre (initial project results discussed in Murphy et al. (2004)) were used for comparison of ensemble spread of regional sea level projections with those of the TAR and AR4 multi-model ensembles. QUMP ensemble coupled models are based on the HadCM3 atmosphere-ocean model structure (with inclusion of an interactive sulphur cycle) and alternative model versions were created by perturbing model

parameters (within plausible limits). In this study we have used two QUMP ensembles of A1B scenario projections together with their respective historical simulations. The first of these ensembles consists of model versions created by simultaneous perturbations of multiple parameters (from a selection of 31 parameters/switches) in the atmosphere model, including some sea–ice parameters contained within the atmosphere component (QUMP_AFA, 17 members, one of which is the standard "unperturbed" version). The second consists of versions with simultaneous perturbations of ocean model parameters (QUMP_OFA, 16 members), where these parameters control aspects of the resolved and sub-grid scale transports of heat, salt and momentum in the horizontal and vertical. Flux adjustment was applied to these ensembles, ensuring a fairly stable control simulation surface climate while allowing a greater range of model parameter space to be sampled (without tuning of other model parameters). The control model simulations did not extend over the full period of the projections, so any model drift was not removed. More details of these QUMP ensembles can be found in Murphy et al. (2007) where they are referred to as PPE_A1B and PPE_A1B_OCEAN.

3 Regional sea level projections in the IPCC AR4 models

Projected 21st century changes in sea level relative to the global mean will consist of a component associated with changes in greenhouse gas and other external forcing agents, together with a component of change arising from variability that would occur in the absence of trends in external forcing. We identified AR4-model projected regional changes which are greater than the 95% significance level given by unforced variability in the control simulations (estimated using 20 year averages, accounting for autocorrelation and with model drift removed), assuming this variability remains unchanged under different levels of external forcing. The major large-scale features of projected changes for the ensemble generally differ from model to model but remain significant when the unforced component for each model is taken into account (Fig. 1). The more common of these significant regional changes for the ensemble are identified as where at least two thirds of the members have significant local changes (as in Fig. 1) of the same sign (Fig. 2a). The AR4 report identified regions of relatively common response (their Fig. 10.32) as where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeded 1. This does not take into account individual model unforced variability, although many of the common features of change identified in AR4 are similar to those of Fig. 2, but more restricted in regional extent.
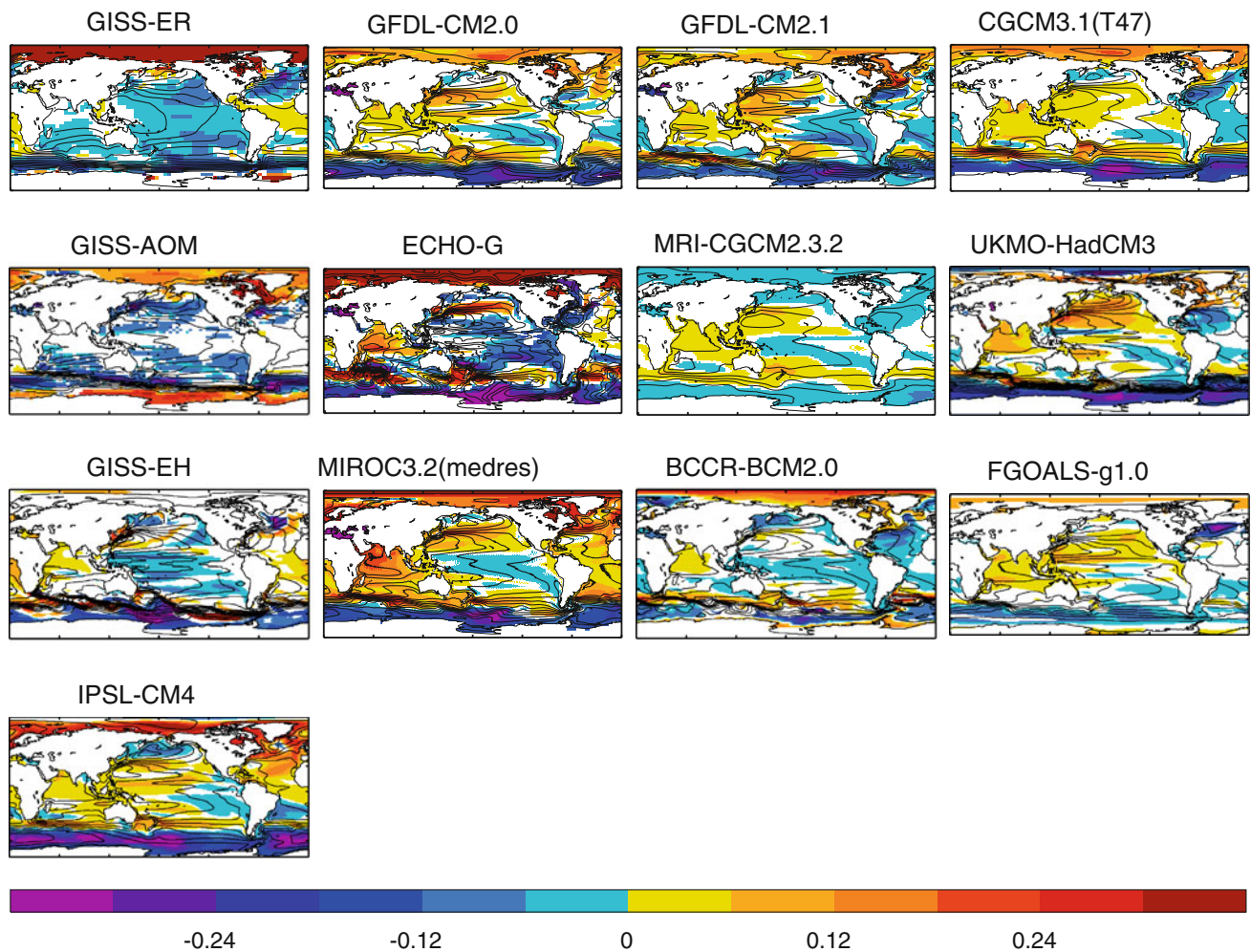
Fig. 1 Sea level changes (1980–1999 to 2080–2099, units of meters) for each of the AR4_13 ensemble of models, relative to each model's global mean. The overlying *contour lines* are of the sea level distribution in the baseline control simulations, averaged over the period parallel to the 1980–2099 projection period (contours are every 0.2 m, *thick countours* for zero and positive deviations; *thin contours* for negative deviations). Changes shown above the 95% significance level given by unforced variability, as determined from the control simulation (using 20 year averages, model drift removed by first applying a high-pass Chebyshev filter with a half-power cut-off of about 165 years). A Student-*t* test (with degrees of freedom from lag-1 autocorrelation) was applied to obtain the significance level. The unforced variability was removed from the control simulation point-by-point (using the filter described above) before calculating and removing model drift, so as to better determine significance of the projected changes. All model data on grids as provided to CMIP3 database. A version of this figure including changes below significance level is shown in Online Resource 1

The more common regional sea level changes relative to the global mean sea level change in the AR4_13 ensemble (Fig. 2a) include the tendency to greater sea level rise in the Arctic (as an example of the differences between this and the AR4 criterion results, the AR4 identified a region that was much more restricted to the Arctic coast), although as can be seen from Fig. 1, this does not apply to all models. There are also commonly increases in Baffin Bay and in the Labrador Sea. There is a common negative change (relative to the global mean change) evident to the south of the Gulf Stream which forms part of an ensemble mean dipole with positive changes to the north. There is a further negative anomaly extending eastward from the South American coast near 20°S. In the Southern Ocean there is a common negative change in a latitude band centered near 60°S, which tends to form a meridional dipole with a band of positive change further north (near 40°S). The Indian Ocean projections are generally greater than the global mean. In the South Pacific there is a common band of negative change extending westward from the South American coast. In the north-west subtropical Pacific, positive changes are located in the Kuroshio current region and in its eastward extension, forming part of an ensemble mean dipole with common negative changes to the north. There remain, however, sizeable areas of the ocean where the sign of model ensemble sea level
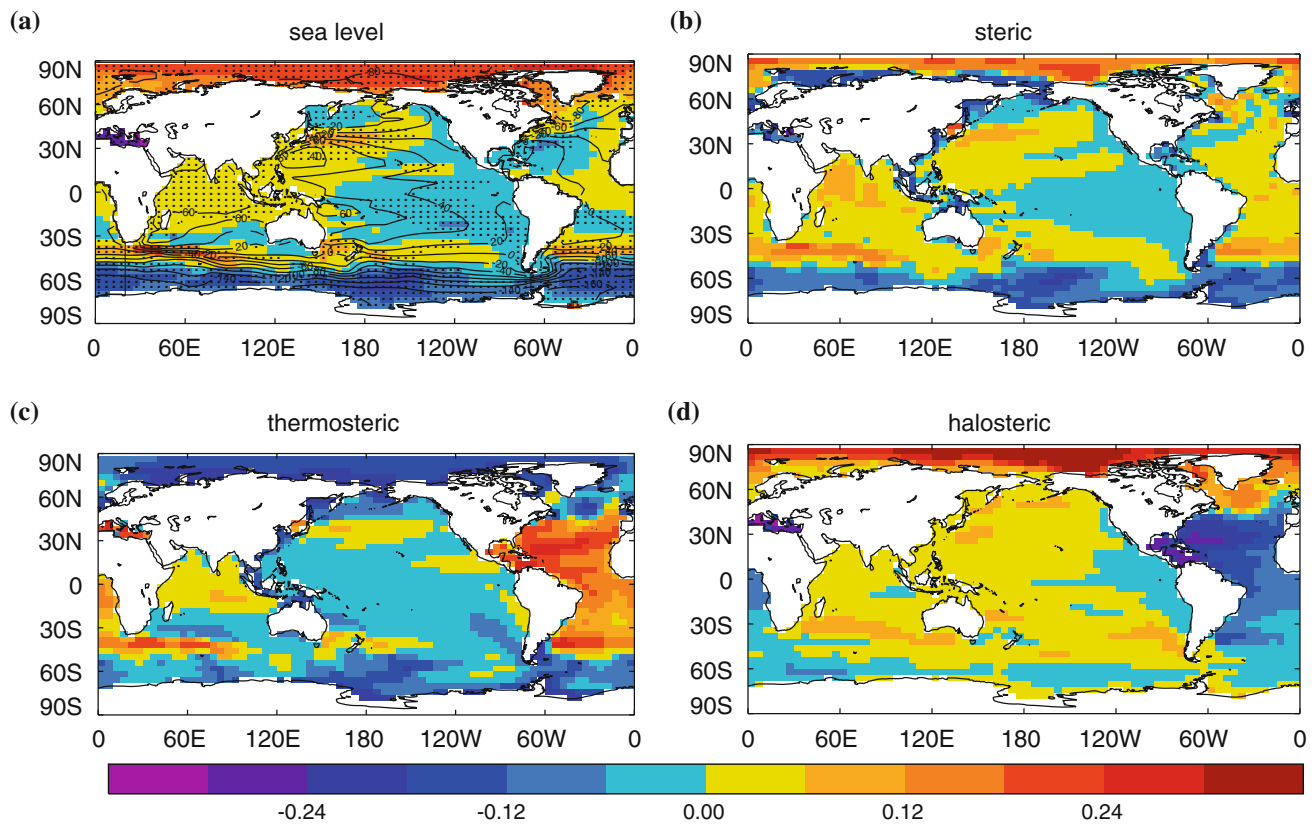
Fig. 2 Ensemble average of AR4_13 model sea level (**a**), steric (**b**), thermosteric (**c**) and halosteric (**d**) subcomponent changes over the 21st century (2080–2099 minus 1980–1999, units of meters) relative to the global mean. Regions where the global-warming-related regional sea level changes show some similarity beween the ensemble members are shown by areas of stippling in (**a**), which mark where more than 66% of the ensemble members have local changes of the same sign and are greater than the 95% significance level when unforced variability is taken into account (as in Fig. 1). The ensemble mean control simulation sea level (for the time period parallel to the projection period 1980–2099) is overplotted as contours (cm) on the sea level changes in (**a**). Ensemble mean changes are of model data (shown in Fig.1 for sea level), regridded to a common grid (5° × 4°), and is only shown where all models have data. Many inland seas areas are thus not shown, but data in these regions may in any case be unhelpful as climate model inland seas may sometimes be unrealistically not connected to the global ocean. The ensemble mean change in sea level is very similar to the change if control drift is calculated from 20 year differences of unfiltered control data (as was used for the steric changes). *Thick black line* in (**a**) shows borders of Arctic/Atlantic and adjoining Southern Ocean section region referred to in paper

changes is not in agreement (Fig. 2a) and even in the areas of agreement the changes can vary substantially in magnitude between models.

Some efforts to reduce uncertainty in future projections of surface temperature have used a weighting derived from model biases against observed climatology, but such an approach may not be valid for sea surface height, partly because the observational sea level records are shorter and subject to more uncertainty (Meehl et al. 2007). Relationships between present-day climate state in a model simulation and its future projections may, however, provide insight relevant to diverse sea level projections (e.g. Russell et al. 2006). We have made a preliminary comparison between changes in regional sea level and the time-mean sea level distributions in the model base state (over plotted as contours in Figs. 1, 2a), which also show model-to-model differences. All parameters for these comparisons

are calculated after conservatively re-gridding to the common 5° × 4° grid. In the ensemble mean, many of the maxima or minima of sea level change are located around regions of large sea surface gradient in the base state, suggesting that model representation of the position and degree of these gradients might influence the changes in regional sea level. In addition, visual comparison between the ensemble member base states and projected changes (Fig. 1) do appear to show some instances of correspondence (e.g. the relatively 'flat' base state and projected changes for the MRI-CGCM2.3.2 model). Spatial correlations between the base states and projected changes, however, vary widely with coefficients between −0.66 and 0.81. The fact that the regional patterns of change do not necessarily correlate well with the base state sea level distributions shows that the projections are not in most cases a global scaling of the existing balance of

Table 1 Measures of the spread of regional sea level change relative to the global mean for the ensembles (described in Sect. 2) we have used

Ensemble name	TAR	AR4_IPCC	AR4_13	QUMP_AFA	QUMP_OFA
No. of members	9	16	13	17	16
Future scenario	IS92a	A1B	A1B	A1B	A1B
Model structure	Various	Various	Various	HadCM3(Atm. pert.)	HadCM3(Ocn. pert.)
% >0.5 correlation	14	25	14	96	98
Global avg. σ (cm)	4.97	7.11	10.45	2.80	2.75

The percentage of correlation coefficients exceeding 0.5 between all possible pairs of ensemble members and the global average of the point-by-point standard deviations (σ) of the ensemble projections are given. All fields were conservatively re-gridded to a 1° by 1° grid before calculating these quantities

mechanisms. There is, however, some tendency for the magnitude of gradients of sea level change to be linked to the magnitudes of the existing gradients (spatial correlations range from 0.26 to 0.84 with nine members > 0.5). Furthermore, a globally-averaged measure of both regional sea level deviations in the base state and of sea level projected changes shows close links between these fields: their spatial root-mean-square (RMS) values have a correlation of 0.76 across the ensemble (95% significance level of 0.62). This could be because the degree of both may be controlled by the same properties within each model formulation, although we cannot at present make further links to model parameters or schemes.

4 Spread of regional sea level projections

The first question we address is whether the spread of regional sea level projections relative to the global mean has been reduced in the more current AR4 set of models relative to those used for the TAR. As we noted earlier, the central estimates of global thermal expansion for the TAR and AR4 (A1B) projections are similar, being 0.27 and 0.23 m respectively over the 21st century (with a small difference in time periods used). The spread of projected regional changes within an ensemble can be analysed using pattern correlations between its members, which can identify similarities in the shapes of features. The analysis for the AR4 report found that the patterns of sea level change within the AR4 IPCC ensemble were more similar to each other than those in the TAR ensemble. This is based on comparison of the percentage of coefficients exceeding 0.5 for correlations between all pairs of projections within the ensembles (Meehl et al. 2007). This greater similarity between AR4 projection patterns than between those from the TAR, however, is not evident when using our AR4_13 ensemble (Table 1). As another measure of the spread, we evaluated at each location the standard deviation (σ) across the models of the projected changes
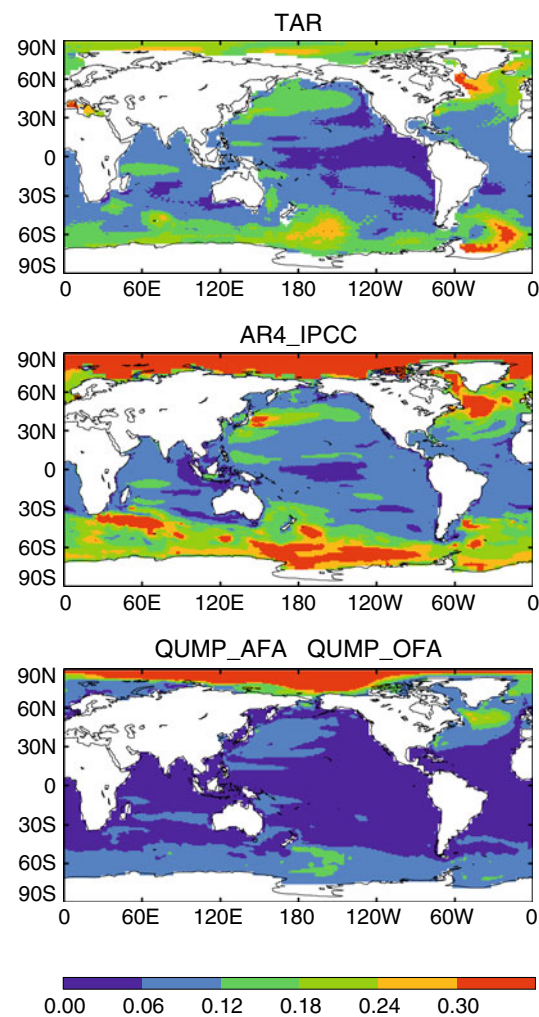

Fig. 3 Spread (represented by twice standard deviation (2σ) among models, units of meters) of local sea level changes relative to the global mean over the 21st century. Spread shown for the TAR ensemble (using final model decade relative to decade 100 years earlier, as in the TAR analysis), the AR4_IPCC ensemble (1980–1999 to 2080–2099) and combined QUMP_AFA and QUMP_OFA ensembles (time periods as for AR4_IPCC but shifted earlier by 1 month). See Table 1 and Sect. 4 for details. All projected changes were regridded to a 1° by 1° grid before calculating 2σ

(2σ fields shown in Fig. 3)). The global averages of σ for each ensemble (Table 1) show that the spread in magnitude of changes is greater for both the AR4_IPCC and AR4_13 ensembles than for the TAR ensemble (Table 1), particularly at higher latitudes (Fig. 3). The spread of projected regional sea level change has thus not been robustly reduced for the AR4 generation of models.

Previous work (Gregory et al. 2001) has suggested that models that are similar in formulation tend to give more similar sea level pattern changes. In addition to our comparison of the multi-model AR4 and TAR ensembles, we have also analysed projections from QUMP model ensembles, where the models share a common structural basis model. Both the pattern correlation and standard deviation measures indicate that the spread of projected regional sea level change in the QUMP ensembles is substantially less than in the AR4/TAR ensembles (Table 1; Fig. 3). Collins et al. (submitted) find that there is similarly a smaller range of climate error patterns in QUMP-type models than AR4 models in a comparison using ensembles of atmosphere models coupled to a mixed layer ocean ('SLAB' ocean model), although they suggest that the QUMP experimental design may play some role in this. Differences in climate model errors may play an important role in projected changes (e.g. Russell et al. 2006). To understand the role of flux adjustment for projected regional sea level changes relative to the global mean, we also analysed two additional QUMP-type coupled ensembles run without flux adjustment (under an idealised future scenario). We found their spread of regional sea level changes to be small, similarly to those from QUMP_AFA and QUMP_OFA. This comparison thus supports the tendency for models of more similar formulation to give more similar regional sea level projections.

The AR4 noted that sea level pattern changes for the same model under different scenarios were qualitatively similar. The sea level pattern changes we have used are thus representative of the models and suggest that model formulation is largely responsible for uncertainty in this. Nicholls et al. (2009) showed that for HadCM3, the A2 and IS92a scenario regional sea level projections relative to the global mean could be appropriately scaled by the ratio of global-mean thermal expansion. While such scaling may be valid for individual models, we found no significant correlation between the global-mean thermal expansion and a global measure (spatial RMS) of the regional sea level deviations for the sample of eleven CMIP3 models for which we have both these quantities. This is true whether the model changes are on the latitude-longitude grids provided or re-gridded to the common $5° \times 4°$ grid before performing the calculations (spatial RMS is equivalent to the spatial standard deviation for the original grid data where the global mean is then zero, regridding will slightly change the global mean). This implies that in a particular model, the processes or model properties that control the degree of model global thermal expansion may also be important for the magnitude of regional changes in sea level, but from model to model the important processes may differ.

5 Regional steric sea level changes

Regional sea level change can be considered to consist of components associated with aspects of the ocean density distribution and circulation, as discussed in detail by Lowe and Gregory (2006). The 'baroclinic' component is related to changes in the ocean density fields and the 'barotropic' component is related to the depth-mean horizontal circulation. Where changes in density are restricted to the upper part of the ocean column, the baroclinic component is closely approximated by steric expansion or contraction of the ocean water column (Lowe and Gregory 2006) as follows:

$$\Delta\eta_{\text{Steric}} = \int_{-H}^{\eta} \frac{\Delta\rho}{\rho_{\text{ref}}} dz \approx \int_{-H}^{\eta} \frac{\Delta\rho_{(T,S_{\text{ref}})}}{\rho} dz + \int_{-H}^{\eta} \frac{\Delta\rho_{(T_{\text{ref}},S)}}{\rho} dz$$

(1)

The steric changes are from changes in density ($\Delta\rho$), relative to a reference state (ρ_{ref}), integrated vertically (over z). For this study, the integral is to the fixed bottom topography depth H for convenience, as this avoids choosing a level of no motion, which would be required by the usual oceanographic method of computing dynamic topography (see Gregory et al. 2001). When the steric approximation to the baroclinic term is a good one, the depth of integration is not critical, because by assumption the changes in density are only important near to the surface. The steric sea-level change can be decomposed approximately into thermosteric and halosteric components (the first and second terms on the right hand side of Eq. 1), which are calculated by only changing the temperature (T) or salinity (S) respectively in the density change calculation. These underlying changes in ocean temperature and salinity are determined by the balance of changes in surface fluxes and ocean transport processes. For several of the AR4 models, the temperature and salinity fields are not provided on the original model vertical (and sometimes horizontal) grids and the calculations are thus not exact.[1]

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[1] In the course of answering reviewer comments we found that for one model (GISS-ER) the difference between the global thermal expansion provided by the modelling groups, and alternatively calculated using subsurface model temperature data provided in the CMIP3 database, was sufficiently large as to give some concern about the accuracy of the steric component patterns for this model. Excluding this model from our analysis of steric components would not affect the conclusions in this paper.

Table 2 Spatial correlations between, and spatial RMS values of, sea level and component changes in AR4_13 ensemble

Correlations of changes	Ens. mean	Ens. range	Fraction > or < value
Sea level-steric	0.65	−0.12 to 0.98	11/13 > 0.5
Steric-thermosteric	0.56	0.25 to 0.74	9/13 > 0.5
Steric-halosteric	0.12	−0.07 to 0.41	0/13 > 0.5
Thermosteric–halosteric	−0.75	−0.84 to −0.53	13/13 < −0.5
RMS of changes (m)	Ens. mean	Ens. range	Avg. for ens. members
Sea level	0.07	0.02 to 0.23	0.11
Steric	0.06	0.05 to 0.12	0.10
Thermosteric	0.10	0.06 to 0.22	0.13
Halosteric	0.08	0.06 to 0.19	0.11

These parameters are calculated for the ensemble means and for each member of the model ensemble to give some measures of the ensemble distribution. These distribution measures include the ensemble range, the average of RMS values for the ensemble members and the fraction of members having correlations between components greater or less than 0.5. All fields were conservatively re-gridded to a common $5° \times 4°$ grid before calculating these quantities and a common land mask applied

The ensemble mean steric, thermosteric and halosteric changes relative to the global mean for the AR4_13 ensemble are shown together with the sea level changes in Fig. 2. The patterns of change in sea level and steric component are very similar, showing a strong link of regional sea level change to this component. It should be noted that local changes in sea level or its steric components relative to the global mean are not necessarily related to any local changes in forcing. A large negative anomaly, for example, may represent a lack of change in local sea level, with the anomaly arising because of the analysis procedure (subtraction of the global mean). Local comparison between changes in steric components relative to the global mean are also subject to such non-local influences. Spatial gradients are not, however, affected by removing the global mean and our analysis includes a comparison of component spatial variations.

Relationships between the sea level component changes over the globe can be evaluated by using spatial correlations and by comparison of spatial RMS values, both for the ensemble mean and the individual ensemble members (Table 2). Such an analysis shows the similarity between sea level and steric changes for the ensemble mean, as noted above, although such similarity is not evident for one or two of the ensemble members (Table 2).[2] In the Arctic, however, there are notable differences between the ensemble mean sea level and steric component changes (Fig. 2, pattern correlation increases from 0.65 to 0.76 if Arctic is excluded), as previously shown for HadCM3 under an idealised future scenario (Lowe and Gregory 2006). Close to the coast, differences between sea level and

steric changes are more prevalent. Steric expansion will tend to be more limited in shallow shelf regions as there is less water to expand. In addition, the steric approximation to baroclinic sea-level change is not accurate in shallow water. For the full baroclinic sea level change it is not sufficient to consider only the local density change; instead, gradients must be calculated, whereby coastal sea-level change is linked to density change off the shelf. Landerer et al. (2007b) and Yin et al. (2009) note that when shallow shelf water columns only allow a much smaller steric expansion than in the adjoining deep water columns, sharp increases in steric gradient across shelf breaks cannot be balanced by geostrophic currents and so result in a redistribution of water (a mass-loading) to increase the sea level in the coastal regions. The extensive shallow shelf regions in the Arctic and in parts of the northern Atlantic may be particularly prone to this effect (Landerer et al. 2007a).

Projected changes in the thermosteric component generally correlate better than those of the halosteric component to the steric changes (Table 2). There is a strong anticorrelation between the thermosteric and halosteric subcomponents which reflects the tendency for density compensation in their contribution to regional sea level change, especially in the Atlantic and Arctic.

The spatial RMS of the sea level changes is 7 cm for the ensemble mean (on the common $5° \times 4°$ grid), but ranges between 2 and 23 cm for the ensemble members. The regional deviations from the global mean are thus a substantial fraction of the global-mean changes ($\approx 20\%$ of the AR4 central estimate for the A1B scenario) even at the relatively coarse resolution of the common grid. The average spatial RMS of sea level change for the ensemble members is greater than the RMS of sea level change for the ensemble mean, reflecting the tendency of the ensemble meaning process to smooth features of sea level change.

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[2] If the GISS-ER model is excluded, the ensemble mean correlation between the sea level and steric component changes increases to 0.74 and the minimum correlation for the ensemble increases to 0.39.
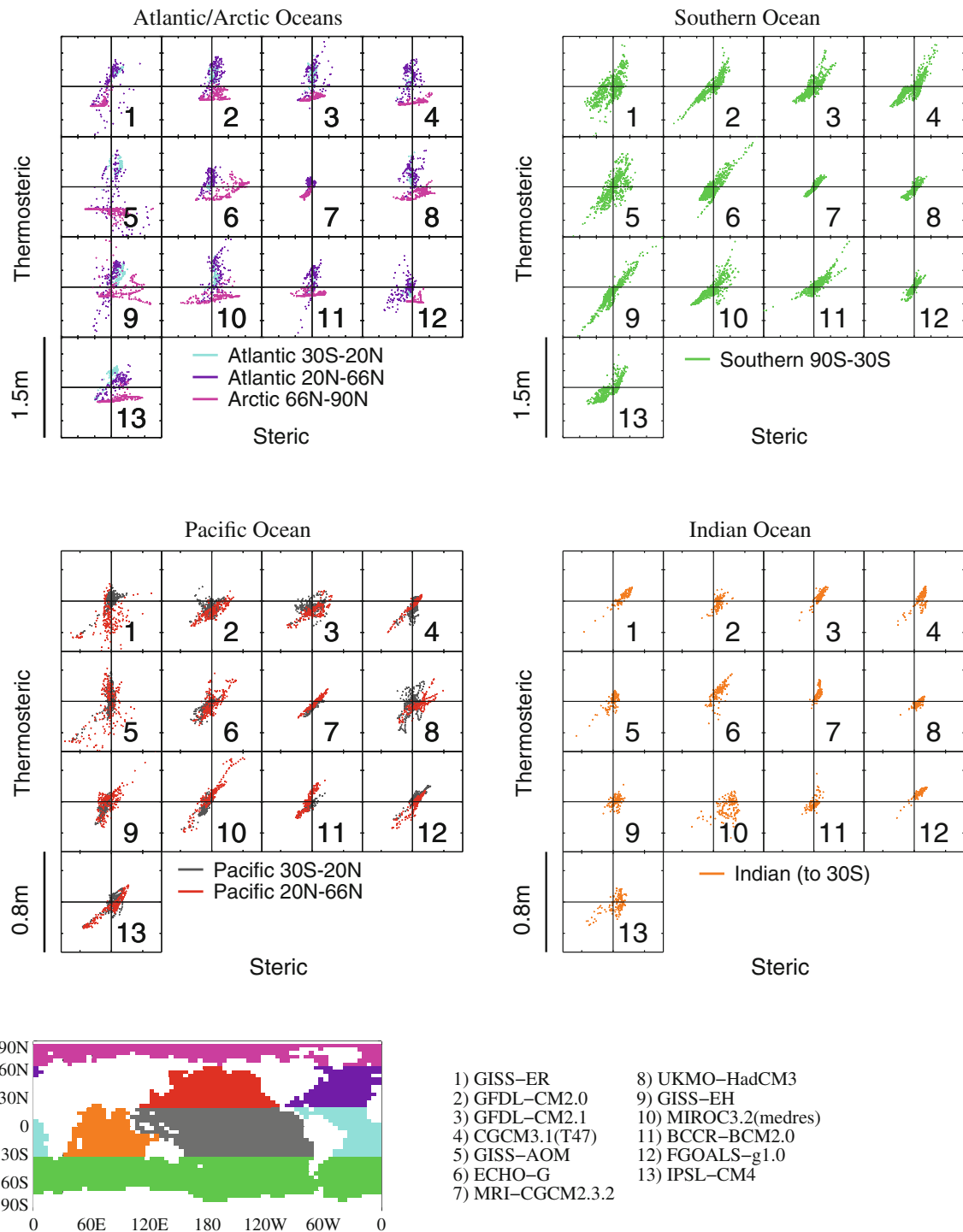
Fig. 4 Relationship between spatial variations in steric and thermosteric components of sea level change (1980–1999 to 2080–2099) for each model (numbered) in subareas of the global ocean which are colour coded as shown in the accompanying map and line keys. *Each point represents the change in steric (x-axis) and thermosteric (y-axis) components relative to the global mean, in gridboxes on a common grid (5° × 4°). The points will tend to lie parallel to the y = x line when the steric spatial variations are dominated by the thermosteric component and parallel to the x-axis when dominated by the halosteric component. For strong density compensation between halosteric and thermosteric variations, the points will lie parallel to the y-axis. The *cross hairs in the boxes* represent the zero axes and each division of the box surrounds represents 0.25 m. The scales for each subregion are shown adjacent to the bottom box

The relationships between changes in sea level components may differ from region to region as well as model-to-model and these differences are not identified by the global parameters of Table 2. These regional relationships can be shown using the forms of grid-box-by-grid-box scatterplots for each model (Fig. 4). These scatterplots show the local steric and thermosteric changes within a number of regions which are designed to encompass particular common model features (Fig. 2a) and/or regions of large spread in model sea level change (Fig. 3). Since local steric change and its components are expressed relative to their global means, comparison of the magnitudes of their local values does not necessarily indicate which component is most important in determining the regional pattern, as pointed out above. However, spatial gradients are unaffected by subtracting the global mean, so it is possible to make inferences from the comparison of spatial variations in steric change and its components. In regions where the pattern of steric sea-level change is dominated by the thermosteric component, the points in the scatter plots of Fig. 4 will tend to lie parallel to the $y = x$ line. Where the pattern is dominated by the halosteric component, they will be parallel to the x-axis i.e. steric sea-level varies geographically but its thermosteric component does not. Where there is strong density compensation between the components, the points will lie parallel to the y-axis i.e. steric sea-level is geographically constant, but its thermosteric component varies, being cancelled by the halosteric component.

The scatterplots show many similarities between models in the steric component relationships for the Atlantic/Arctic region (Fig. 4). In the Atlantic, the models generally show substantial compensation between the halosteric and thermosteric component changes (clusters extending along or close to the y-axis) with relatively small steric changes, as already seen for the ensemble means (Fig. 2). The magnitudes of the thermosteric and halosteric component changes, however, differ fairly substantially from model to model. Over the Arctic, spatial variations are largely determined by the halosteric component. The thermosteric changes are more uniform over the Arctic and are predominantly negative. The magnitudes of these Arctic steric component changes differ between models.

In the Southern Ocean, the ensemble mean steric changes (which strongly resemble the sea level changes) show much more similarity to the thermosteric changes than to the halosteric changes (Fig. 2). The scatterplots show that this is also the case for the individual models, although for some (e.g. GISS-ER) broadening in the y-axis direction shows a role for some compensation from the halosteric component. Therefore the positive gradient of sea-level change from south to north across the Southern

Ocean, seen in all models, is predominantly thermosteric; the reduced sea-level to the south is due to a relative lack of thermal expansion. Over the Pacific and Indian Oceans, the ensemble-mean steric change is mostly thermosteric, including the pronounced sea-level rise in the Kuroshio region, with a generally positive halosteric addition. The scatterplots show, however, that in these oceans, there is a variety of behaviour among the models. The GISS-AOM model, for example, shows substantial compensation between the halosteric and thermosteric gradient changes over much of the Pacific, whereas for the MRI-CGCM2.3.2 model the Pacific steric changes and its gradients are dominated by thermosteric changes.

For the remainder of this study we concentrate on the projected sea level changes in the Atlantic/Arctic and its adjoining Southern Ocean sector. As we have shown, within each of these regions the steric component relationships tend to be similar amongst the ensemble members, but with wide variations in the magnitude of component changes. The zonal mean changes in sea level and its components for this region (Fig. 5) allows us to look at the spread of model changes in an alternative way, highlighting the latitudinal variations. Many features of projected sea surface height changes (Fig. 1) and components of this tend to be fairly zonal, consistent with the changes being due to enhancements/reductions or meridional shifts of underlying zonal features, e.g. associated with the Antarctic Circumpolar Current. For the individual models, the zonal-mean component changes in this Atlantic/Arctic/Southern Ocean region generally track the broader-scale increases or decreases with latitude of the ensemble means.

6 Atlantic sea level changes and the MOC

A reduction in the MOC is a robust feature of almost all TAR and AR4 model projections under 21st century BAU future scenarios, although the amount of weakening can vary substantially, being 0–50% or more in the AR4 models (Meehl et al. 2007). None of the AR4 models simulates an abrupt shut-down of the MOC within the 21st century. As noted in Sect. 1, a number of studies have discussed possible connections between Atlantic sea surface height and MOC changes. For selected AR4 generation models, Yin et al. 2009 and Katsman et al. 2008 have linked projected increases in sea level relative to the global mean, at localised northern Atlantic regions, to MOC decreases. We have used a correlation analysis between sea level changes (together with components) and changes in the MOC at 30°N (MOC_30) to highlight associations over the Atlantic for the AR4_13 ensemble (eleven models are used for which the MOC changes are

Fig. 5 Zonal mean changes
(1980–1999 to 2080–2099) in
sea level and steric,
thermosteric and halosteric
subcomponents relative to the
global mean for each model of
the AR4_13 ensemble, in the
Arctic, Atlantic and adjoining
section of the Southern Ocean
(region as shown masked in
Fig. 2a). Zonal mean changes
are interpolated to a 1°
latitudinal spacing
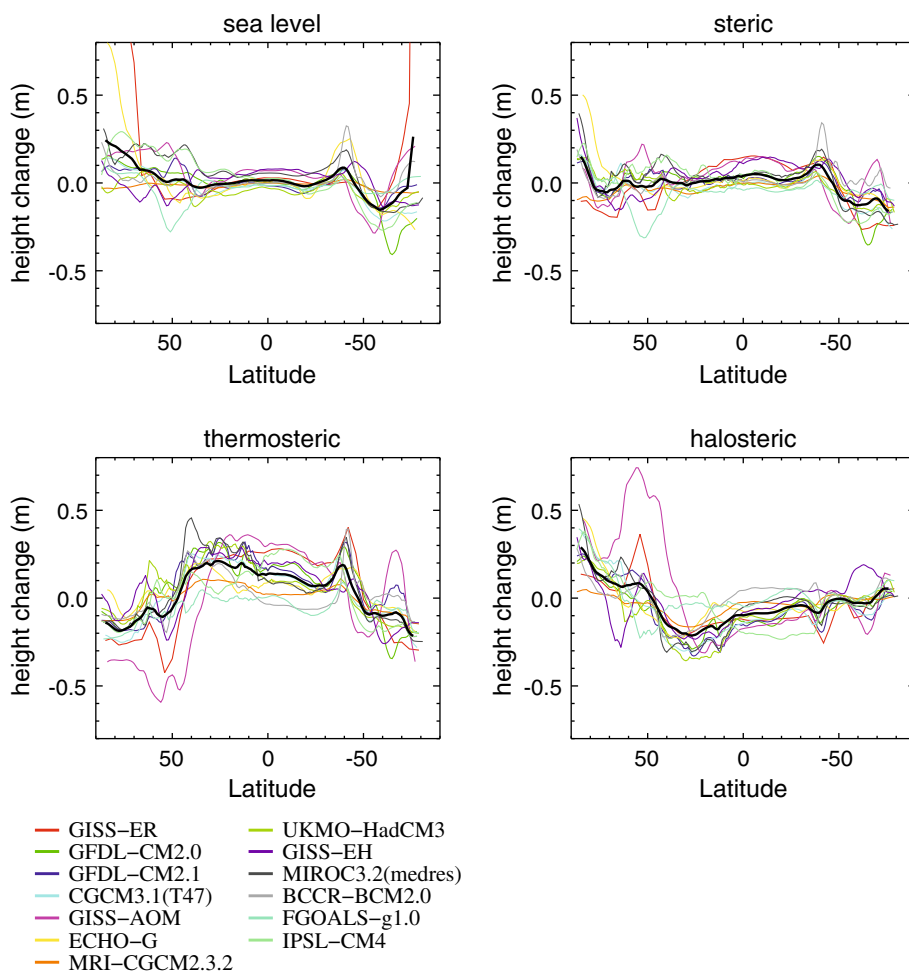
available).[3] Correlation, however, does not necessarily reflect causal relationships and a mechanistic analysis is necessary to establish any causal link.

The large-scale pattern of correlation between sea level and the MOC is similar to the correlation pattern for the steric component (Fig. 6, top row), with some differences around coastal regions and in the Caribbean, Gulf of Mexico and North Sea. In general, sea level and steric changes over the Atlantic (30°S to Greenland–Iceland–Scotland ridge) correlate negatively with the MOC, indicating increasingly positive sea level changes for larger MOC decreases. The regions where these correlations are significant at the 90% level are fairly well distributed over the Atlantic for the steric changes. The small ensemble size will inevitably make it difficult to identify changes as robust if they occur with some scatter (which might arise from, for example, unforced variability).

The thermosteric and halosteric components of sea level change relative to the global mean show a large scale north to south change in sign of correlation with MOC_30 changes (Fig. 6, top row). When the GISS models, which show fairly distinct changes in these components in the northern Atlantic (Fig. 5), are excluded (leaving 8 models) the correlations are generally weaker, the change in sign is shifted northwards, and the northern regions fall below significance (Fig. 6, bottom row). The thermosteric(halosteric) component is negatively(positively) correlated with MOC_30 in the tropical-subtropical part of the basin, but positively(negatively) correlated in the northern Atlantic. These correlation patterns suggest that the overall basin-scale positive change in steric sea level for greater weakening of the MOC tends to be dominated by the halosteric term (freshening) in the more northerly Atlantic and by the thermosteric term (warming) to the south. The precise locations of the largest changes in the northern Atlantic thermosteric and halosteric subcomponents tend to vary from model to model (these may be affected by, for example, locations of deep ocean convection), and these regional details are likely to affect the strength of

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[3] The iap model is excluded as it has a near collapsed MOC in the latter part of its twentieth century simulation (Meehl et al. 2007 their Fig. 10.15).
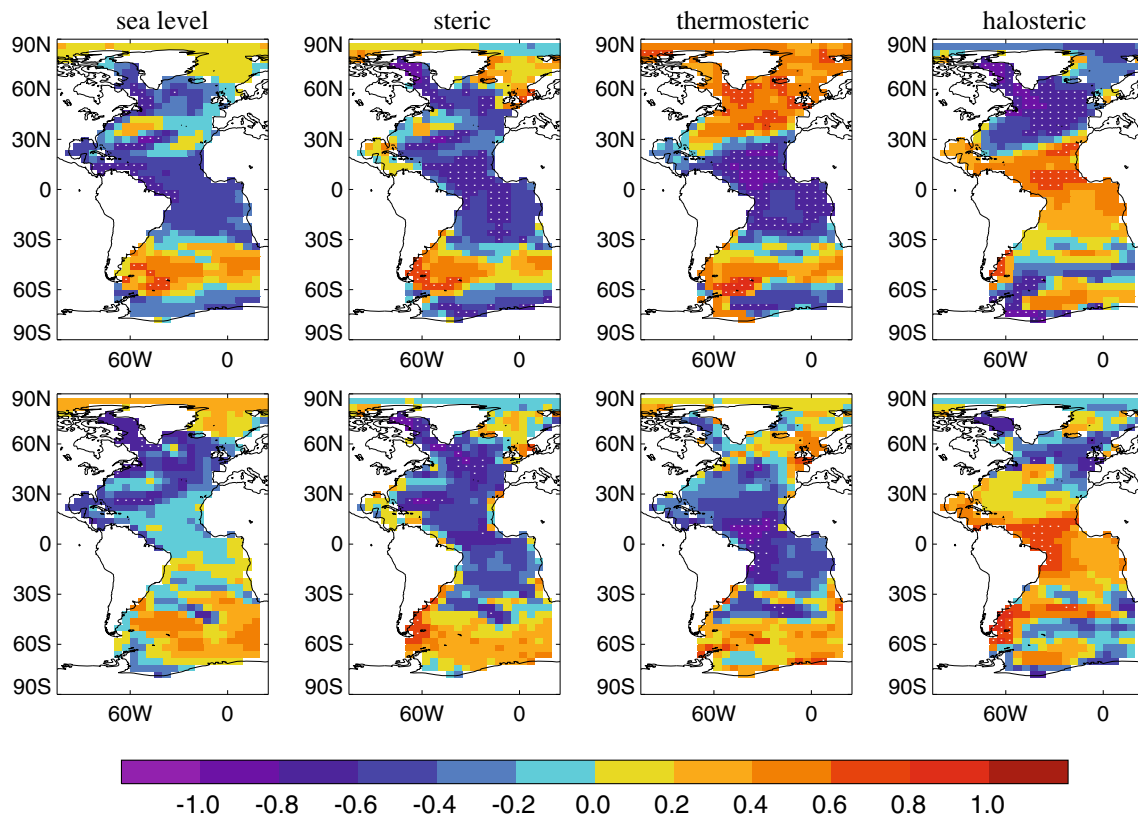
Fig. 6 For each Atlantic grid cell, correlation coefficients among models for sea level change (1980–1999 to 2080–2099) or components relative to the global mean, with MOC changes at 30°N. Correlation patterns along the top row are for the 11 models of AR4_13 for which we have all necessary fields, while correlations along the bottom row exclude the GISS models. *Areas of white stippling* indicate that the correlation is significant at the 90% level. All data were regridded to a common 5° × 4° grid before calculations

point-by-point correlations. Larger-scale changes in the halosteric and thermosteric subcomponents also, however, reflect a north–south change in their relationship with MOC changes, albeit with some scatter (Fig. 7). There are some regions of relatively high correlation between sea level component changes and MOC_30 in the Southern Ocean, but we do not focus on them in this paper.

The GISS-AOM, MRI-CGCM2.3.2 and UKMO-Had-CM3 models project the largest, smallest, and a more typical, reduction in the MOC at 30°N respectively for the ensemble. Consistent with the correlation plots of Fig. 6, these models also tend to reflect much of the ensemble spread in sea level component changes (Fig. 5). The anti-correlated thermosteric and halosteric contributions for these example models are the result of anticorrelated changes over much of the water column (Fig. 8). The much reduced magnitude of these component changes in the MRI-CGCM2.3.2 model relative to the GISS-AOM model are associated with subsurface temperature and salinity changes that are much more confined to the shallower part of the water column. The sharp gradients of thermosteric and halosteric change near 40°N for the GISS-AOM model are underpinned by a northward transition from warming/

salting to cooling/freshening, while for the more latitudinally flat subcomponent changes in the MRI-CGCM2.3.2 model there is a only a gradual reduction in the warming/ salting as you move further north. The UKMO-HadCM3 changes are broadly intermediate to these two more extreme model changes. There appears to be some correspondence between the profiles of these subsurface changes and baseline model fields (Fig. 9). The greater confinement of the potential temperature changes to the upper part of the water column in the MRI-CGCM2.3.2 model relative to the GISS-AOM model, for example, is reflected in differences between the baseline model thermoclines which are relatively shallow or extend to greater depth respectively.

Changes in ocean temperature and salinity that underlie steric changes, arise from the balance of changes in surface and ocean advective fluxes. Analysing and understanding changes in the model heat and freshwater budgets thus allows closer investigation of the processes involved in sea level change. Here we focus on Atlantic heat budget changes, which we present and discuss as relative to their global mean changes, in order to correspond with the thermosteric changes. The zonal-mean net heat content changes per unit area for the GISS-AOM, UKMO-

HadCM3 and MRI-CGCM2.3.2 example models clearly reflect the features of their respective thermosteric changes (Fig. 10). Much, but not all of these heat content changes arise from temperature changes in the upper 1,000 m of the Atlantic. For the GISS-AOM model, the overall form of the changes in heat content with latitude is evident from the upper 1,000 m changes, but the deeper ocean contribution is generally similar in magnitude. The changes in zonal-mean heat content are a residual of the larger, strongly anti-correlated contributions from changes in surface and ocean transport fluxes (Fig. 10). Such anti-correlation might arise, for example, from increased input of heat at the surface being subsequently dispersed by the ocean advection or from increased advective convergence of heat leading to greater heat loss at the surface.

In the northern Atlantic, the models show a tendency for the surface heat flux changes to warm (relative to their global ocean average effect) and the advective flux changes to cool, while south of around 35°N the surface fluxes generally cool and the advective fluxes warm. All three models show relatively large net increases in heat content per unit area (and in thermosteric component) in the North Atlantic tropical to subtropical latitudes and these increases are larger for models with greater MOC decreases (in agreement with the correlations of Fig. 6). Further north, near 45–50°N, the zonal-mean heat content changes are small but positive for the MRI-CGCM2.3.2 and UKMO-HadCM3 models, while the changes are negative for the GISS-AOM model. These large northern Atlantic heat content reductions in the GISS-AOM model (which has the largest MOC reduction) relative to relatively small heat content increases in the MRI-CGCM2.3.2 and UKMO-HadCM3 models (which have smaller MOC changes) are consistent with positive MOC-thermosteric correlations here.

The zonal-mean heat content changes (and hence thermosteric changes) for the GISS-AOM model are dominated by the ocean advective contribution to the budget (Fig. 10) in terms of sign and broad latitudinal variations. For the UKMO-HadCM3 and MRI-CGCM2.3.2 models, where the MOC changes are smaller, the heat content changes follow the sign of the advective changes to the south of 35N and the sign of the surface changes in the northern Atlantic although the latitudinal gradients in heat content for UKMO-HadCM3 tend to follow the advective contributions. We do not have the diagnostics to analyse the heat budget changes in all of the AR4_13 models, but the differences in model behaviour between these example models suggest that the advective term can be the dominant influence on the sign and latitudinal variations of Atlantic thermosteric changes when MOC changes are large, but that this influence reduces for smaller MOC changes. Lowe and Gregory (2006) included an alternative analysis of different aspects of heat budget change and thermosteric contributions for an idealised scenario UKMO-HadCM3 projection (under which changes in Atlantic sea level and steric subcomponents are similar to those for the UKMO-HadCM3 member of AR4_13). Their results show (their Fig. 7) that the tendency for the zonal mean thermosteric height to decrease (in a zonal mean sense) between the North Atlantic subtropics and the more northerly region (to around 50°N) is dominated by change in ocean advection.

7 Summary and discussion

The analysis of multi-model sea level projections for the 21st century by Gregory et al. (2001) and Church et al. (2001) and more recently Meehl et al. (2007) have shown that there is considerable uncertainty in regional changes
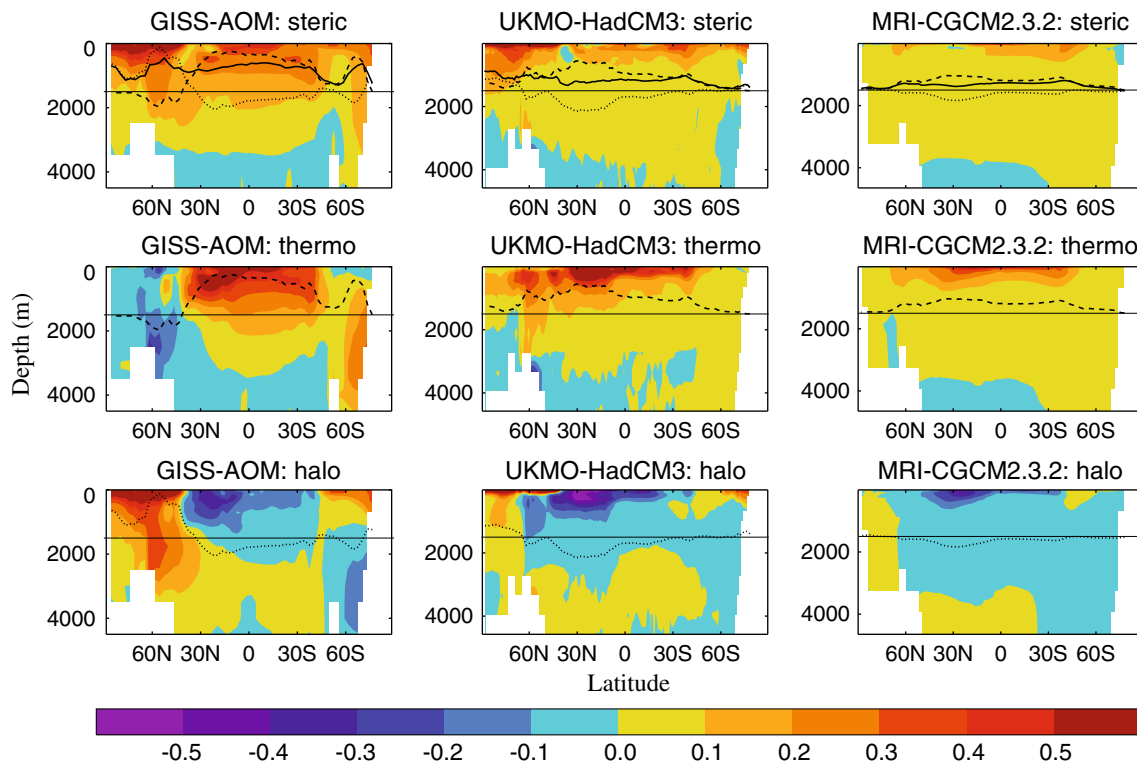
Fig. 8 Contributions with depth to zonal mean steric, thermosteric and halosteric sea level changes over the 21st century (1980–1999 to 2080–2099, units are meters expansion per 1,000 m) in the Arctic/ Atlantic and adjoining Southern Ocean section (region as outlined in Fig. 2a). These contributions are to the total zonal mean changes (i.e. not relative to global mean) which are overplotted: steric (*solid line*); thermosteric (*dashed line*) and halosteric (*dotted line*) in arbitrary units (*thin horizontal line shows zero line*). Changes are shown for the GISS-AOM, UKMO-HadCM3 and MRI-CGCM2.3.2 models which have the largest, an intermediate and the smallest MOC change respectively at 30° of the models shown in Fig. 7
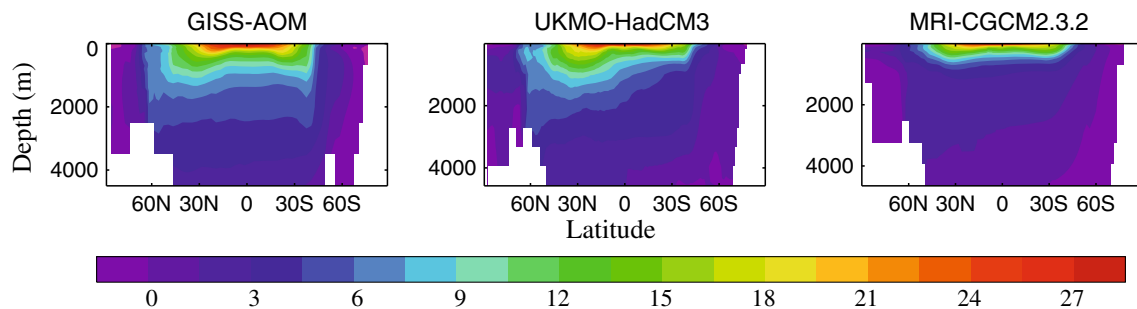

Fig. 9 Zonal mean potential temperature distribution (°C) in the model control simulation (period parallel to 1980–1999) in the Arctic/Atlantic and adjoining Southern Ocean section (region as outlined in Fig. 2a) for the GISS-AOM, UKMO-HadCM3 and MRI-CGCM2.3.2 models

relative to the global mean. Reducing this uncertainty is crucial to understanding the likely relative impacts of sea level change for different regions. The spatial RMS of sea-level change in the thirteen member ensemble of AR4 model projections (AR4_13) considered in this study and which were run under the A1B future scenario is about 20% of the IPCC AR4 central estimate of global mean sea level change. There is no significant correlation across the AR4_13 ensemble between the global thermal expansion and spatial RMS of sea-level change.

A comparison of AR4 and TAR model projections has shown that the ensemble spread in pattern and magnitude of projected regional sea level changes relative to the global mean has not been reduced in the newer generation AR4 models. In contrast, this spread is substantially smaller for an ensemble of flux-adjusted perturbed

Fig. 10 Atlantic heat budget
changes over the 21st century
(1980–1999 to 2080–2099) for
the GISS-AOM, UKMO-
HadCM3 and MRI-CGCM2.3.2
models (*left hand panels*)
together with their associated
thermosteric sea level changes
(*right hand panels and colour
bar* (m)). The zonal mean
budget changes shown are heat
content per m^2 relative to the
global ocean average, together
with contributions to this from
the surface and ocean transport
heat fluxes. Heat content change
shown on expanded scale in the
lower part of the panels with
contribution from the upper
1,000 m also shown (both
relative to their respective
global means). Budget
components are averaged over
5° latitude bands. *Red dashed
lines* (which almost coincide
with the *solid red lines*) show
the contribution from ocean
advective flux changes
calculated as a residual from the
heat content and surface fluxes
and act as a quality check on the
results. UKMO-HadCM3
budget components shifted
earlier by 1 month as calculated
from local decadal means stored
in this way
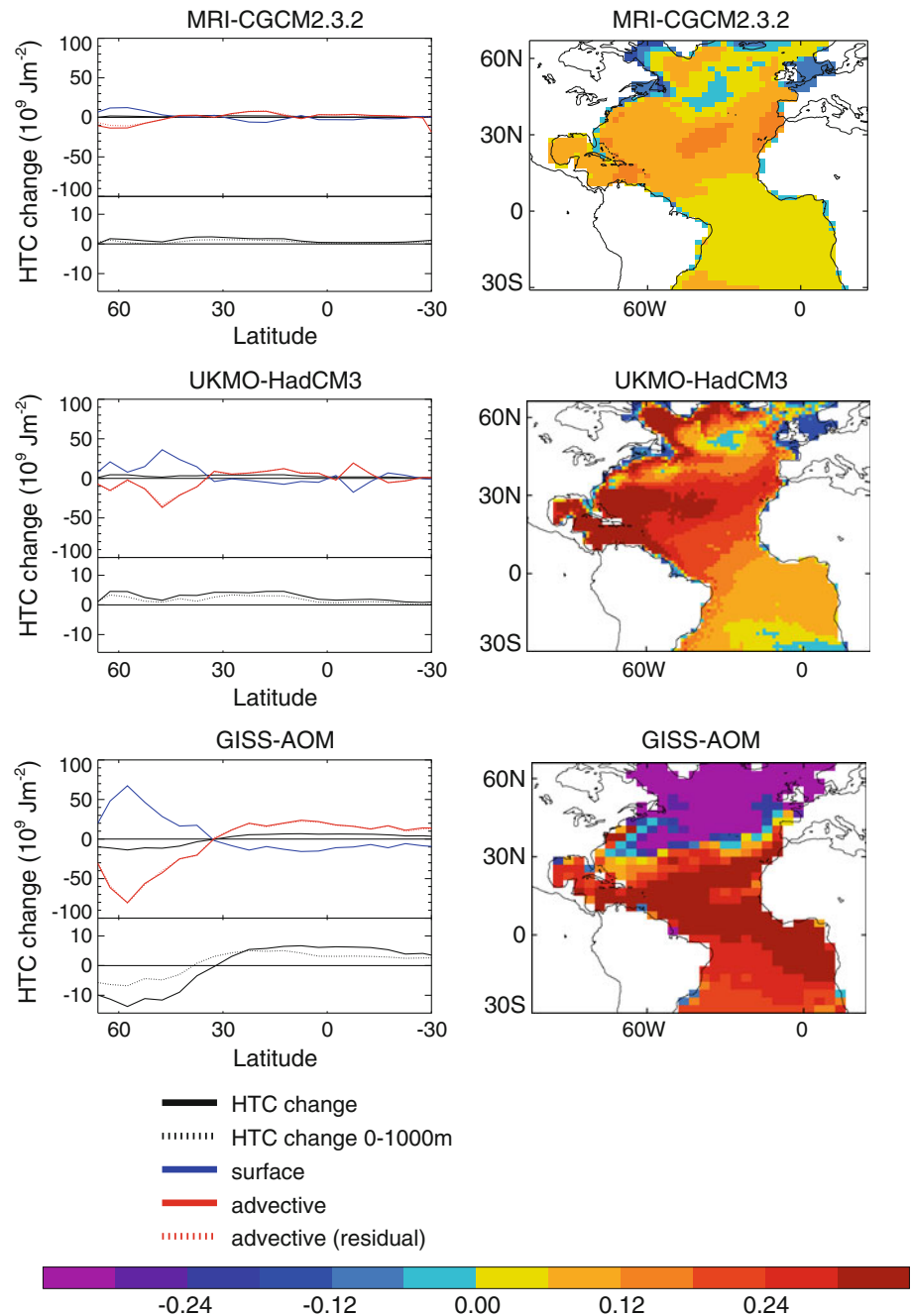
parameter QUMP coupled models, which are structurally based on the HadCM3 model. The use of flux-adjustment will generally reduce the spread in climate base states through reduction of model climate drift and different climate errors in model base states may affect the spread of projected changes (e.g. Russell et al. 2006). We have found, however, that ensembles of QUMP coupled models which are not flux-adjusted have a similarly small spread in regional sea level changes to the flux-adjusted QUMP ensembles discussed in this study. Given ensembles of models for which reasonable efforts have been made to

minimise climate errors, the suggestion of Gregory et al. (2001) that models that are more similar in formulation tend to give more similar regional sea level projections would seem to be robust.

For our ensemble of AR4 A1B scenario projections, there remain sizeable areas of the ocean where the projections show little agreement between their regional sea level changes relative to the global mean. The limited agreement in patterns of sea level change is not reconciled by considering the influence of unforced variability (variability which would occur even in the absence of changes

in external forcing), although changes in some locations and for some models are found to be not significant (at the 95% level) relative to this variability. Locations where the sign of regional sea level change relative to the global mean is in reasonable agreement for the ensemble members and the changes are significant relative to unforced variability include: increases in the Arctic; increases in the Indian Ocean; increases in the Kuroshio Current region and its eastward extension which form the southern part of a south–north positive–negative dipole; decreases in the higher latitude Southern Ocean, which form a dipole with increases to the north; a band of decrease in the South Pacific extending westward from the South American coast; a decrease in the northwest Atlantic forming the southern part of a south–north dipole in the ensemble mean. Within these regions of relatively good model agreement, however, the magnitudes of change can vary widely and systematic uncertainty between models remains. Even where most models show relatively good agreement outliers cannot be necessarily be excluded. This paper has taken the approach of understanding differences between model projections in terms of underlying processes, as a step to addressing uncertainty. The possibility of using observational constraints on projections (through evaluation of the model present-day simulations) is also an approach that should be investigated.

For the AR4 model projections we have analysed, the regional sea level changes fairly strongly reflect the steric component (linked to the ocean density field) both for the ensemble means and generally for the individual ensemble members, although close correspondence between sea level and steric changes is less prevalent in the Arctic and some coastal regions. This study has therefore focused on the steric changes. Regional variations in the steric changes are generally better reflected in the temperature-determined thermosteric component rather than in the salinity-determined halosteric component, again with qualitative and quantitative differences among models. The spatial variations in the Southern Ocean steric changes are strongly thermosteric. Within the Arctic, however, halosteric (freshening) changes generally dominate the changes in spatial variations (with a fairly uniform negative thermosteric deviation offsetting part of the halosteric increases). In the Atlantic, the thermosteric and halosteric component changes relative to the global mean substantially compensate. At low to mid-latitudes, the ensemble mean Atlantic steric increases result from there being larger increases in the thermosteric (warming) component than decreases in the compensating halosteric component; at more northern latitudes the steric increases are from larger halosteric (freshening) increases than thermosteric decreases relative to the global mean. Lowe and Gregory (2006) and Landerer et al. (2007b) have previously noted similar

changes in steric component contributions to future sea level change for individual models.

A correlation analysis, albeit somewhat limited by the sample size of our AR4 ensemble, suggests that the spread in magnitude of many of the Atlantic basin sea level and steric component changes may be related to the amount of weakening of the Atlantic MOC. Yin et al. (2009) and Katsman et al. (2008) showed a link between MOC changes and sea level increases in a selection of AR4 models for localised Atlantic regions. Our results suggest that changes in Atlantic sea level and its steric component are increasingly positive for greater decreases in the MOC (at 30°N) over much of the basin. These positive steric increases are associated with the dominance (within largely compensating changes) of increasing thermosteric contributions in tropical-subtropical latitudes and increasing halosteric contributions in northern latitudes. Broad-scale latitudinal differences in the North Atlantic halosteric and thermosteric changes also show a relationship with amount of MOC weakening.

Temperature and salinity changes of the ocean water column, which underlie halosteric and thermosteric changes, are very different in the Atlantic basins of three example AR4 models (GISS-AOM, UKMO-HadCM3, MRI-CGCM2.3.2) which span the extremes of our ensemble MOC changes, with GISS-AOM having the largest and MRI-CGCM2.3.2 the smallest MOC changes. The changes in temperature and salinity extend to greater depth and show a sharper decrease to the north of the subtropical warming/salting for greater reductions in the strength of the MOC at 30°N. There is widespread cooling/freshening in the northern Atlantic for the largest MOC reduction. The ocean subsurface temperature changes can be analysed in terms of contributions from the heat budget to the heat content changes they represent. Changes in meridional ocean advective heat flux are found to dominate the pattern of heat content (and thus thermosteric) changes when the MOC reduction is large, but play a lessening role for smaller MOC changes. Sensitivity studies of Lowe and Gregory (2006) also show the importance of ocean advection for the thermosteric decrease to the north of the North Atlantic subtropical maximum in a UKMO-HadCM3 idealised scenario projection.

Köhl and Stammer (2008) find that sea level regional trends over the historical 1952–2001 period, as given by an ocean circulation model with dynamically consistent data assimilation, are also largely steric, as found for the future projections analysed here. They suggest that prevalent compensation in the thermosteric and halosteric regional trends is due to a dominant role for wind-driven advection of ocean water masses (for which high ocean temperatures are generally associated with high salinities). Pardaens et al. (2008) looked at the observed historical changes in

Atlantic subsurface salinity (freshwater content) in terms of changes found in HadCM3 climate simulations. They found that unforced near-centennial variability evident in the HadCM3 control simulation Atlantic freshwater content (with anticorrelated heat content changes) primarily resulted from ocean advective flux changes, with MOC changes acting as the pacemaker. Freshwater content increases(decreases) in the northern Atlantic lag MOC decreases(increases) by about 15 years. This lends support to a strong role for larger forced MOC changes projected under future scenarios in giving compensating halosteric and thermosteric changes in the Atlantic, as suggested by this study.

An important aim of analysing and understanding the systematic uncertainty in projected regional sea level changes over the 21st century is to try to reduce this uncertainty. We have noted the likely importance of model structure, which suggests that particular projection features could potentially be linked to aspects of model formulation, which may be known to be more or less realistic. Model resolution may play some role (e.g. Hsieh and Bryan 1996) and Yin et al. 2009 eliminated some models from their study on the basis of their coarse resolution. Suzuki et al. (2005) found similar large-scale regional changes in the MIROC3.2(hires) model (ocean resolution of $0.2° \times 0.3°$) and a coarser resolution version (MIROC3.2(medres), $0.5 - 1.4° \times 1.4°$), but some AR4 ocean models have considerably lower resolutions. Any consistent relationships between model projections and aspects of their simulated present-day climate can give scope for constraining the range of projections, based on the quality of simulated present-day climate as evaluated against observations. For the AR4_13 ensemble we have shown a relationship between the spatial RMS of sea level distribution and of sea level projected changes. This could suggest that the same dominant model properties/processes are responsible for both of these characteristics (but may differ from model to model). Furthermore, for three example models which span the ensemble range of MOC weakening and extremes of Atlantic subcomponent changes, the extent to which changes in temperature and salinity penetrate the Atlantic water column show differences which broadly correspond to similar differences in the depth of the base state thermocline. The AR4 finds that the multi-model mean thermocline is too diffuse and given the above results this may introduce biases to projections of regional sea level change. The suggested links between changes in MOC and in sea level imply that efforts to reduce uncertainty in projections of one of these quantities will benefit both. We have noted that our conclusions are based on a limited model sample and similar analysis of a larger sample would be beneficial.

This study has made progress in highlighting factors which contribute to model differences in projected regional sea level change relative to the global mean. There remain a number of questions which our study has not considered. We have focused on steric changes, which generally dominate projected regional sea level changes, but an understanding is also needed of when and how non-steric changes make an important contribution. While we analysed Atlantic sea level changes in some detail, analysis of sea level changes in other regions and for a larger ensemble of models is required. An approach similar to that for the Atlantic sea level change analysis in this study could be extended and used for other regions. The role of heat budget changes and also of freshwater budget changes could be investigated further by a more detailed investigation of watermass changes. We have shown some links between projected changes and baseline model climate. These links provide avenues for further investigation to try and reduce uncertainty in regional projections.

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