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Sea level projections to AD2500 with a new generation of climate change scenarios

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ABSTRACT

Sea level rise over the coming centuries is perhaps the most damaging side of rising temperature (Anthoff et al., 2009). The economic costs and social consequences of coastal flooding and forced migration will probably be one of the dominant impacts of global warming (Sugiyama et al., 2008). To date, however, few studies (Nicholls et al., 2008; Anthoff et al., 2009) on infrastructure and socio-economic planning include provision for multi-century and multi-metre rises in mean sea level. Here we use a physically plausible sea level model constrained by observations, and forced with four new Representative Concentration Pathways (RCP) radiative forcing scenarios (Moss et al., 2010) to project median sea level rises of 0.57 for the lowest forcing and 1.10 m for the highest forcing by 2100 which rise to 1.84 and 5.49 m respectively by 2500. Sea level will continue to rise for several centuries even after stabilisation of radiative forcing with most of the rise after 2100 due to the long response time of sea level. The rate of sea level rise would be positive for centuries, requiring 200–400 years to drop to the 1.8 mm/yr 20th century average, except for the RCP3PD which would rely on geoengineering.

1. Introduction

The conventional approach to estimate the sea level rise has been to model the major components: ocean thermal expansion, melting from ice sheets and glaciers and terrestrial storage (Meehl et al., 2007; Pardaens et al., 2011). However, measurements of all these components are fraught with difficulty; hence models of their behaviour rely on significant extrapolation from a small observational dataset (Meehl et al., 2007). Conceptually the best way to estimate future rises in sea level would be physical models of all the water storage reservoirs on the planet and how they behave under a changing climate. This task is complex and the subject to intense research efforts, and at present the behaviour of the large ice sheets is limited by physical understanding of dynamics and to a lesser degree by lack of computing power and geophysical observations (Durand et al., 2009; Goldberg et al., 2009). Physically based climate models simulate the thermal expansion component and surface mass balance of Greenland and Antarctic ice sheets while the numerous smaller glaciers budget is parameterized (Meehl et al., 2007; Pardaens et al., 2011). At present, there are very few estimates of dynamical ice sheet loss which are not simply statistical extrapolations (Katsman et al., 2011) or expert opinion (Pfeffer et al., 2008) and all models lack a proper representation of key processes such as calving (Graversen et al., 2010; Price et al., 2011). The best estimates from these modelled components amount to only 1/3 of observed 20th century sea level rise (Gregory et al., 2006), or about 2/3 of that for the past 50 years (Hegerl et al., 2007).

Another approach is to simulate observed sea level using physically plausible models (von Storch et al., 2008) of reduced complexity that respond to histories of global temperature (Rahmstorf, 2007a; Grinsted et al., 2010) or radiative forcing (Jevrejeva et al., 2009; Jevrejeva et al., 2010). Sea level rise in these models is caused by changes in global ice volume and global ocean heat content as a response to changes in global temperature or radiative forcing with a characteristic response time. This characteristic response time is assumed to be infinite (Rahmstorf, 2007a) or estimated by the model as a probability density function spanning a wide range of time scales (Jevrejeva et al., 2009; Grinsted et al., 2010). All semi-empirical models, by construction, simulate recent past and present sea level rise very well. In addition, the latest semi-empirical models (Grinsted et al., 2010; Jevrejeva et al., 2010) reproduce climate system modelled sea level behaviour at scales from centennial to multi-annual, e.g. the impact of volcanic eruptions on sea level simulated by semi-empirical models is in excellent agreement with that given by a coupled climate model (Moore et al., 2010). Semi-empirical simulation of 1993–2006 sea level rate is 3–4 mm/yr (Rahmstorf et al., 2007; Grinsted et al., 2010), which is very similar to the rate of 3.3 mm/yr calculated from satellite altimetry observations; in contrast process based models estimate of the rate is 1.9 mm/yr (Church et al., 2001). Vermeer and Rahmstorf (2009) have concluded that there is a good agreement

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Table 1
Reconstructions of radiative forcings (Crowley et al., 2003; Goosse et al., 2005; Tett et al., 2007) over the past 1000 years used to calculate three different sets of model parameters a, b, τ, S_0.

Experiment name	Historical forcings
CBK_2003	Solar, volcanic, greenhouse gases, aerosols
GRT_2005	Solar, volcanic, greenhouse gases, aerosols
TBC_2006	Solar, volcanic, greenhouse gases, aerosols, orbital, land use, ozone

between thermal expansion simulated by their semi-empirical method and two coupled climate models for the past 1000 years. Conversely, the analysis by von Storch et al. (2008) of their ECHO-G millennial run to simulate one of the component of sea level, thermal expansion of the ocean (also used by Vermeer and Rahmstorf, 2009), suggests that it is difficult to make an estimate of thermal expansion forced by global temperature on centennial timescales. However, they find that sea level forced by radiative forcing (as used in this study) is significantly better on all timescales than forcing with temperatures. Projections by semi-empirical models are based on the assumption that sea level in the future will respond as a linear system, so that future response is analogous to the past. This may not hold in the future if potentially non-linear physical processes come into play (e.g. ice-sheet dynamic feedbacks). Another limitation of semi-empirical models is the lack of spatial variability, hence regional sea level rise prediction is beyond the scope of this paper. There has also been some discussion of the statistical procedures used in some semi-empirical studies (Holgate et al., 2007; Rahmstorf, 2007a,b; Schmith et al., 2007; Vermeer and Rahmstorf, 2009; Taboada and Anadón, 2010; Vermeer and Rahmstorf, 2010), however the models used here (Jevrejeva et al., 2009; Grinsted et al., 2010) have not attracted statistical criticism.

In this study, a semi-empirical model (Jevrejeva et al., 2009; Grinsted et al., 2010) is constrained by the 300 years of global sea level records from tide gauges (Jevrejeva et al., 2008) and driven by various radiative forcing time series (solar, volcanic, greenhouse gases and aerosols) over the past 1000 years (Crowley et al., 2003; Goosse et al., 2005; Tett et al., 2007), shown in Table 1. We assume that global sea level is an integrated response of the entire climate system to the changes in radiative forcing that reflects alteration in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere. The use of radiative forcing removes the substantial uncertainties in the relationship between forcing and temperature response and subsequent sea level response and implicitly includes the effects of feedback mechanisms.

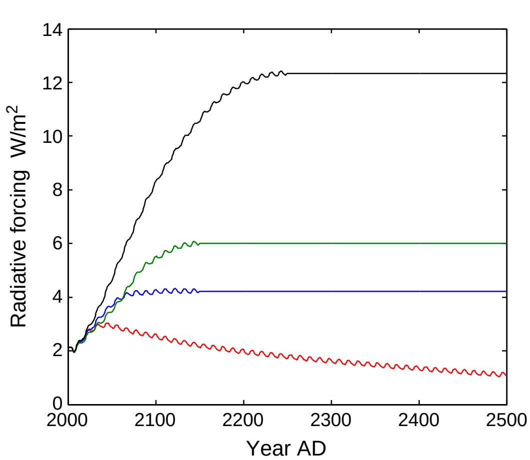

Fig. 1. Radiative forcings for the RCP scenarios; red— RCP3PD, blue— RCP4.5, green— RCP6 and black — RCP8.5.

In this study we do not include any changes in sea level associated with non-climate related components such as contribution from groundwater mining, urbanization and water storage in reservoirs. This is in contrast to the approach by Vermeer and Rahmstorf (2009) where the contribution from reservoir construction of −0.55 mm/yr (Chao et al., 2008) was taken into account, but not the potentially cancelling effects of groundwater mining (0.55–0.64 mm/yr; Huntington, 2008) and urbanization (Cazenave and Nerem, 2004). Hence we follow the suggestion of Lettenmaier and Milly (2009) that land, overall, contributes essentially nothing to sea-level rise today. This is consistent with closure of the sea level budget using only climate related components since 1955 (Moore et al., 2011).

Here we use suites of observationally tuned models driven by the four new RCP radiative forcing scenarios (Fig. 1) to project future sea level by AD2100 and to explore the range of uncertainties in sea level rise by AD2500 associated with changes in radiative forcings.

2. Methods and data

2.1. Description of the new Representative Concentration Pathways scenarios

Interest in modelling climate system components, such as global sea level, the oceans and the ice sheets, has created the demand for emission scenarios to extend well beyond the end of 21st century. The new Representative Concentration Pathways (RCPs) scenarios (Moss et al., 2010) of future radiative forcings have been developed since the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), providing a framework for modelling in climate change research up to 2500. The RCPs provide a starting point for wide-ranging research and map a broad range of climate outcomes. However, they are not forecasts or policy recommendations.

In this study we have utilised data for four RCPs available from http://www.pik-potsdam.de/~mmalte/rcps/. The RCPs are consistent sets of projections of the components of radiative forcing (Fig. 1), named according to their 2100 radiative forcing level estimated from the greenhouse gases and other forcing agents. The RCP scenarios are produced by integrated assessment models to 2100, then extended using simple algorithms intended for use as pathways to drive long-term earth-system simulation experiments (Meinshausen et al., in review).

The RCP3PD scenario is characterised by very low greenhouse gas concentrations, producing forcings around 3.1 W/m^2 mid-century, and dropping to 2.6 W/m^2 by 2100. In order to achieve such radiative forcing levels, greenhouse gas concentrations are reduced substantially over time. The RCP 4.5 (medium low) and RCP6.0 (medium high) are stabilisation scenarios, where total radiative forcing is stabilised before 2100 and after 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. The RCP8.5 is characterized by high greenhouse gas concentration levels, stabilising emissions post-2100 and atmospheric concentrations post-2200.

2.2. Model

In our study we assume that for a given mean global radiative forcing (F) there is an equilibrium sea level (S_{eq}). As we argued previously (Jevrejeva et al., 2009; Grinsted et al., 2010) the relationship between S_{eq} and F must be non-linear for large changes in sea level such as those that occur on glacial–interglacial timescales (Rohling et al., 2009). However, for interglacial climate the relationship is near linear, with a considerably lower sensitivity than during glacials (Rohling et al., 2009). Therefore we expect a linearization to be valid for global temperatures several degrees warmer than present:

$$S_{eq} = aF + b \quad (1)$$

where a is the sensitivity of sea level to a forcing (F) change and b is a constant.

Potential sea level rise is the result of changes in global ice volume and global ocean heat content, both of which we model as reacting to changes in radiative forcing with some single response time of the climate system (τ). Global ocean heat content and ice volume will have different response times, however both are plausibly centennial (Grinsted et al., 2010). We therefore assume that sea level will approach S_{eq} with response time (τ) as follows:

$$\frac{\partial S}{\partial t} = \left(S_{eq} - S\right)/\tau. \tag{2}$$

To obtain sea level (S) we integrate Eq. (2) over time using the 1000 years of available forcing (F) and knowledge of the initial sea level at the start of integration (S_0). We employ 2,000,000 member ensemble Monte Carlo inversion to determine the likelihood of probability density functions of the unknown parameters a, b, τ, S_0 (Grinsted et al., 2010) by calculating the misfit between observed and modelled sea level. Following Mosegaard and Tarantola (2002), the likelihood function is written:

$$L(m) = ke^{-\frac{1}{2}(S(m)-S_{obs})^T C^{-1}(S(m)-S_{obs})} \tag{3}$$

where k is a normalisation constant, S_{obs} and $S(m)$ are the vectors of observed and modelled sea level respectively, ^{T} denotes transpose, and C is the uncertainty covariance matrix where C_{ij} is the covariance between the global sea level uncertainty at time-instants i and j (C is estimated in Grinsted et al., 2010). The negative exponent is a measure of the misfit between model and observations normalised by the observational uncertainties. Once the likelihood function is defined we can estimate the full range of likely model parameters which result in a "reasonable" fit to the observations. Reasonable is defined by the likelihood function, such that acceptable models do not give a much worse misfit than the best guess model (which would be the result of a singular value decomposition). When we quote a 5–95% confidence interval then it refers to the percentiles in likelihood distribution function.

We calculate three different sets of model parameters a, b, τ, S_0 (Table 2) using three independent reconstructions of radiative forcings (Crowley et al., 2003; Goosse et al., 2005; Tett et al., 2007; Table 1). Likelihood probability functions of the model parameters are shown in Fig. 2. We combine the outputs from 3 models (Table 2) into a single simulated sea level that reflects the spread of values across all three models. There is an excellent agreement of simulated sea level with available observations since 1700 (Jevrejeva et al., 2008) and very good agreement with climate model simulations of the response to volcanic eruptions (Moore et al., 2010), suggesting that model works well on all scales from multi-year to multi-centennial (Grinsted et al., 2010).

The modelled sea level response by 2500 (Fig. 4a) is largely controlled by the model equilibrium sensitivity. Large sensitivities must be accompanied by slow response times in order to match the observed sea level rise record (Grinsted et al., 2010). Our results explore response times ranging from ~10–5000 years with 5–95% interval of 30–2000 years (Table 2) and associated equilibrium sensitivities in the range 0.2–5 m/(W/m^2) (Jevrejeva et al., 2009). The range of response times spans the typical time constants of the main sea level reservoirs representing the responses of glaciers, thermal expansion of the ocean and ice-sheets to the changes in radiative forcing.

3. Results

3.1. Sea level projections by 2100

The sea level responses to radiative forcing from four new RCP scenarios by the end of the 21st century are presented in Fig. 3. Sea level is insensitive to RCP forcing until 2050 with a range of about 0.32–0.38 m above the 1980–2000 reference level. However, by the end of the 21st century there are clear consequences depending on which scenario is followed, with sea level rise ranging from 0.57 to 1.10 m by 2100 (with lower and upper 5–95% confidence limits of 0.36 m to 1.65 m, Table 3), largely due to distinct differences in fossil fuel burning projections. The maximum rate of sea level rise by 2100 reaches 17 mm/yr for the RCP8.5 scenario. Even for the low emission RCP3PD scenario with the peak in radiative forcing around 2050 and declining forcing thereafter, sea level continues to rise by 0.57 m at the end of the 21st century, despite the decrease in forcing.

Sea level projections of 0.57–1.10 m by 2100 with the new RCP scenarios are slightly lower than our previous estimated range of 0.6–1.6 m using six Special Report on Emission Scenarios (SRES)(Jevrejeva et al., 2010), which reflect the differences in radiative forcings between the old (SRES) and new (RCP) scenarios (Table 3). The new RCP3PD scenario is more optimistic, in terms of emissions, than any previous scenario. Radiative forcing in the new RCP8.5 "business as usual" high emission scenario is lower than the previous highest A1Fi SRES scenario, as it envisages increasing competiveness of clean power technology.

We can attempt to quantify how the different components of the sea level budget contribute to our scenarios of sea level rise. Sea level rise estimates from ocean thermal expansion by AD2100 under the RCP6 scenario are from 0.10 (Vizcaino et al., 2008) to 0.20 m (Solomon et al., 2009); while small glaciers may contribute 0.18–0.37 m (Bahr et al., 2009). Then ice sheets would need to provide about 0.5 m by AD2100, independent of scenario. This contribution is well within plausible expectations of 0.29–1.16 m (Pfeffer et al., 2008) or possible 0.56 m contribution from ice sheets (Rignot et al., 2011).

3.2. Sea level projections by 2500

Fig. 4a shows how, even after stabilisation in radiative forcing, sea level continues to rise. Even for the RCP3PD low emission scenario sea level will rise to 0.74 m in AD2240 compared with 0.32 m in AD2050 (time of stabilisation). For the RCP4.5 scenario with stabilisation of forcing before AD2100 the rate of sea level rise will fall to the 20th century mean rate of 1.8 mm/yr only between AD2300-2400, at least 200 years after stabilisation in radiative forcing (Fig. 4b). For the high emission scenario RCP8.5 the total sea level rise at the end of 25th century will be 5.49 m, with a 2.86 m rise from AD2200 to AD2500. Maximum rate of sea level rise is 20 mm/yr around AD2150 with a decline to 3.3 mm/yr

Table 2
Model parameters calculated using the past forcing from experiments named CBK_2003 [Crowley et al., 2003], TBC_2006 [Tett et al., 2007] and GRT_2005 [Goosse et al., 2005]. Parameters presented as median (50%), upper (95% confidence interval) and lower (5% confidence interval) limits.

Model parameters	Experiment								
	CBK_2003			TBC_2006			GRT-2005		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
τ (years)	90	200	1045	90	176	1776	43	99	324
a (m/W/m^2)	0.3	0.5	2.4	0.4	0.7	4.9	0.2	0.3	0.7
b (m)	0.2	0.5	2.8	0.2	0.5	4.9	0.1	0.3	0.9
S_0 (m)	−0.44	−0.10	0.39	0.36	−0.06	0.33	−0.43	−0.4	0.41

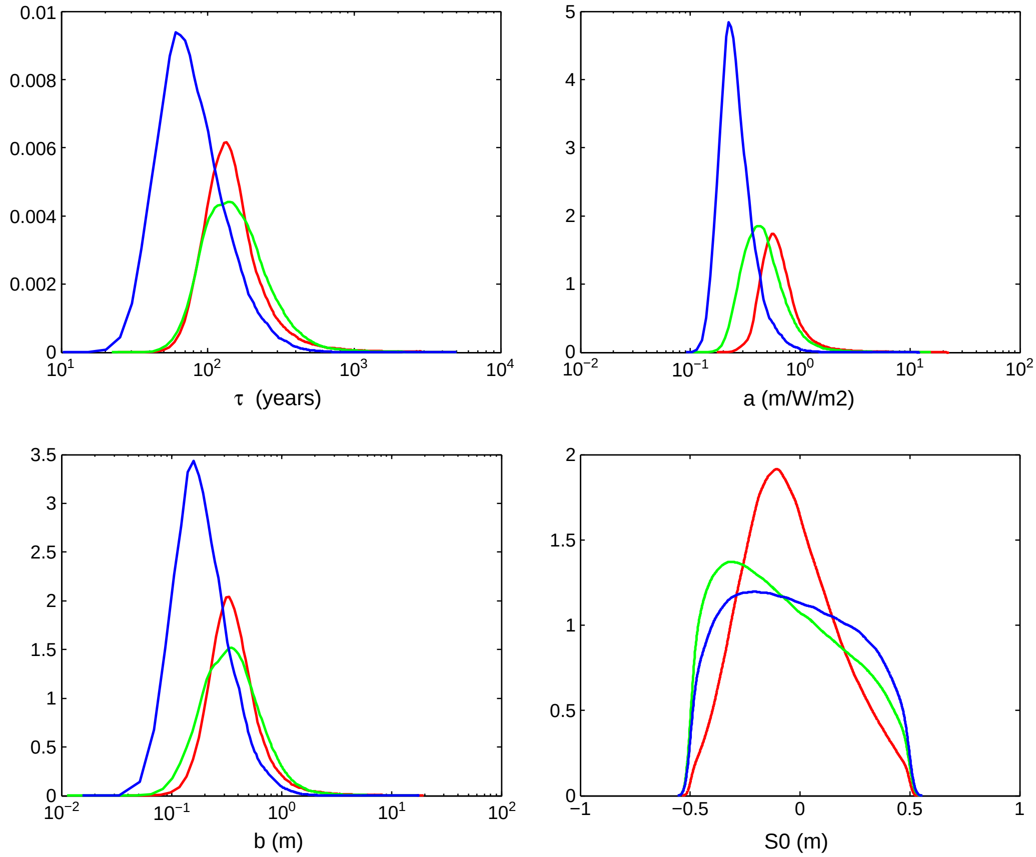

Fig. 2. Empirical likelihood probability density functions of the four model parameters for each of the three experiments (red— "TBC_2006", blue— "GRT_2005", green— "CBK_2003" on each panel). Response time (τ, years); parameter a (m/W/m^2); parameter b (m); parameter S_0 (m).

(similar to the rate of present day sea level rise calculated over the satellite altimetry time period 1992–2008) at the end of 25th century.

The impact of different emission scenarios is most keenly seen in sea level after 2100, with rises by AD2500 of 0.42–2.86 m depending on which RCP is followed, (Fig. 4a). However, if stabilisation of radiative forcing had been done in 2000, the sea level rise for the 21st century would be only 0.18–0.22 m (Jevrejeva et al., 2010), reflecting the cumulative impact of rising thermal storage.

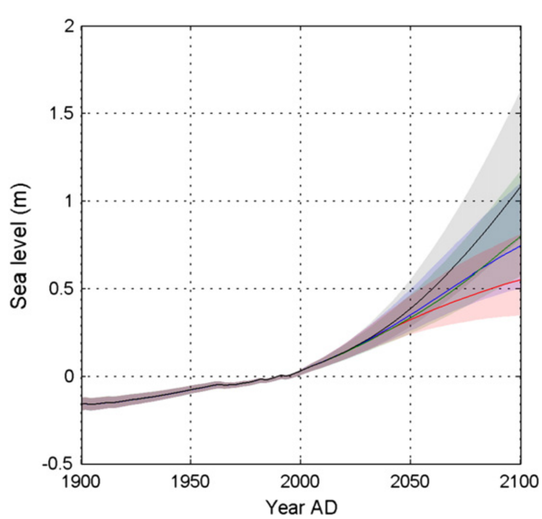

Fig. 3. Sea level projections by 2100 with RCP scenarios; red— RCP3PD, blue— RCP4.5, green— RCP6 and black — RCP8.5. Shadows with similar colour around sea level projections are upper (95%) and low (5%) confidence levels.

There are large uncertainties on sea level projections beyond the 21st century. Thermal expansion under the RCP6 scenario contributes from 0.4 m (Vizcaino et al., 2008) to 0.7 m (Solomon et al., 2009) by AD2200. By then about 1.1–1.3 m of sea level rise would have to come from ice melting, including about 40 cm from small mountain glaciers, 60% of which would have disappeared (Raper and Braithwaite, 2006). By AD2300 thermal expansion would reach 0.5–0.75 m (Vizcaino et al., 2008; Solomon et al., 2009) with up to 1.2 m sea level rise coming from melting of ice sheets alone, since mountain glaciers and ice caps disappear almost completely by the end of the 23rd century (Raper and Braithwaite, 2006). This contribution from ice sheets is slightly larger than the upper limit of 1.1 m per century estimated on glaciological grounds (Pfeffer et al., 2008) for the 21st century, and this may be reasonable given the stronger radiative forcing and long-term positive feedbacks expected by the 22nd century. Thermal expansion would continue to rise over many centuries reaching 0.8 m by AD2500 (Vizcaino et al., 2008; Solomon et al.,

Table 3
Projected sea level rise (m) by 2100 for the RCP scenarios. Results presented as median, upper (95% confidence interval) and lower (5% confidence interval) limits, calculated from 2,000,000 model runs. Sea level rise is given relative the period 1980–2000. Results are give as average of the experiments named CBK_2003 [Crowley et al., 2003], TBC_2006 [Tett et al., 2007] and GRT_2005 [Goosse et al., 2005].

RCP scenarios	Sea level rise (m)		
	5%	50%	95%
RCP8.5	0.81	1.10	1.65
RCP6	0.60	0.84	1.26
RCP4.5	0.52	0.74	1.10
RCP3PD	0.36	0.57	0.83

Table 4
Projected sea level rise (m) by 2500 for the RCP scenarios. Results presented as median, upper (95% confidence interval) and lower (5% confidence interval) limits, calculated from 2,000,000 runs of the model. Values of sea level rise are given relative the period 1980–2000. Results are give as average of three experiments named CBK_2003 [Crowley et al., 2003], TBC_2006 [Tett et al., 2007] and GRT_2005 [Goosse et al., 2005].

RCP scenarios	Sea level rise (m)		
	5%	50%	95%
RCP8.5	2.26	5.48	11.51
RCP6	1.03	2.62	5.79
RCP4.5	0.72	1.84	4.30
RCP3PD	0.13	0.53	1.74

2009). In contrast with these estimates from our model, results from a climate model (Vizcaino et al., 2008) show a negative contribution of −0.5 m from Antarctica by 2500 due to enhanced precipitation and only 0.15 m sea level rise contribution from Greenland ice sheet.

4. Discussion

It is unclear how the climate system will respond to the changes in radiative forcing envisaged by the new scenarios, since long-term feedbacks will affect climate sensitivity, greatly increasing uncertainty in projections of long-term climate change. The main uncertainty for the sea level projections is the response of the ice sheets in Greenland and Antarctica to hundreds of years of warmer temperatures, which is the focus of several ice sheet dynamical modelling initiatives (e.g. Timmermann et al., 2011). Our model does not consider the large non-linearities such as those that might arise from a partial collapse of the West Antarctic ice sheet (Vaughan, 2009), which would significantly amplify the sea level response. Ocean heat uptake and deep-water formation are the sources

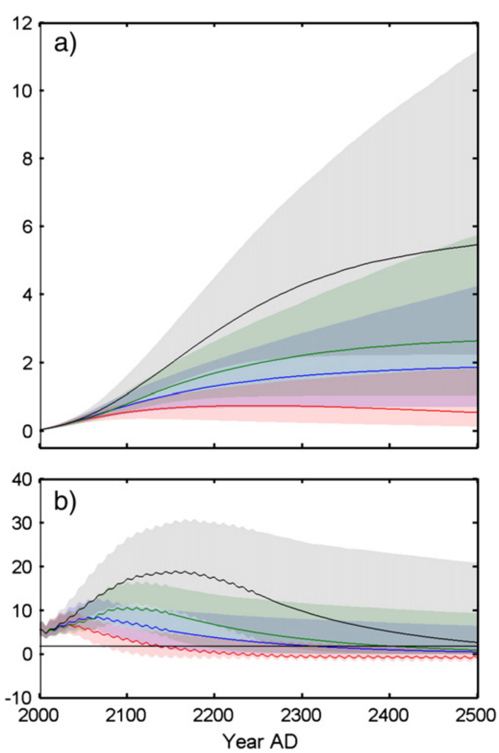

Fig. 4. (a) Sea level projections by 2500 with RCP scenarios; red— RCP3PD, blue— RCP4.5, green— RCP6 and black — RCP8.5. Shadows with similar colour around projections are upper (95%) and low (5%) confidence level. (b) Rates of sea level rise (colour scheme the same as panel a). The black horizontal line corresponds to the rate of sea level rise during the 20th century (1.8 mm/yr).

for uncertainties to estimate future contribution from thermal expansion, especially given near-certain removal of Arctic Ocean summer season ice cover; however, for the next few hundred years present day process based models show no changes in ocean heat uptake (Gregory, 2000; Church et al., 2001).

We utilise paleo data (Rohling et al., 2009) to justify the use of linear approximation in our Eq. (1), describing the link between global radiative forcing (F) and equilibrium sea level (S_{eq}). We have established that a linear approach is valid only under the conditions that global temperature will change less than perhaps 10 °C, with a sea level sensitivity of 6–10 m/°C, which will limit the use of our model. However, the new RCP scenarios are comfortably inside the linear approximation range. The high sea level rise rate of 20 mm/yr around AD2150 simulated for RCP8.5 scenarios is not unprecedented: the period 14,100 and 13,600 BP experienced sea level rise at rates of 40 mm/yr (Stanford et al., 2006), associated with melt-water pulse 1A, adding the equivalent of 1.5 to 3 Greenland ice sheets to the ocean over a period of less than five centuries (Alley et al., 2005). We do not expect to see anything like that volume of ice melted in the next 5 centuries, however, during the last interglacial sea level was around 7 m higher than present levels (Kopp et al., 2009), with rise rates of 0.56–0.92 m per century, though potentially reaching higher rates for shorter periods (Blanchon et al., 2009; Kopp et al., 2009). Rohling et al. (2008) imply that during the Marine Isotope Stage 5e global mean surface temperatures were at least 2 °C warmer than present and mean sea level stood 4–6 m higher than modern sea level, with an important contribution from a reduction of the Greenland ice sheet. Modelling with a fully coupled ocean–atmosphere model of two periods of rapid melting (without ice dynamics) of the Laurentide ice sheet during the Holocene suggests that melting ice contributed about 13 mm/yr and 7 mm/yr of sea level rise (Carlson et al., 2008). The addition of ice dynamics in the model would probably increase the rate of melting (Alley et al., 2005). Hence both the magnitude of sea level rise and its rate that our models give are within the range of known paleo variability and sensitivity.

The long term view of rising sea level has implications for both policy and adaptation strategies. The relative costs of damages due to loss of coastal land (or associated poisoning of freshwater and agricultural land), and forced migration as approximately 150 million people that live presently within 1 m of high tide (Anthoff et al., 2009; Sugiyama et al., 2008), and urban city damage suggest that costs due to urban flooding is dominant (Moore et al., 2010). This is because of the greater rates of urbanization, increased capital and asset risk concentration than general population growth (Nicholls et al., 2008). However, traditional cost benefit analysis relies on accounting procedures that are ethically questionable when applied to future generations (Goes et al., 2011). The development of sophisticated (or at least plausible) sea level prediction models – including any geoengineering – and their incorporation within socio-economic Integrated Impact Models is an urgent requirement for planning. In any case policy decisions that reflect only sea level rise to AD2100, or which envisage only sub-metre rises, need to go much further given the inertia in the sea level system. For urban planning of new coastal development long-term sea level needs to be considered as street layout is much more difficult to revise and leaves a longer legacy than simple building redevelopment. This is a pressing issue, for example, in Helsinki present day regulations are based on sea level rise research done in the 1990s (Kari Silfverberg personal communication, 2010). Additionally the issue of possible large regional variations in sea level due to differential melting of polar ice sheets is not considered in planning, which in any case almost never go beyond 200 years into the future even for entirely new urban developments. In the case of Helsinki, the bottom of the metropolitan area for planning purposes is 2.3 m above present. Sea level rise by 2200 is expected to be 1–2 m, (Fig. 4), leaving perhaps 1.5 m available for storm surges. The highest measured storm flood in the Gulf of Finland occurred in January 2005, when the so-called Gudrun storm brought a flood to the west coast of Estonia approximately 2.75 m height, to

Helsinki about 1.51 m, and to St. Petersburg more than 2.5 m (Haanpaa et al., unpublished, available from http://www.gsf.fi/projects/astra/sites/download/ASTRA_WSS_report_final.pdf). Hence, planning needs to accommodate several metres of sea level rise over several centuries (Anthoff et al., 2009).

Adaptation of existing coastal communities needs to take into account the increase in flood risk as well as rising mean sea level. In the Baltic Sea where long term statistics on return periods for high water are available (Johansson et al., 2004), a 30 cm rise in mean sea level corresponds to a 100 fold increase in probability of a given flood level, so that a present 1000-year high water level would be a 10-year occurrence with a 30 cm rise in mean sea level. Additionally the limited extreme event analysis available on sea level suggests that some places may experience rising relative rates of extreme sea levels, while others see a decrease of extremes towards the mean (Barbosa, 2008).

There are unavoidable large uncertainties on sea level projections, especially those made for time beyond the 21st century since unknown and possibly unpredictable long term feedback effects will determine the magnitude and pattern of planetary warming. As with the RCP scenarios, projection of sea level rise beyond the 21st century only demonstrates that after stabilisation of forcing, sea level will continue rising for centuries in all four RCP scenarios. The details of sea level rise will depend on what non-linearities are introduced by the decays of the large ice sheets as the continental ice sheet system enters a regime unprecedented in recorded history.

5. Conclusion

The sea level rise due to ocean thermal expansion and melting of glaciers and ice sheets has a characteristic timescale of 100–200 years (Grinsted et al., 2010; Jevrejeva et al., 2010). This is comparable to the residence time of CO_2 in the atmosphere and hence the radiative forcing timescale. Thus sea level and anthropogenic climate forcing are linked by two multi-centennial time scales. Sea level rise of 0.57–1.10 m by 2100 has been estimated as medians from 2,000,000 runs by our model. Simulation shows that sea level will continue to rise for many centuries after stabilisation of radiative forcing, eventually reaching 1.84–5.48 m by 2500 for all scenarios, except the RCP3PD low emission scenario. The rate of sea level rise will remain positive for several centuries, in all except the RCP3PD scenario. A maximum rate of 20 mm/yr was found for the RCP8.5 scenario, but even for the medium emission RCP6 scenario, the maximum rate will reach 10 mm/yr, which is five times the rate of the 20th century sea level rise.

Policy and adaptation strategies at widely discussed at present envisage only sub-metre sea level rises up to 2100, but should include provision for multi-century and multi-metre rises in coastal infrastructure planning and socio-economic development.

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