nature climate change

LETTERS

PUBLISHED ONLINE: 24 JUNE 2012 | DOI: 10.1038/NCLIMATE1584

Long-term sea-level rise implied by 1.5 °C and 2 °C warming levels

Michiel Schaeffer[1,2]*, William Hare[1,3], Stefan Rahmstorf[3] and Martin Vermeer[4]

Sea-level rise (SLR) is a critical and uncertain climate change risk, involving timescales of centuries[1]. Here we use a semi-empirical model, calibrated with sea-level data of the past millennium[2], to estimate the SLR implications of holding warming below 2 °C or 1.5 °C above pre-industrial temperature, as mentioned in the Cancún Agreements[3]. Limiting warming to these levels with a probability larger than 50% produces 75–80 cm SLR above the year 2000 by 2100. This is 25 cm below a scenario with unmitigated emissions, but 15 cm above a hypothetical scenario reducing global emissions to zero by 2016. The long-term SLR implications of the two warming goals diverge substantially on a multi-century timescale owing to inertia in the climate system and the differences in rates of SLR by 2100 between the scenarios. By 2300 a 1.5 °C scenario could peak sea level at a median estimate of 1.5 m above 2000. The 50% probability scenario for 2 °C warming would see sea level reaching 2.7 m above 2000 and still rising at about double the present-day rate. Halting SLR within a few centuries is likely to be achieved only with the large-scale deployment of CO_2 removal efforts, for example, combining large-scale bioenergy systems with carbon capture and storage[4].

As opposed to the warming goals mentioned in the 2010 Cancún Agreements[3], less attention has focused on SLR limits. In 2006 the German Advisory Council on Global Change called for a global guardrail of 1 m SLR that should not be exceeded over many centuries[5]. Here we examine how emission reductions over the course of the twenty-first century may affect global mean SLR up to AD 2300. We assess a range of scenarios with emission reductions sufficient to meet the global warming goals in the Cancún Agreements with different probabilities. We then analyse the divergence in SLR and rates of SLR by 2100 implied by these and a broader set of emission pathways. The difference in rates of twenty-first century SLR is found to be an indicator for the divergence in post-2100 SLR, but is also important in its own right: higher rates of rise pose a greater challenge to adaptation by ecosystems and socioeconomic systems in the coastal zones.

Multi-century sea-level projections have previously been attempted by process modelling for only the steric component[1,6], by expert opinion[7] and with a single-timescale semi-empirical model[8]. Here we present projections using a semi-empirical model[2] for the total SLR, which accounts for multiple timescales of sea-level response and has been calibrated with sea-level proxy data for the past millennium, as well as with tide-gauge data for the past 130 years (Supplementary Sections S1 and S5). On this basis, sea-level projections beyond the year 2100 can now be explored with the semi-empirical method. The finite response timescale accounts for SLR gradually slowing down as it adjusts fully to a temperature change (see Fig. 1 of ref. 9). We used probabilistic parameter estimates derived from palaeodata sets of temperature and sea level over the past millennium (as in ref. 2) to estimate sea level over the coming 300 years (Supplementary Section S2). The sea-level projections are driven by temperature projections of the MAGICC6 climate/carbon-cycle model[10,11]. Projection uncertainty ranges here represent 90% uncertainty intervals.

As a first class of scenarios (Fig. 1a), we analysed a policy scenario reflecting emission-reduction pledges by individual countries worldwide that are associated with the Copenhagen (CPH) Accord and Cancún Agreements, along with a reference scenario that does not include such pledges[12]. Both scenarios exceed 3 °C warming above pre-industrial by 2100, but the policy scenario achieves a reduction of 0.5 °C compared with the reference scenario in 2100 (Fig. 1b).

Second, we used several representative concentration pathways[13,14] (RCPs), prepared for analysis in the Intergovernmental Panel on Climate Change's fifth assessment report (AR5). The RCP4.5 scenario[15] implies relatively minor adjustments of the energy and industry sectors, whereas RCP3-PD (ref. 16) is a strong mitigation scenario and the additional RCP4.5 to 3PD scenario[14] represents delayed strong mitigation as a post-2100 transition from RCP4.5 to RCP3-PD. Whereas RCP4.5 reaches a peak warming of 3 °C by 2300, RCP3-PD results in a gradual post-peak cooling and is likely to hold warming below 2 °C.

Using RCP3-PD and two other scenarios (Supplementary Section S3), we examine medium (≈50%) and likely (>66%) probabilities of meeting the 2 °C and 1.5 °C goals. The Stab 2 °C scenario was developed by applying the equal quantile walk method[17] and our climate model iteratively to reach about a 50% probability of meeting the 2 °C goal by 2100, as opposed to the 80% probability in RCP3-PD (Table 1). The MERGE400 scenario[18] aims at reaching a CO_2 equivalent concentration of 400 ppm by the end of the century, which is close to the level reached in RCP3-PD. However, MERGE400 provides a contrasting energy-economic strategy compared with RCP3-PD, by realizing late reductions in short-lived greenhouse gases such as methane, balanced by earlier and deeper reductions of CO_2 emissions. By 2100, MERGE400 achieves net negative CO_2 emissions about four times those reached in RCP3-PD, through large-scale application of bioenergy systems and carbon capture and storage[18–20]. The result is a relatively rapid decline in warming by 2100, with a high (80%) probability of warming to drop below 1.5 °C by 2150, which does

[1]Climate Analytics, Karl-Liebknecht-Strasse 5, 10178 Berlin, Germany, [2]Environmental Systems Analysis Group, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, The Netherlands, [3]Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, D-14412 Potsdam, Germany, [4]Department of Real Estate, Planning and Geoinformatics, Aalto University School of Engineering, PO Box 15800, FI-00076 AALTO, Finland. *e-mail: michiel.schaeffer@climateanalytics.org.

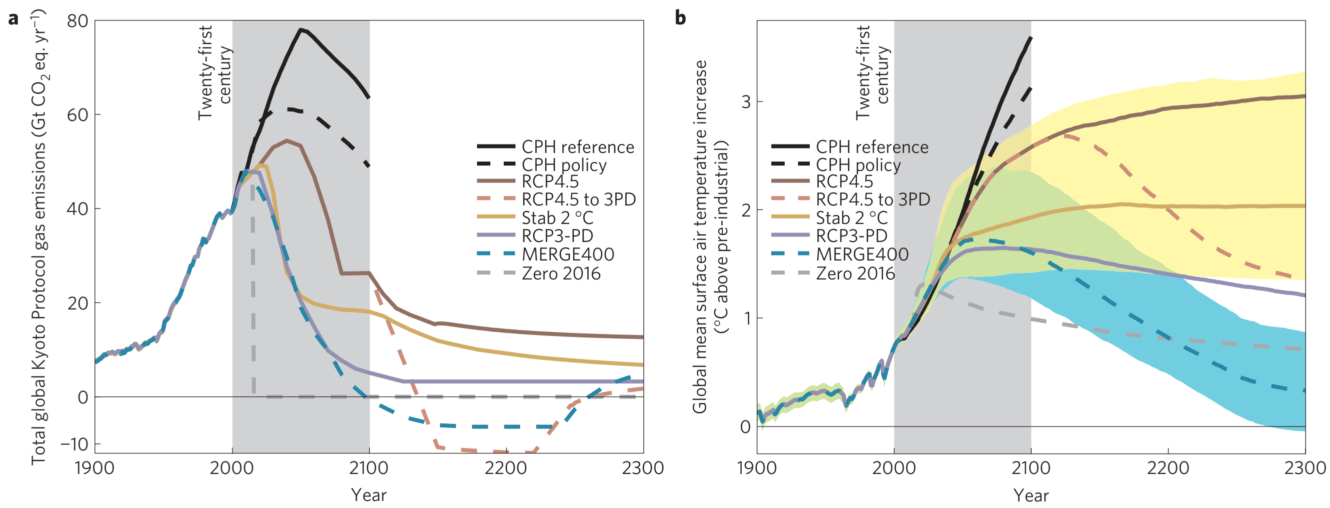

Figure 1 | Emission scenarios and modelled temperature increase above pre-industrial levels. a, Total global greenhouse-gas emissions (so-called Kyoto Protocol gases—methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and SF_6). **b**, Projections of global mean temperature increase above pre-industrial levels for the CPH and longer-term scenarios. Shaded areas in **b** show 90% uncertainty range calculated from Monte-Carlo runs of the climate model, shown for only two scenarios to enhance readability, focusing on the lowest and highest temperature-goal scenarios. Lines indicate median estimates.

Table 1 | Model estimates of approximate probability[11] to achieve warming goals and projected corresponding SLR.

	CPH reference	CPH policy	RCP4.5	RCP4.5 to 3PD	Stab 2 °C	RCP3-PD	MERGE400	Zero 2016
$P(T \leq 2\,°C)$ (peak in twenty-first century)	<5%	<5%	10%	10%	55%	80%	80%	>95%
$P(T \leq 1.5\,°C)$ (peak in twenty-first century)	<5%	<5%	<5%	<5%	10%	30%	15%	80%
$P(T \leq 1.5\,°C)$ (by 2100)	<5%	<5%	<5%	<5%	10%	35%	40%	95%
SLR 2100 (cm above 2000)	102 (72-139)	96 (68-132)	90 (64-121)	90 (64-121)	80 (56-105)	75 (52-96)	77 (54-99)	59 (40-80)
Rate of SLR 2100 (mm yr^{-1})	18 (13-26)	16 (11-23)	13 (8-19)	13 (8-19)	10 (6-14)	9 (5-12)	9 (5-12)	5 (3-8)
SLR 2300 (cm above 2000)	N/A	N/A	355 (212-527)	270 (159-421)	267 (156-401)	199 (118-309)	149 (87-236)	131 (76-208)
Rate of SLR 2300 (mm yr^{-1})	N/A	N/A	12 (6-20)	4 (1-9)	8 (4-14)	4 (2-9)	0 (−2-3)	2 (1-6)

Temperature target probabilities are rounded to nearest 5%. Central SLR values indicate median estimates and bracketed ranges indicate 90% uncertainty interval given by the full set of SLR-model parameters and temperature projections. *T*, Global mean surface-air temperature increase (°C above pre-industrial).

not occur for RCP3-PD. We use MERGE400 as a proxy for a 1.5 °C scenario. Although the probability of returning warming below 1.5 °C in the twenty-first century is lower than 50% it is high in the longer term. Other, equally deep mitigation scenarios exist, but at this stage there are no lower energy-system scenarios in the literature, as far as we know.

Finally, we evaluated a hypothetical scenario to estimate future SLR implications of only past emissions, cutting global emissions to zero in the year 2016. After a short-term peak in temperature owing to removal of anthropogenic aerosols, which until the present have had a net global mean cooling effect[21], warming decreases quickly in the first few decades. The subsequent slower decrease over centuries is associated with the slow decline in increased CO_2 concentration, owing to the long timescales of ocean uptake of carbon by natural processes (as opposed to scenarios where CO_2 is actively removed from the atmosphere by technology).

Figure 2 focuses on SLR over the twenty-first century and shows that the estimated rate of SLR starts to diverge by the 2050s in these scenarios. Reducing emissions from the reference case to the reduction-pledge case (CPH policy) slows the rate of SLR somewhat by 2100. The 1.5 °C and 2 °C scenarios reduce the rate of SLR by about half compared with the reference case, but it still reaches around three times the present-day rate by 2100. Even in the case of a hypothetical stop to all global emissions, as in the zero 2016 scenario, the rate of SLR reaches double present-day values around the 2050s, before slowly declining.

In terms of the extent of projected SLR (Fig. 2b), we find that the reference scenario leads to 102 (72–139) cm over the twenty-first century, which is reduced to 59 (40–80) cm for the hypothetical zero 2016 case. This suggests about 40 cm of SLR by 2100 can be theoretically avoided. The 1.5 °C and 2 °C scenarios limit SLR to about 75 cm by 2100, realizing 60% of the theoretical avoidance potential, albeit with the help of net negative CO_2 emissions.

Given the inertia in the physical system, the large and growing differences in rates of change by 2100 (Fig. 2a) imply a strong further divergence of SLR over centuries to come. For a multi-century perspective, and in search of the probable conditions

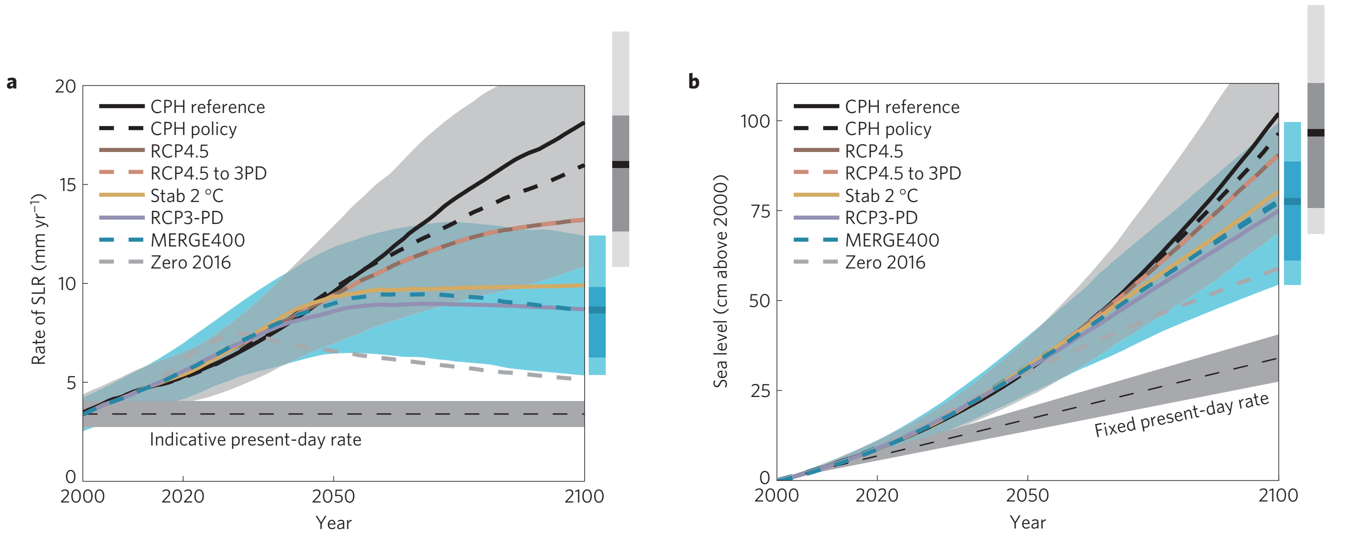

Figure 2 | SLR over the twenty-first century. a, Rate of SLR and **b**, SLR projections 2000–2100. Error bars on the right-hand side show 90% uncertainty range, resulting from the full set of parameter values used in the semi-empirical SLR equations combined with median temperature projections (dark shaded) and the wider uncertainty resulting from including the full range of temperature projections as well (light shaded). Uncertainty ranges are shown for only two scenarios for reasons of readability, focusing on the mitigation scenarios that reach the lowest and highest rates of SLR by 2100. Lines indicate median estimates. The indicative/fixed present-day rate of 3.3 mm yr^{-1} is the satellite-based mean rate 1993–2007 (ref. 23).

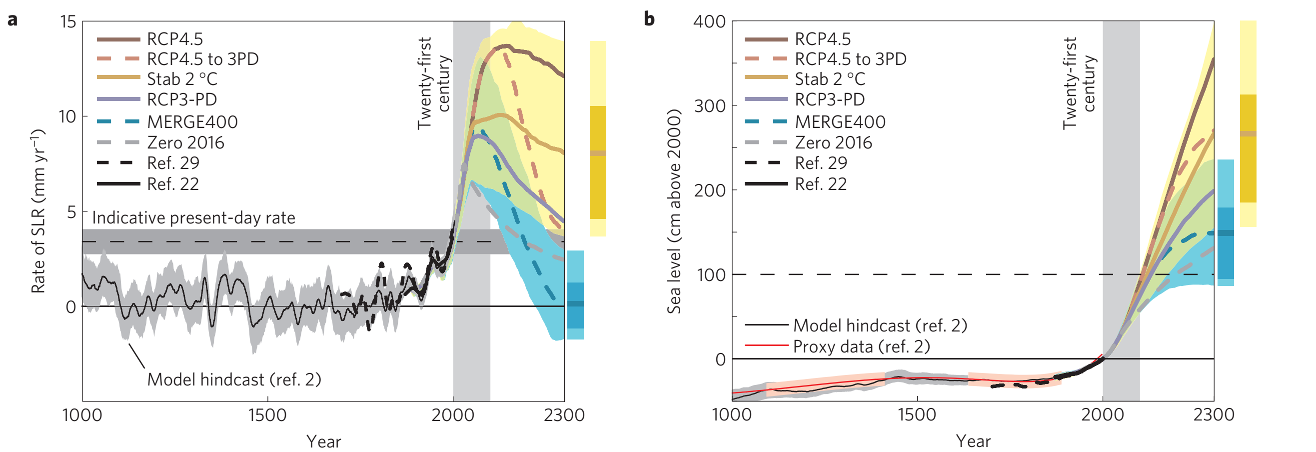

Figure 3 | Long-term SLR. a, Rate of SLR and **b**, SLR calculated from temperature reconstructions[28] for 1000–2006 and from climate-model projections 1860–2300. For comparison, observed and proxy reconstructions for SLR are given as well from refs 2,22,29. 90% uncertainty ranges are shown for only two scenarios for reasons of readability, focusing on the lowest and highest temperature-goal scenarios. Error bars on the right-hand side as in Fig. 2.

for a strong slow-down of SLR, we show in Fig. 3 the results of both the calculations for the historical period 1000–2006 (the calibration period of our sea-level model) and the model projections through 2300. We constrain this analysis to scenarios with a maximum warming of 3 °C or less. The semi-empirical model is validated only over a past range of temperature changes of about 1 °C and it is possible that greater warming could increasingly lead to nonlinear responses, for instance in ice-sheet dynamics.

The sea-level proxy data suggest that the twentieth-century rate of SLR already exceeds that experienced in the preceding millennium[2]. After a peak in the twenty-first century, the projected rate of SLR (Fig. 3a) declines in zero or negative emission scenarios. In zero 2016 the rate of SLR does not decline much further after 2200, that is, it will stay close to present-day values. This is in line with our understanding of the long memory in the climate system, here owing to the slow uptake of anthropogenic CO_2 by the oceans and the long response timescale of sea level (see also ref. 6). By contrast, the rate of change drops to zero by 2300 in the 1.5 °C scenario (MERGE400).

By 2300, sea level in our projections has risen by 2.7 (1.6–4.0) m in the ≈50% probability 2 °C scenario (Fig. 3b) and is still rising at twice the present rate. The higher probability 2 °C scenario (RCP3-PD) produces 2.0 (1.2–3.1) m SLR by 2300 and would return rates of SLR to roughly present-day values. The 1.5 °C scenario (MERGE400) limits SLR to 1.5 (0.9–2.4) m and is the only scenario that implies no further rise by 2300.

Unless post-2100 net negative CO_2 emissions are even stronger than those in MERGE400, a lower sea level by 2300 can be achieved only with less warming over the twenty-first century. This suggests that limiting multi-century SLR to the 1 m guardrail of the 2006 German Advisory Council on Global Change is possible only with more rapid twenty-first century emission reductions than in the MERGE400 scenario (illustrative scenarios on Supplementary Section S4).

In the RCP4.5 scenario, SLR approaches 2–5 m by 2300 and reaches rates of SLR much higher than observed over the twentieth century[22], or estimated using satellite-based data over the period 1993–2007 (ref. 23). The RCP4.5 to 3PD scenario shows that if mitigation is delayed for many decades, not even a massive mitigation effort (starting in 2100 when SLR is still under 1 m) can prevent sea levels from rising by at least 1.6 m and possibly even 4.2 m by the year 2300, because of the large inertia in the system.

Projecting sea level into the future is still associated with large uncertainties. Physics-based models attempting to predict the combined contributions from thermal expansion, glaciers and ice sheets are not yet mature and underestimate the SLR observed in past decades[1,9]. One of the largest uncertainties at present is the response of the Greenland and Antarctic ice sheets, where process-based models do not capture the full response so far observed[1], nor the timescales of response seen in the palaeorecord. While these models are further developed, semi-empirical models have emerged as a complementary approach[2,8,9,24–27] and have shown their ability to reproduce sea-level evolution over the past millennium and the modern tide-gauge record well, leading to projections that are robust against different choices of input data and statistical approach[25]. It remains open, however, how far the close link between global sea level and temperature found for the past will carry on into the future.

Despite this caveat, the results presented here provide at least plausible estimates for sea-level evolution in the coming centuries and a number of robust insights into how it can be affected by mitigation measures. A key aspect of this, irrespective of the exact numbers, is the long response time of sea level that is physically expected from the slow response of large ice sheets and the deep ocean to climate change, and also found in palaeoclimate data[2]. This slow response means that about half of the twenty-first century SLR is already committed from past emissions. It further means that mitigation measures, even an abrupt switch to zero emissions, have practically no effect on sea level over the coming 50 years and only a moderate effect on sea level by 2100. However, the scale of mitigation can have a large effect on the rate of rise by 2100 and a major effect on magnitude of SLR in the centuries thereafter. Twenty-first century mitigation can substantially slow down the rate of SLR and ultimately limit the rise, in the absence of nonlinear, dynamical responses from the ice sheets.

Our projections show that limiting SLR to 1.5 m or below on a multi-century timescale is consistent only with high levels of mitigation. In our model, this is illustrated by a scenario that approaches a 50% probability of reducing warming below 1.5 °C by 2100, with a high (80%) probability of doing so within the following half century. This scenario suggests that stopping further rise of sea level within a few centuries is achieved only with the large-scale deployment of CO_2-removal technologies[4]. A 2 °C warming limit, if interpreted either as a temperature-stabilization level, or as holding temperature below this level, would probably lead to many metres of SLR in the coming few centuries and would maintain rates of SLR higher than today for many centuries.

Received 19 January 2012; accepted 15 May 2012; published online 24 June 2012

References

1. Meehl, G. A. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
2. Kemp, A. C. *et al.* Climate related sea-level variations over the past two millennia. *Proc. Natl Acad. Sci. USA* **108,** 11017–11022 (2011).
3. UNFCCC *Report of the Conference of the Parties on its Sixteenth Session, held in Cancún from 29 November to 10 December 2010* (UNFCCC, 2011); available via http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf.
4. Van Vuuren, D. & Riahi, K. The relationship between short-term emissions and long-term concentration targets. *Climatic Change* **104,** 793–801 (2011).
5. German Advisory Council on Global Change *The Future Oceans - Warming Up, Rising High, Turning Sour. 110* (Earthscan, 2006).
6. Meehl, G. A. *et al.* How much more global warming and sea level rise? *Science* **07,** 1769–1772 (2005).
7. Deltacommissie *Samen werken met water. Een land dat leeft, bouwt aan zijn toekomst* (The Netherlands, 2008).
8. Jevrejeva, S., Moore, J. C. & Grinsted, A. Sea level projections to AD2500 with a new generation of climate change scenarios. *Glob. Planet. Change* **80-81,** 14–20 (2012).
9. Rahmstorf, S. A Semi-Empirical approach to projecting future sea-level rise. *Science* **315,** 368–370 (2007).
10. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6. Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
11. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
12. Rogelj, J. *et al.* Analysis of the Copenhagen Accord pledges and its global climatic impacts, a snapshot of dissonant ambitions. *Environ. Res. Lett.* **5,** 034013 (2010).
13. Vuuren, D. P. *et al.* The representative concentration pathways: An overview. *Climatic Change* **31,** 5 (2011).
14. Meinshausen, M. *et al.* The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109,** 213–241 (2011).
15. Thomson, A. *et al.* RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Climatic Change* **109,** 77–94 (2011).
16. van Vuuren, D. *et al.* Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change* **81,** 119–159 (2007).
17. Meinshausen, M. *et al.* Multi-gas emissions pathways to meet climate targets. *Climatic Change* **75,** 151–194 (2006).
18. Magné, B., Kypreos, S. & Turton, H. Technology options for low stabilization pathways with MERGE. *Energy J.* **31,** 83–107 (2010).
19. Knopf, B. *et al.* Managing the Low-Carbon Transition — From Model Results to Policies. *Energy J.* **31,** 223–245 (2010).
20. Azar, C. *et al.* The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100,** 195–202 (2010).
21. Hare, B. & Meinshausen, M. How much warming are we committed to and how much can be avoided? *Climatic Change* **75,** 111–149 (2006).
22. Church, J. A. & White, N. J. A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.* **33,** L01602 (2006).
23. Cazenave, A. & Llovel, W. Contemporary sea level rise. *Annu. Rev. Marine Sci.* **2,** 145–173 (2010).
24. Vermeer, M. & Rahmstorf, S. Global sea level linked to global temperature. *Proc. Natl Acad. Sci. USA* **106,** 21527–21532 (2009).
25. Rahmstorf, S., Perrette, M. & Vermeer, M. Testing the robustness of semi-empirical sea level projections. *Clim. Dynam.* http://dx.doi.org/10.1007/s00382-011-1226-7(2011).
26. Grinsted, A., Moore, J. & Jevrejeva, S. Reconstructing sea level from paleo and projected temperatures 200 to 2100. *Clim. Dynam.* **34,** 461–472 (2010).
27. Jevrejeva, S., Moore, J. C. & Grinsted, A. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophys. Res. Lett.* **37,** L07703 (2010).
28. Mann, M. E. *et al.* Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc. Natl Acad. Sci. USA* **105,** 13252–13257 (2008).
29. Jevrejeva, S., Grinsted, A., Moore, J. C. & Holgate, S. Nonlinear trends and multiyear cycles in sea level records. *J. Geophys. Res.* **111,** C09012 (2006).

Acknowledgements

We thank M. Meinshausen for providing the Monte-Carlo methodology and tools for the climate-model simulations, as well as the adjusted RCP scenario RCP4.5 to 3PD. We thank H. Turton for advising on the application of the MERGE scenario and for kindly providing us with gas-specific emissions data.

Author contributions

M.S. jointly conceived the study with W.H., S.R. and M.V., designed and carried out simulations, developed the methodology, analysed data and wrote the paper with W.H., S.R. and M.V. W.H. conceptualized and selected scenarios with M.S. S.R. and M.V. advised on methodology and statistical analysis.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.S.