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MITIGATION OF SHORT-LIVED CLIMATE POLLUTANTS SLOWS SEA-LEVEL RISE

Aixue Hu, Yangyang Xu, Claudia Tebaldi, Warren M. Washington and Veerabhadran Ramanathan

Online Supporting Materials:

Coupled climate model:

The National Center for Atmospheric Research Community Climate System Model version 4 (CCSM4) is a global scale fully coupled climate model. It includes a finite volume nominal 1 degree (0.9° x 1.25°) 26 level version of the atmospheric model Community Atmospheric Model version 4 (CAM4), with improved components of ocean, land and sea ice compared to the older version (CCSM3)[1]. The ocean is the Parallel Ocean Program version 2 (POP2) with a nominal latitude-longitude resolution of 1° and 60 levels in the vertical with a rotated North Pole to Greenland. The grid points in the ocean have a uniform 1.11° spacing in the zonal direction, and 0.27° near the equator, extending to 0.54° poleward of 35° N and S meridionally. No flux adjustments are used in CCSM4.

The ocean component of CCSM4 uses the Boussinesq approximation, leading to a conservation of the total ocean water volume. Therefore, the thermosteric sea level change is calculated offline after the model simulation is done. The control simulation trend of SLR in CCSM4 has been removed from the CCSM4 20th and 21st century simulations as shown in Figure SF2. In comparison with other climate models which participated in the Coupled Model Intercomparison Project phase 5 (CMIP5)[2], the simulated 20th and 21st centuries' thermosteric SLR by CCSM4 falls within the mid to upper range.

In addition, we compared the radiative forcing changes of the BC, CH4 and Halocarbon (CFCs, HCFCs, HFCs) relative to 2005 under RXM mitigation and RCP 2.6 scenarios (SF10). It shows significant similarities between these two scenarios.

Validation of the linear fit of the global mean temperature and thermosteric SLR: We used the empirical model from Vermeer & Rahmstorf[3] by fitting it to the global temperature time series and corresponding global SLR time series (thermal expansion component only) as output from CCSM4 historical and RCP simulations, after averaging all available ensemble members into ensemble mean time series, separately for each RCP experiment.

For each of the CCSM4 RCP experiments, we used in turn the remaining three RCP experiments to estimate the coefficients of the linear model by least squares. We then applied these coefficients to the global temperature time series of the fourth RCP (not used to estimate the coefficient) to determine the sea level rise as predicted by the semi-empirical model and compare it to the actual thermosteric sea level rise produced under that experiment. The R^2 of the 4 regressions are all above 0.98, and the mean of the squared residuals of the out-of sample prediction ranges between 2 cm (thermosteric SLR from RCP4.5 when predicted on the basis of the regression model fitted to all remaining three RCPs) and 6 cm (RCP2.6).

Once we verified the goodness-of-fit, we estimated a new set of coefficients by using CCSM4 output from all 4 RCP experiments together in a single regression. We used these coefficients to predict sea level rise (thermal component only) from the RXM[4] output of global temperature for the RCP simulations as shown in SF7 and other mitigation simulations as shown in Figure 2.

Semi-empirical approach:

The main criticisms levied to the semi-empirical approach are characteristic of statistical model estimation and prediction based on observational records: the extent of the calibration period is limited, and based on uncertain observations, and thus the nature of the prediction is in essence that of an extrapolation beyond the behavior already observed, which can also show sensitivity to the choices of observational records and its pre-processing. Some of the sea level change used for calibration may be due to sources unrelated to climatic changes, like ground water storage and river dams, but the magnitude of this component is highly uncertain and therefore its exclusion (or in turn its effect on the prediction) are not easily assessed[5-10], although attempts to assess these effects have been made in recent years[11-13].

Like every prediction based on empirical fits the assumption is that the behavior of the system remains the same in the future. If highly non-linear behavior kicks in it would not be accounted for by these predictions. Lastly, the reason why semi-empirical models produce on average higher projections than process-based models is still not understood, thus making the adoption of these techniques a source of debate in the community.

Nevertheless, we only use this semi-empirical model to qualitatively show how the SLCPs mitigation would affect the future SLR in conjunction with a process based coupled climate model. We are not intending to produce precise numerical SLR projection for the future. Since the estimated effect of the SLCPs mitigation on both thermosteric SLR derived from the process based model and the semi-empirical model derived SLR is on the same direction, in our opinion, the model and methodology we used here will not severely influence our conclusions. If other models and methodologies had been used, we would not expect our conclusions regarding the percent changes due to the mitigation actions to be changed significantly.

Further we also tested the semi-empirical model with b being set zero (SF11). In all scenarios, the projected SLR changes of the upper bound with b=0 in comparison to the standard VR model[3] are very small at 2100. However, with b=0, it does affect the projected mean and the lower bound SLR at the end of the 21st century. For the SLCP+CO2 scenario, the mid value of SLR projection reduces by about 10%, but the lower bound reduces by more than 20%.

Choice of input data sets:

We have tested the projected SLR using the coefficients derived from the Church and White (2011, CW11)[10] data against the SLR derived from Church and White (2006, CW06)[9] data. We found that the projected SLR by 2100 using CW11 data is about 1/3 less than that using CW06 data (see new Figure SF4 in supplements). In the end, we still chose to use CW06 data, for the following reasons:

a). The percent reduction in projected SLR between the mitigation case and the baseline (BAU) case is nearly the same (about 40% for the scenarios shown in SF4). As a result, in the main text, we describe our findings using the percent change as the metric, instead of absolute values of SLR changes.

b). We were also influenced by the conclusion of Rahmstorf et al[6]. They suggested that the fit obtained by CW06 data, simulates the observed surface temperature changes better (compared with CW11); and furthermore, it is consistent with results from 3 different methods and does not produce an estimate of the base temperature that conflicts with the stationarity of sea level rise during the 1400-1800 period (as derived by proxies).

We also tested different surface temperature data sets (HadCRUTv3[14], HadCRUTv4[15], GISS[16], and NOAA[17]) as suggested, and we found that the estimated coefficients of the four resulting models are nearly identical, well within the confidence intervals of the linear fits and thus do not produce significantly different projections. We therefore continued to use the original GISS temperature data.

General discussion on Sea Level rise

The global mean sea level change is related to many processes, such as the changes of the sea water temperature (thermosteric) and redistribution of salt (halosteric), the mass changes of the land-based ice (glaciers, ice caps and the two major ice sheets), the changes of the gravity field associated to the mass change of land-based ice, and the changes of the earth crust due to the changes of land-based ice mass. The global mean sea level change is also affected by direct human activities, such as ground water mining and dam building[11-13]. Due to lack of accurate and long-term observations on all contributing factors, it has proven to be very difficult to attribute the contributions of each of these processes to the observed SLR although intensive efforts have been made in the past decades[5-13, 18-25]. Because of the potential significant impact of SLR on human society, the projection of future SLR has caught significant attention in the scientific community[26-36]. However, it remains a grand challenge to the scientific community for accurately predicting the future global mean SLR and its regional pattern due to the uncertainty rising from the uncertainty of the climate sensitivity (such as shown in Figure SF3), the heat uptake by the ocean, response of the land-based ice to the climate changes, and the associated gravity field changes and the uplift of the earth crust underneath the land-based ice, and the ground water mining and dam buildings. Due to all of these uncertainties, we acknowledge that projections of SLR are valid only in a qualitative sense in our research. Keeping up with this perspective, we restrict our attention to the percent change in SLR and SLR rate instead of the absolute changes.

References:

1. Gent, P. R. et al. The Community Climate System Model Version 4. *J. Climate*, 24, 4973–4991 (2011).

2. Yin, J. Century to multi-century sea level rise projections from CMIP5 models. *Geophys. Res. Lett*., 39, L17709, doi:10.1029/2012GL052947 (2012).

3. Vermeer, M. and Rahmstorf, S. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America* ,106, 21527-21532 (2009).

4. Ramanathan, V., and Xu, Y. The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues. *Proceedings of the National Academy of Sciences of the United States of America*, 107(18), 8055–62, doi:10.1073/pnas.1002293107 (2010).

5. Lowe, J. A. and Gregory, J. M. A sea of uncertainty. *Nature Reports Climate Change*. pp. 42-43. ISSN 1753-9315 doi: 10.1038/climate.2010.30 (2010)

6. Rahmstorf, S., Perrette, M. M. and Vermeer, M. Testing the robustness of semi-empirical sea level projections. *Climate Dynamics*, *39*(3-4), 861–875, doi:10.1007/s00382-011-1226-7 (2011).

7. Nicholls, R. J. et al. Sea-level rise and its possible impacts given a 'beyond 4^{o}C world' in the twenty-first century. *Phil. Trans. R. Soc*. A, 369, 161-181 (2011).

8. Willis, J. K. and Church, J. A. Regional Sea-Level Projection. *Science*, 336, 550-551, doi:10.1126/science.1220366 (2012).

9. Church, J.A., White N.J. A 20th-century acceleration in global sea-level rise. *Geophys Res Lett,* 33, L01602 (2006).

10. Church, J.A., White, N.J. Sea-level rise from the late 19^{th} to the early 21^{st} century. *Surv. Geophys.,* 32, 585-602, doi:10.1007/s10712-011-9119-1 (2011).

11. Chao, B. F., Wu, Y. H., & Li, Y. S. Impact of artificial reservoir water impoundment on global sea level. *Science*, 320, 212-214, doi:10.1126/science.1154580 (2008)

12. Wada, Y. et al. Past and future contribution of global groundwater depletion to sea-level rise. *Geophysical Research Letters*, 39, 1-6, doi:10.1029/2012GL051230 (2012).

13. Winkelmann, R., Levermann, A., Martin, M. A., & Frieler, K. Increased future ice discharge from Antarctica owing to higher snowfall. *Nature*, 492(7428), 239-242. doi:10.1038/nature11616 (2012).

14. Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B. and Jones, P. D. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *J. Geophys. Res*., 111, D12106, doi:10.1029/2005JD006548 (2006).

15. Morice, C. P., Kennedy, J. J., Rayner, N. A. and Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *J. Geophys. Res*., 117, D08101, doi:10.1029/2011JD017187 (2012).

16. Hansen, J. et al. Global surface temperature change. *Reviews of Geophysics,* 48, 1-29 (2010).

17. Smith, T. M., Reynolds, R., Peterson, T. C. and Lawrimore, J. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *J. Clim.,* 21, 2283–2296, doi:10.1175/2007JCLI2100.1 (2008).

18. Mitrovica, J.X., Tamisiea, M. E., Davis, J. L. and Milne, G. A. Recent mass balance of polar ice sheets inferred from patterns of global sea level change. *Nature*, 409, 1026-1029 (2001).

19. Kopp, R. E. et al. The impact of Greenland melt on regional sea level: a partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. *Climatic Change*, **103**, 619-625, doi:10.1007/s10584-010-9935-1 (2010).

20. Peltier, W.R. Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment. *Quaternary Science Review*, doi:10.1016/j.quascirev.2009.04.004 (2009).

21. Van den Broeke, M. et al. Partitioning recent Greenland mass loss. *Science*, 326, 984-986, doi:10.1126/science.1178176 (2009).

22. Rignot, E., Velicogna, I., van den Broeke, M.R. Monaghan, A. and Lenaerts, J. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett*., **38**, L05503, doi:10.1029/2011GL046583 (2011).

23. Church, J.A. et al. Revisiting the Earth's sea level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, 38, L18601, doi:10.1029/2011GL048794 (2011).

24. Jacob, T. et al. Recent contributions of glaciers and ice caps to sea level rise. *Nature*, 482, 514-518, doi:10.1038/nature10847 (2012).

25. Stepherd, A. et al. A reconciled estimate of ice-sheet mass balance. *Science*, 338, 1183-1189 (2012).

26. Kuhlbroudt, T. and Gregory, J. M. Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change. *Geophys. Res. Lett*, 39, L18608, doi:10.1029/2012GL052952 (2012).

27. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2 degrees C. *Nature*, 458, 1158-1162. doi:10.1038/nature08017 (2009).

28. Moore, J. C., Jevrejeva, S., & Grinsted, A. Efficacy of geoengineering to limit 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 15699-703. doi:10.1073/pnas.1008153107 (2010).

29. Radić, V., Hock, R., & Radi, V. Regionally differentiated contribution of

mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience*, 4, 91-94. doi:10.1038/ngeo1052 (2011).

30. Rahmstorf, S. A semi-empirical approach to projecting future sea-level rise. *Science*, 315(5810), 368-370. doi:10.1126/science.1135456 (2007).

31. Schaeffer, M., Hare, W., Rahmstorf, S., & Vermeer, M. Long-term sea-level rise implied by 1.5^{o}C and 2^{o}C warming levels. *Nature Climate Change*, 2, 3-6. doi:10.1038/nclimate1584 (2012).

32. Wigley, T. M. L., & Raper, S. C. B. Extended scenarios for glacier melt due to anthropogenic forcing. *Geophysical Research Letters*, 32, L05704. doi:10.1029/2004GL021238 (2005).

33. Pardaens, A. K., Gregory, J. M., Lowe, J. A. A model study of factors influencing projected changes in regional sea level over the twenty-first century. *Climate Dynamics*, 36, 2015-2033, doi:10.1007/s00382-009-0738-x (2011).

34. Yin, J. Century to multi-century sea level rise projections from CMIP5 models. *Geophys. Res. Lett*., 39, L17709, doi:10.1029/2012GL052947 (2012).

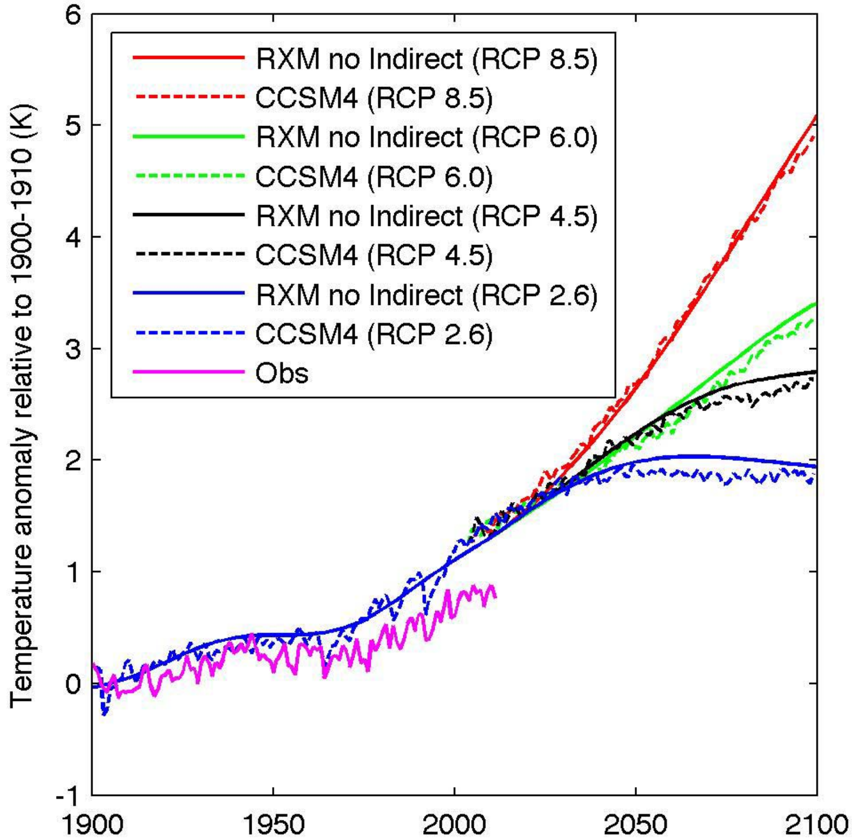
35. Yin, J., Schlesinger, M. E., and Stouffer, R. J. Model projections of rapid sea level rise on the mortheast coast of the United States. *Nature Geoscience,* **2**, 262-266, doi: 10.1038/NGEO462 (2009).

36. Hu, A., Meehl, G. A., Han, W., and Yin, J. Effect of the Potential Melting of the Greenland Ice Sheet on the Meridional Overturning Circulation and Global Climate in the Future. *Deep Sea Res. Part II*, **58**, doi: 10.1016/j.dsr2.2010.10.069, 1914-192 (2011).

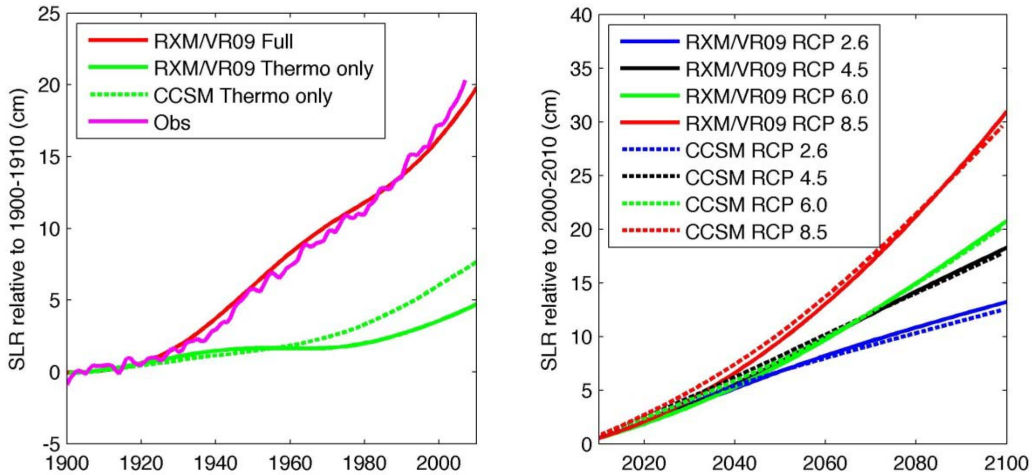
Supplement Table 1: Observed and simulated temperature and sea level change in the 20th century.

Case	20th Century (1900 to 2005)		
	ΔT (°C)	SLR_R (cm/yr) at 2005	ΔSLR (cm)
Observed	0.72 (ref 16)	0.41 (ref 9)	19.9 (ref 9)
Semi-empirical SLR	0.7	0.34	17.9±3.7
Thermosteric SLR	0.7	0.11	4.3±0.1

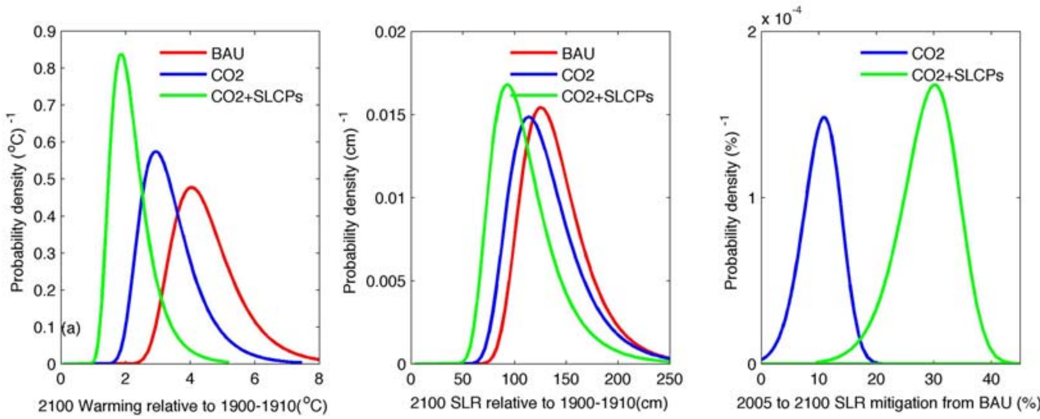
Supplement figures



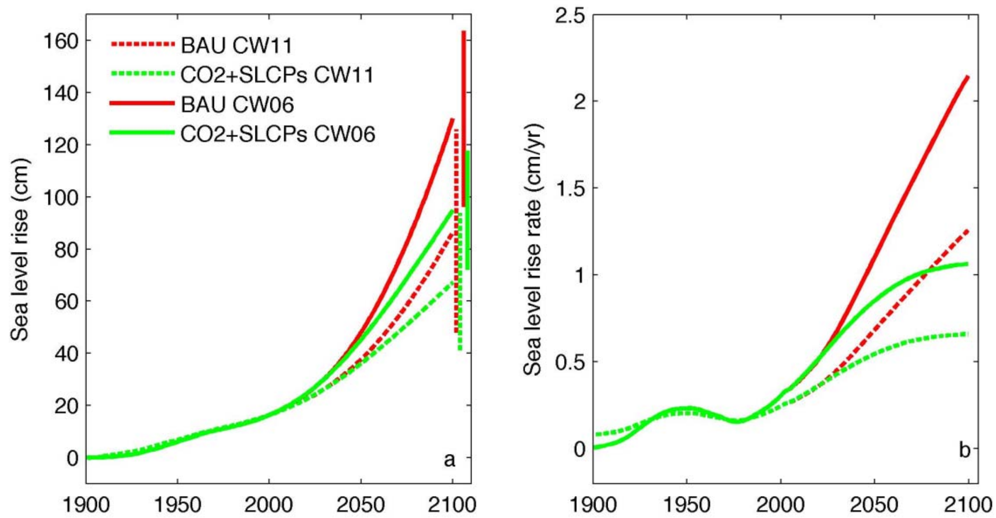
SF1. Temperature simulated by RXM and CCSM4 (anomaly relative to 1900-1910 mean). As CCSM4 does not include aerosol indirect effect, we exclude that from RXM in this simulation only. Both models agree with each other during the 20th century but both overestimate observed temperature increase[16].



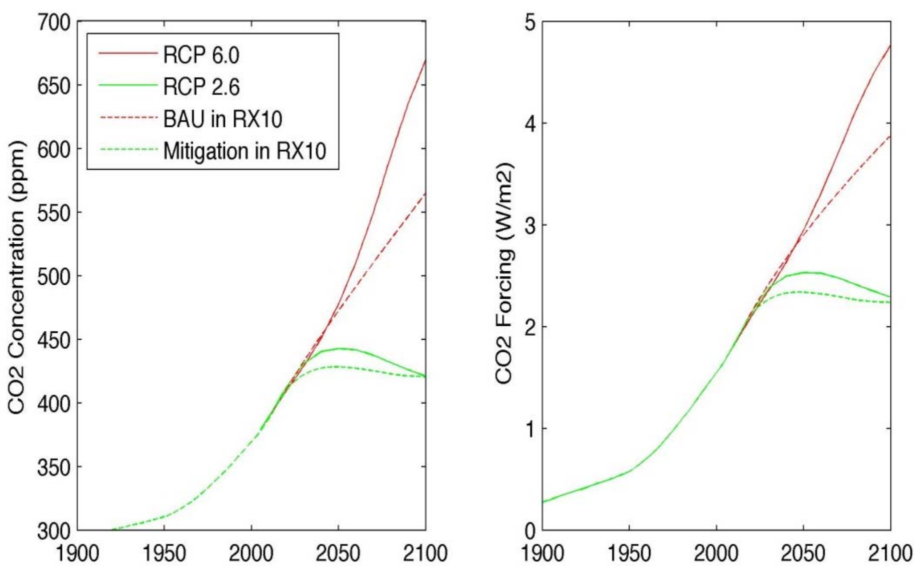
SF2. SLR simulated by a semi-empirical model[3] (labeled as RXM/VR09) and CCSM4 thermal expansion only simulation[1]. (a) Historical SLR simulation (relative to 1900-1910) compared with observation[9]. RXM/VR09 Full is semi-empirical model developed by fitting with observed temperature[14] and SLR[9]. RXM/VR09 Thermo only is the semi-empirical model developed by fitting with future temperature increase and thermal expansion SLR simulated by CCSM4. Historical SLR directly simulated by CCSM4 (green dash line) is higher than RXM/VR09 Thermo only because CCSM4 does not take into account aerosol indirect effect and therefore overestimated historical warming (also see SF1). (b) Future SLR due to thermal expansion only (relative to 2000-2010) under various RCP scenarios.



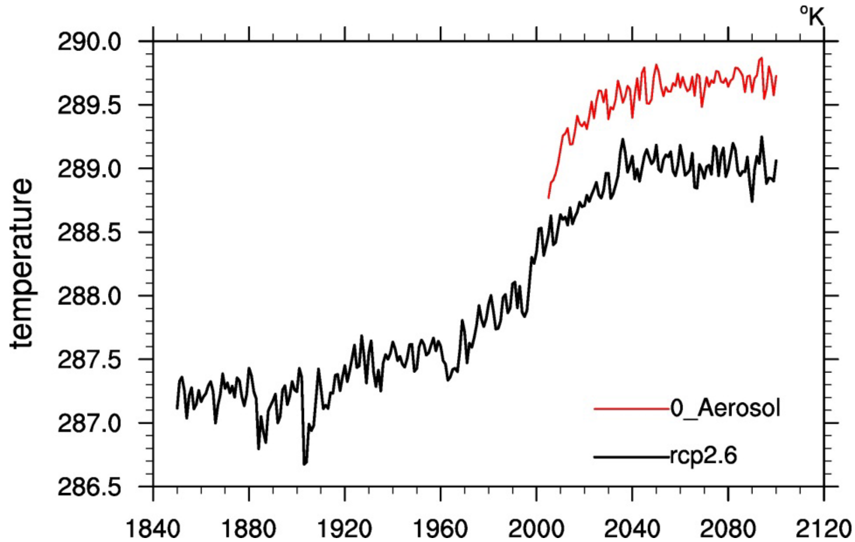
SF 3. (a)Probability distribution of temperature warming at 2100 under three scenarios (BAU, CO2 mitigation and CO2+SLCPs mitigation). The uncertainty range is caused only by climate sensitivity uncertainty. The most likely value is shown in Fig 1 and Table 1. (b) same as (a) but for SLR. The most likely value is shown in Fig 2a and Table 1. (c) SLR (2005-2100)reduction from BAU under CO2 and CO+SLCPs mitigation scenarios.



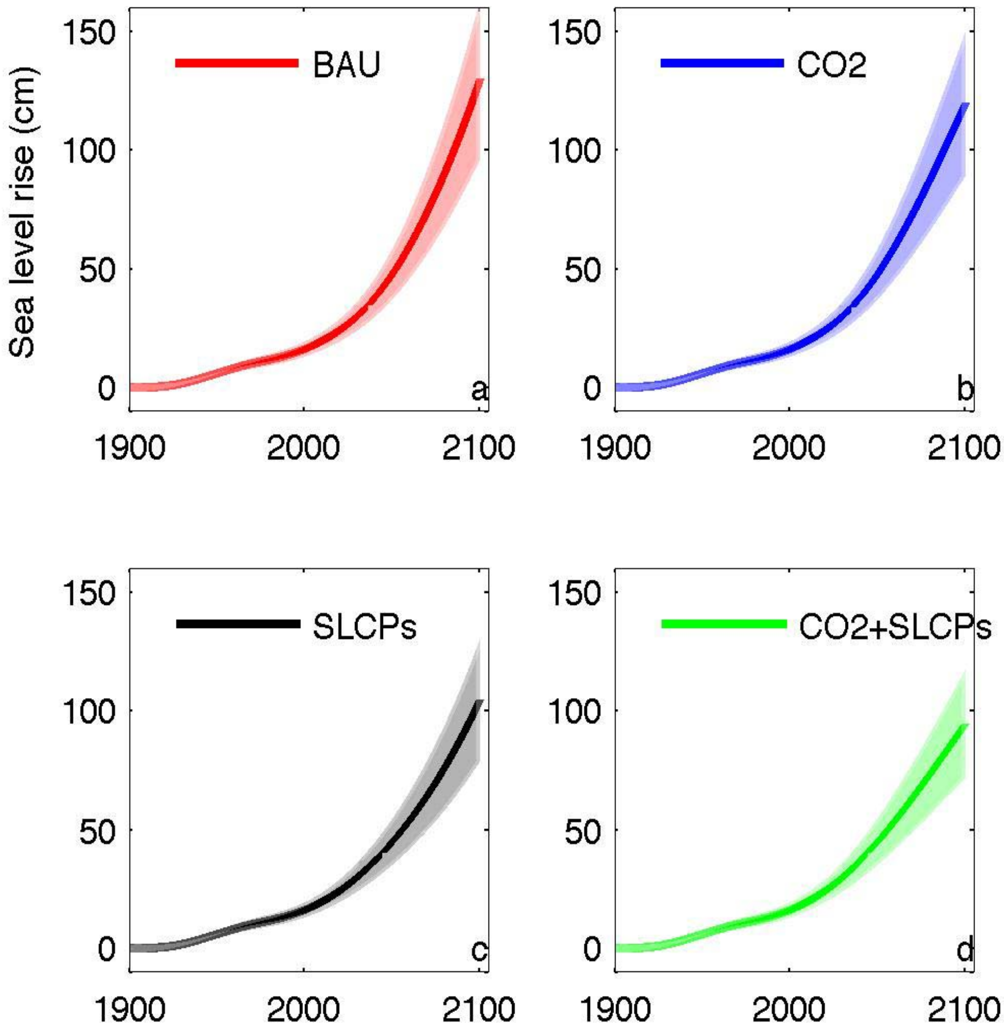
SF 4. The sensitivity of the projected SLR in the 21st century from the VR[3] model to the input SLR data sets[9,10]. CW11 represents Church and White 2011 data[10] and CW06 represents Church and White 2006 data[9].



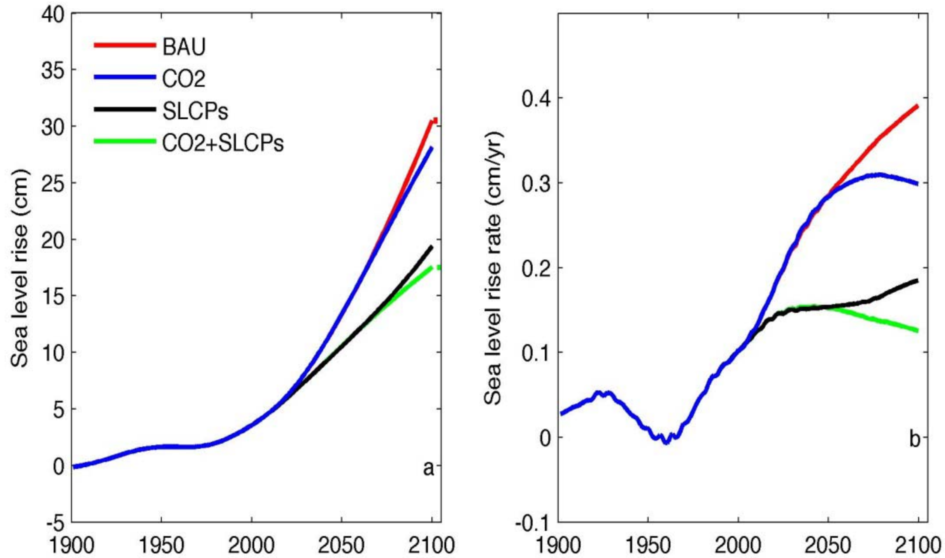
SF5. A comparison of the CO_2 concentration and forcing used in ref 4 (labeled as RX10) and RCP6.0 and RCP2.6 scenarios.



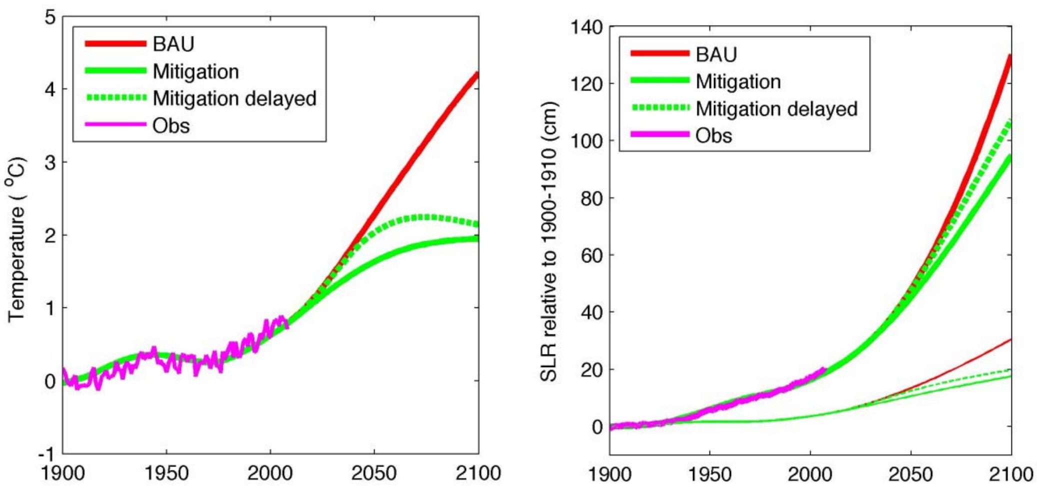
SF6. Simulated global mean surface temperature from 1850 to 2100 using NCAR CCSM4. For the historical period, all know climate forcings, such as CO_2, methane, SO_2, black carbon, solar etc., are used. The overall warming is about 1.1°C averaged over 1996-2005 from the mean of 1850-1899. This warming is slightly higher than that suggested by observations. From 2006-2100, the model is forced by IPCC RCP2.6, a scenario designed to keep the global mean temperature rise to less than 2°C by the end of the 21st century. In this scenario, heavy mitigation of CO_2 has been assumed and the CO_2 concentration will peak at about 450ppm in the mid-21st century, and then decline to about 420ppm by the end of the 21st century. In our model, the warming by the end of the century is 2.4°C relative to the mean of 1850-1899. To test the sensitivity of the climate to aerosols, we set all aerosols in RCP2.6 to zero, and the climate is about 0.65°C warmer than that simulation including the aerosols. This suggests that the increased aerosol concentration since the industrialization is indeed masking part of the warming from the rising CO_2 concentration. In the other word, by making our air cleaner, we could potentially see a larger warming.



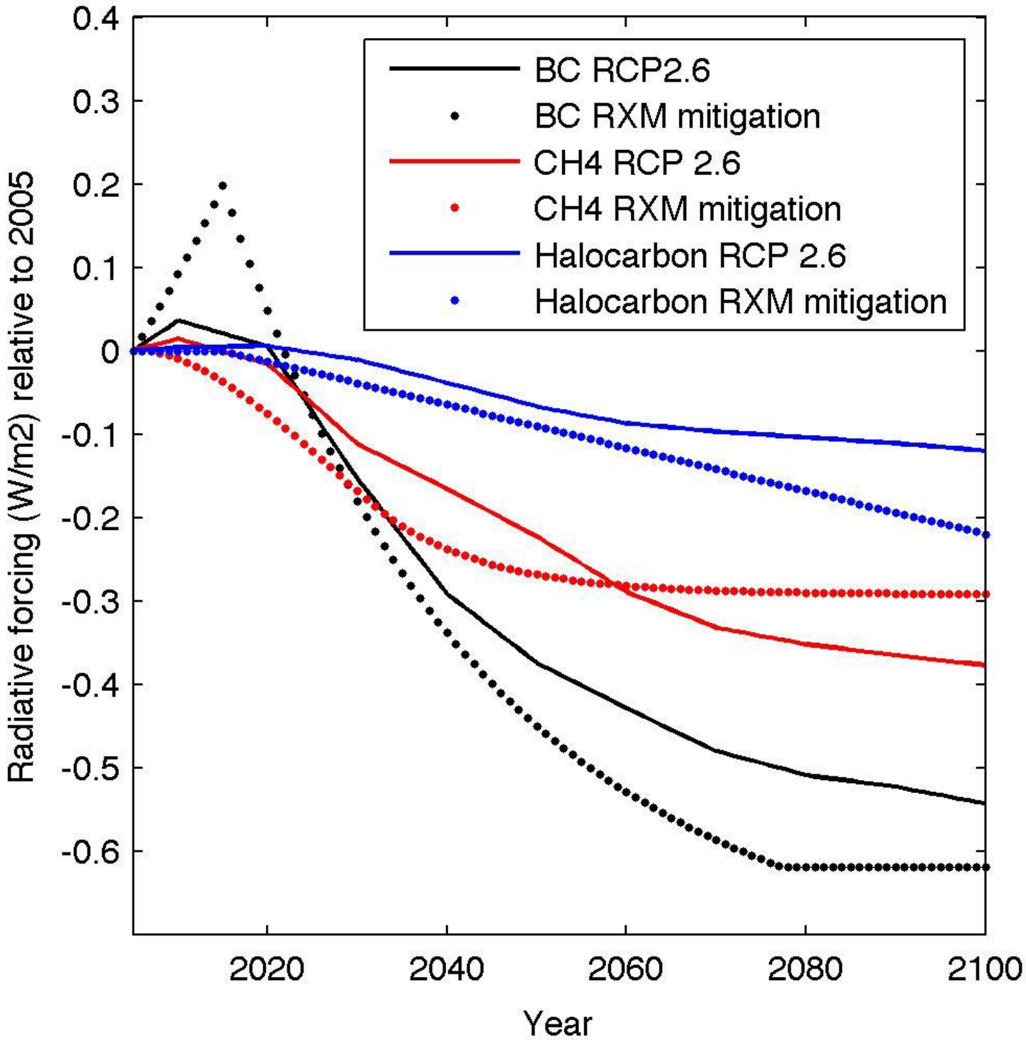
SF7. SLR_{full} under different scenarios as shown in Fig 2a solid lines, except that time-dependent uncertainty range are illustrated in color shades. The uncertainty shown here are only due to SLR model but not climate sensitivity.



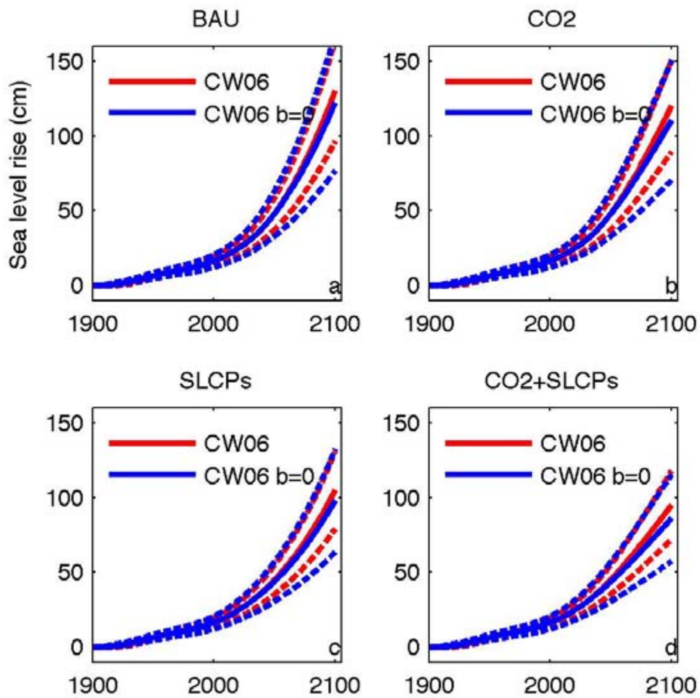
SF8. Same as Fig 2, except that only thermal expansion SLR (the dash lines in Fig 2) is shown.



SF9. Temperature and SLR responses if mitigation efforts on SLCPs were delayed by about 25 years. The delayed emission reduction starts at 2030(methane) or 2040(BC). Observed temperature[16] and SLR[9] are shown for reference. The three thinner lines in right panel are SLR due to thermal expansion only.



SF10. BC, CH4 and Halocarbon (CFCs, HCFCs, HFCs) radiative forcing change relative to 2005 under RXM mitigation and RCP 2.6 scenarios. Note that for both scenarios, BC forcing is calculated by scaling future emission, and CH4 forcing is calculated from future atmospheric concentration which takes into account indirect contribution to ozone.



SF11. A comparison of the VR[3] model with b=0 (blue lines) and not zero (red lines) for CW06 data[9].