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Sea level rise projections for current generation CGCMs based on the semi-empirical method

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[1] The semi-empirical relationship between global surface air temperature and mean sea level first developed by Rahmstorf is here applied to the latest generation of Coupled Global Climate Models (CGCMs) used for the IPCC Fourth Assessment Report (AR4). Our results produce a broader range of sea level rise projections, especially at the higher end, than outlined in IPCC AR4. The range of sea level rise results is CGCM and emissions-scenario dependent, and not sensitive to initial conditions or how the data are filtered temporally. Both the IPCC AR4 and the semi-empirical sea level rise projections described here are likely to underestimate future sea level rise if recent trends in the polar regions accelerate. **Citation:** Horton, R., C. Herweijer, C. Rosenzweig, J. Liu, V. Gornitz, and A. C. Ruane (2008), Sea level rise projections for current generation CGCMs based on the semi-empirical method, *Geophys. Res. Lett.*, *35*, L02715, doi:10.1029/2007GL032486.

1. Introduction

[2] Sea level rise has emerged as arguably the preeminent threat posed globally by climate change, despite large uncertainty about the range of possible sea level rise this century and beyond. The latest Intergovernmental Panel on Climate Change Fourth Assessment Report [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007] has produced estimates ranging from 0.18 to 0.59 m by the last decade of the 21st century, relative to the last two decades of the 20th century. Because these projections are based on CGCMs with coarse spatial resolution and limitations in representation of the model physics, they cannot accurately describe important aspects of ice sheet dynamics and thermodynamics. These include frictional forces at the base of the ice sheet, the impact of calving and thinning at the ice sheet boundaries on the upstream ice flow rates, and implications of changes in grounding lines.

[3] There is some evidence that changes in the ice sheets may be accelerating. The Greenland and the West Antarctic ice sheets may together be adding some 0.0035 m/decade to sea level rise in recent years [*Shepherd and Wingham*, 2007]. Satellites detect a thinning of parts of the Greenland Ice Sheet at lower elevations, and glaciers are disgorging ice into the ocean more rapidly, adding 0.0023 to 0.0057 m/decade to the sea within the last decade [*Rignot and Kanagaratnam*, 2006]. The West Antarctic Ice Sheet is also showing some recent signs of thinning [*Shepherd and Wingham*, 2007; *Velicogna and Wahr*, 2006].

[4] How these ice sheets may respond to the higher polar temperatures expected this century is a critical question. The extent of polar warming projected by 2100 in the SRES A1B scenario [*IPCC*, 2000], for example, is comparable to that of the last interglacial, ~125,000 years ago, when global sea level stood 4–6 m higher. Climate models project increased snow and ice accumulation on Antarctica and hence a negative sea level contribution there of approximately 0.004 to 0.02 m/decade for SRES A1B at 2100 greenhouse gas levels [*IPCC*, 2007]. However, this accumulation effect could be offset by increased ice discharge, especially if buttressing by the major West Antarctic ice shelves were to be reduced. Warming of 1°C under major ice shelves could lead to their disappearance within centuries [*IPCC*, 2007], and a 2°C global warming might be enough to destabilize the West Antarctic Ice Sheet (WAIS) [*Oppenheimer and Alley*, 2005].

[5] Because current climate models do not include all relevant dynamic ice processes, analogies are often drawn from paleoclimate evidence. *Hansen et al.* [2007] point out that although ice sheets may take centuries to millennia to disintegrate if only responding to weak orbital forcings of climate change, evidence exists for episodes of more rapid ice break-up. For example, during "meltwater pulse 1A" [*Fairbanks*, 1989], which occurred ~14,600–14,000 years ago, maximal rates of sea level rise have been variously estimated at .39 m/decade [*Fairbanks*, 1989], or .53 m/decade within 300 years [*Hanebuth et al.*, 2000; *Kienast et al.*, 2003]. Such high dynamical discharge rates, even if possible under current boundary conditions, are unlikely to be sustained for long, since WAIS is now 20 times smaller than the Northern Hemisphere ice sheets of the Last Glacial Maximum, c. 20,000 years ago.

[6] An alternative to the IPCC AR4 SLR approach pioneered by *Rahmstorf* [2007a] estimates sea level rise indirectly from changes in global average near surface temperature, one of the more accurate variables in CGCMs. This semi-empirical technique estimates sea level rise based on changes in global average temperature and sea level between 1880 and the present. The procedure passes the test of predicting one-half of the dataset from the other half, is relevant at decadal timescales, and is valid both with and without the inclusion of the linear trend (*Rahmstorf* [2007b] in response to *Holgate et al.* [2007], and *Schmith et al.* [2007]). Future sea level rise was projected by Rahmstorf using temperature simulations from the *IPCC* [2001] TAR

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CGCMs and this semi-empirical approach based on global average near surface temperature. The results represent a 'middle ground', since they lead to a broader range of sea level rise estimates than the IPCC AR4. However, they do not directly include the possibility of non-linear ice dynamics producing extreme future changes in sea level.

[7] Here we apply the semi empirical method using the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, comprised of results from the CGCMs used for the IPCC AR4 report [*IPCC*, 2007]. In support of the IPCC AR4, an expanded number of climate modeling groups worldwide have performed the most comprehensive suite of coordinated experiments during 2004–2005, including the climate of the 20th century with observed anthropogenic or natural forcing and the 21st century with the prescribed IPCC SRES, A1B, A2, and B1 scenarios. This latest generation of CGCMs has improved spatial resolution and simulation of climate features such as the El Niño Southern Oscillation (ENSO), relative to that of the IPCC TAR [*IPCC*, 2001] model cycle. Our results can be compared to those of *Rahmstorf* [2007a] and considered as an update of his results.

2. Data and Methods

[8] Eleven CGCMs on the WCRP/PCMDI data portal had model simulations for the B1, A1B, and A2 SRES emissions scenarios. Because the various CGCMs differ in their formulations of physical processes in the atmosphere, ocean, sea ice and land components, the simulations are model-dependent (detailed information can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php).

[9] To limit the source of varying sea level rise projections across models and emissions scenarios to the effects of varying temperature increase in the 21st century, we neutralize biases and intermodel differences in temperature climatology. This was accomplished by subtracting the base temperature climatology in each simulation from the future-year values in the same simulation. Future year temperature anomalies were increased by 0.93°C, our estimate of the difference between equilibrium temperature and the base 2001–2005 temperature. Of this 0.93°C, 0.5°C is based on *Rahmstorf*'s [2007a] estimate of the disequilibrium as of the 1951–1980 period relative to the pre-industrial era, and the remaining 0.43°C represents the observed change in global surface air temperature between 1951–1980 and the current 2001–2005 values. Because the projections are relative to current values, rather than 1990, they are lower than the Rahmstorf projections by approximately 0.04 meters. An additional subtle difference between our methodology and that of *Rahmstorf* [2007a] is that we apply his fit designed for 5-year bins to the current generation of CGCMs at annual temporal resolution. An offline analysis indicates that using the one year rather than 5 year binning introduces a small upward bias to our results that reaches approximately .04 m by the year 2100.

[10] Only one simulation was included for each model and emissions scenario for consistency, since the majority of the models did not have multiple runs available for all emissions scenarios. Furthermore, the large variation in the number of ensemble members causes the interannual variability of the ensemble means to be highly inconsistent across models. However, our analysis of a subset of runs reveals that the global surface air temperature for individual runs does not differ significantly from the same model's ensemble mean (see details in Results section), indicating that by using one member, interannual variability can be preserved without introducing 'selection error' based on the ensemble member chosen. Because these small deviations have a short persistence period, they have only a minute effect on global mean sea level rise when the procedure is applied.

[11] The time-slice projections of SLR shown as histograms are based on a five-year window centered around the designated year. For example, 2020 represents an equal weighting of each year from 2018–2022. Since near surface air temperature and sea level rise at the global scale are characterized by small interannual variability, signal exceeds noise over a five-year period [*IPCC*, 2007]. Tests with longer (10 year) and shorter (3 year) windows produced very similar sea level rise results.

[12] The uncertainty range through time for the sea level rise projections was also calculated by combining the yearly maximum and minimum sea level rise projections with the added uncertainty due to the statistical error of the fit between historical sea level rise and surface warming [*Rahmstorf*, 2007a]. This error estimate, which includes both a base temperature and fitted slope component, was calculated based on the Matlab code provided by S. Rahmstorf at http://www.sciencemag.org/cgi/content/full/sci;317/5846/1866d/DC1.

3. Results

[13] Figure 1 shows the range of global sea level rise projections over the 21st century for the AR4 simulations. Due to the high thermal inertia of the ocean, it is not until mid-century that the sea level rise results begin to diverge significantly, depending upon emissions scenario. Although A2 cumulative emissions exceed A1B cumulative emissions in 2100 by approximately 20 percent, sea level rise projections are very similar over the 21st century. Due to the large inertia of the climate system and long residence time of several key greenhouse gases, the A1B emissions trajectory—characterized by relatively high values early in the century—exerts disproportionate influence on temperature (and sea level/rise through Rahmstorf's formulation) relative to A2. Acceleration of sea level rise occurs in all three scenarios throughout the century, since sea level rise rates are dependent on departures from equilibrium temperature, not rates of temperature change.

[14] In 2100, the mean sea level rise increase is 0.71 m, with individual simulations ranging from 0.54 m to 0.89 m. When uncertainty in the statistical error of the fit is included the range expands to 0.47 m to 1.00 m. Also shown as a point of interest in Figure 1 is the amount of sea level rise associated with minimization and maximization across the 33 simulations of global surface air temperature increase; by 2100 these two sea level increases are .48 and .94 m respectively.

[15] The values described above can be compared to the IPCC AR4 estimates for the last decade of the 21st century

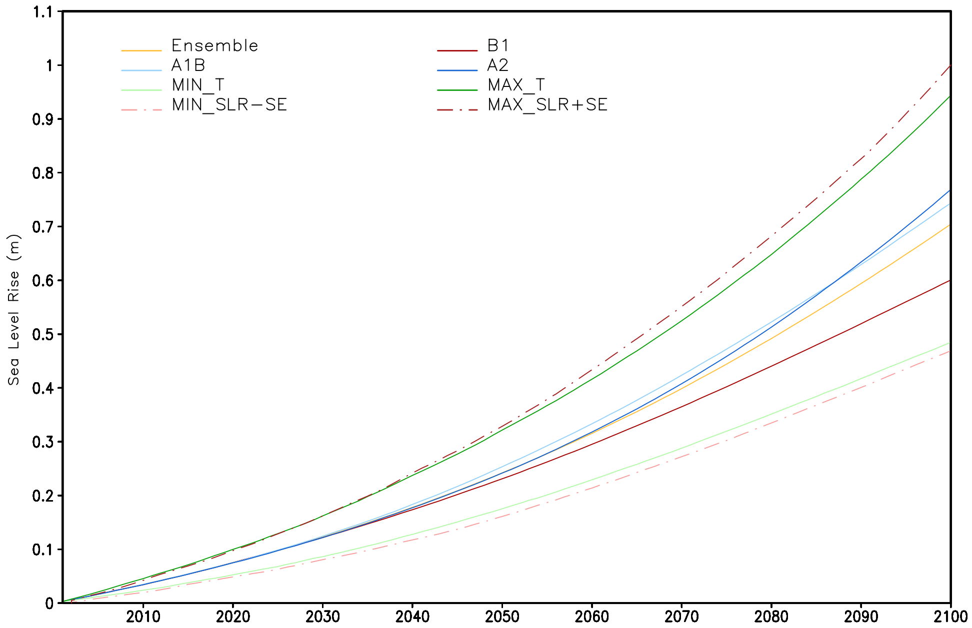

Figure 1. Averages of sea level rise, in meters, over the 21st century. To more broadly bound the uncertainty the annual maximum and minimum sea level rise of the 33 simulations are combined with the statistical error of the fit (MAX_SLR + SE and MIN_SLR − SE, respectively). Also shown are the two sea level rise projections generated by maximizing (MAX_T) and minimizing (MIN_T) annual temperature increase relative to the base period in the 33 simulations.

relative to the last two decades of the 20th century, of 0.18 to 0.59 m (see Table 1, which also shows the IPCC TAR estimates for comparison). The primary difference between the semi-empirical technique and the IPCC results is the former's higher overall values, although the technique also yields some expansion in the range of results.

[16] Comparison of our results to those from the earlier generation CGCMs reveals many similarities. The upper bound for the earlier simulations is approximately 0.24 m higher than the results here. This is primarily due to the inclusion of the high A1FI emissions scenario in the TAR (the A1FI emissions scenario was not included here since it is not available from the WCRP data portal). The A2, A1B, and B1 results by contrast are lower here by approximately.10 m. The overall similarities between the results can be explained simply by the relative consistency of CGCM global average temperature projections between the TAR and AR4 model cycles.

[17] Figure 2 shows SLR projections from the 11 CGCMs under the A1B emissions scenario. In this scenario, sea level rise in 2100 ranges between a low of 0.62 m in the CSIRO model and a high of 0.88 m in MIROC. Although the intermodel range is substantial, the upward trend for all the models is clear.

[18] The relatively small role of natural variability, by contrast, can be seen by comparing sea level rise for the seven available ensemble members, and the ensemble mean, for NCAR CCSM3.0 scenario A1B. No two runs differ in sea level rise by more than 0.04 m for any year during the 21st century. The ensemble mean is slightly closer to the lowest-sea level rise ensemble member, but never differs from even the maximum simulation by more than 0.025 m in any year.

[19] An estimate of the model-based probability/relative frequencies of sea level rise for 2020, 2050, and 2080 based on all models and emissions scenarios is presented in Figure 3. In keeping with the IPCC approach each emissions scenario and CGCM is given equal weight. Because of this, because neither the range of emissions scenarios nor the range of CGCMs encompass the uncertainty in future sea level rise, and because no error estimate is included here, the histogram should not be mistaken for a true probability distribution [*Cox and Stephenson*, 2007; *Stainforth et al.*, 2005].

Table 1. Comparison of Sea Level Rise Estimates in Meters

Sea Level Rise Estimate	B1	B2	A1B	A1T	A2	A1F1
IPCC-TAR[a]	0.31 (0.09–0.57)	0.36 (0.11–0.65)	0.39 (0.13–0.69)	0.37 (0.18–0.86)	0.42 (0.16–0.74)	0.49 (0.11–0.67)
IPCC-AR4[b]	0.18 to 0.38	0.20 to 0.43	0.21 to 0.48	0.20 to 0.45	0.23 to 0.51	0.26 to 0.59
Semi-empirical method, using TAR models[c]	0.70	~.79	~.84	~.84	~.87	~1.01
Semi-empirical method, using AR4 models[d]	0.60 (0.54–0.75)	NA	0.74 (0.62–0.88)	NA	0.77 (0.68–0.89)	NA

[a] 1990 to 2100 [*IPCC*, 2001] (m).

[b] 1980–1999 to 2090–2099 [*IPCC*, 2007]. Numbers represent the 5–95% range.

[c] 1990 to 2100, courtesy of S. Rahmstorf.

[d] 2001–2005 to 2100. Both the mean value and the range across the 11 GCMs are shown.

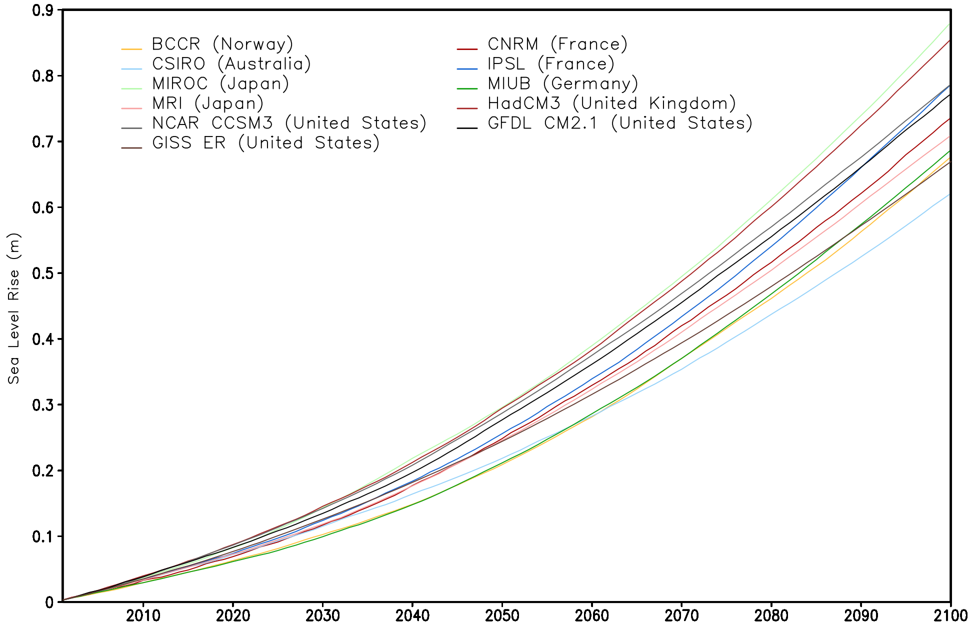

Figure 2. Averages of sea level rise, in meters, over the 21st century for the eleven individual CGCMs under the A1B emissions scenario.

[20] As the sea level rise projections increase over the course of the 21st century, the range of sea level rise results increases as well. Only for the 2020 period does the histogram bear any similarity to a normal distribution, with approximately 2/3 of all values falling within 0.065 and 0.08 m. By 2080, approximately 80 percent of the results are clustered between 0.425 and 0.575 m, although within that range the probabilities are fairly uniform, rather than normally distributed.

4. Summary and Conclusions

[21] These results provide an alternate range of potential global sea level projections to those provided in the IPCC AR4. We note that this methodology also has a number of shortcomings and cannot capture the full range of sea level rise uncertainty. The projections are based on: (1) SRES emissions scenarios (which effectively omit carbon-cycle feedbacks); (2) CGCM simulations which do not include all relevant processes; and (3) historical relationships between global temperature and sea level rise (which may not be valid as climate change alters the ice-albedo and other climate feedbacks). Key aspects that need to be better understood include frictional forces at the base of the ice sheet, the impact of calving and thinning at the ice sheet boundaries on the upstream ice flow rates, and implications of changes in grounding lines. Also important are the effects of meltwater ponds, both at the surface and at depth, where they influence basal lubrication of the ice sheet beds. Changes in source precipitation must also be better understood.

[22] Recent observations indicate accelerating sea ice loss in the Arctic are far beyond levels predicted by the most climate-sensitive CGCMs [*Holland et al.*, 2006]. The higher SLR projections (relative to *IPCC* [2007]) provided here may also be too low (http://nsidc.org/news/press/2007_seaiceminimum/20070810_index.html).

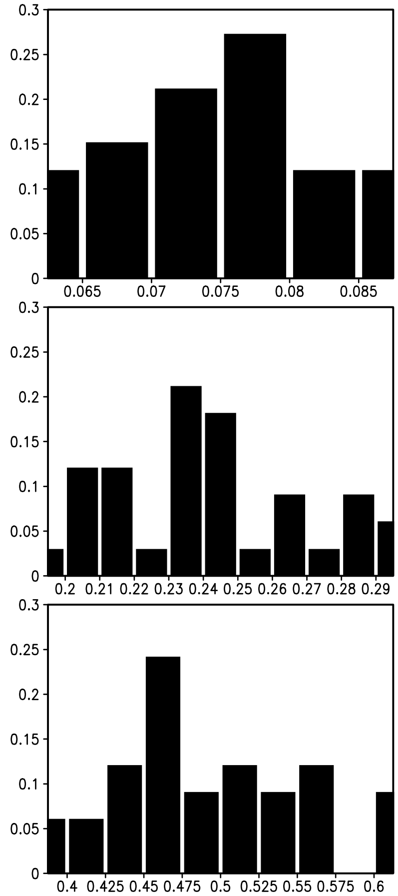

Figure 3. Model-based fractional probability distribution of global mean sea level rise relative to 2001–2005, based on 11 GCMs and 3 emissions scenarios for 2020, 2050, and 2080.

[23] While melting sea ice has negligible effect on global sea level, it suggests a high degree of Arctic climate sensitivity and a possible positive feedback whereby higher Arctic air and ocean temperatures and reduced ice might eventually undermine Greenland's ice sheets.

[24] It is therefore essential that ice sheet monitoring be expanded. Future studies using WCRP/PCMDI CGCM output and observations should focus on understanding high-latitude atmosphere and ocean temperatures (and salinity) both as drivers and diagnostics of ice sheet melt. Additional paleoclimate and modeling studies using evolving ice models will continue to improve our understanding of the full range of possible sea level outcomes in the 21st century. As modeling centers embark on earth system modeling, land ice is poised to join the historical triumvirate of ocean, land, and sea-ice components. Research should simultaneously proceed to improve CGCM resolution, ice-sheet/flow models, and means of coupling the two. Finally, other perhaps more complex semi-empirical methods, including for example delayed sea level response to the surface air temperature forcing (to mimic vertical heat propagation in the ocean), might be worthy of further investigation.

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