Probabilistic Forecast for 21st Century Climate Based on an Ensemble of Simulations using a Business-As-Usual Scenario

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Summary

The behavior of the climate system is examined in an ensemble of runs using an Earth System Model of intermediate complexity. Climate "parameters" varied are the climate sensitivity, the aerosol forcing, and the strength of ocean heat uptake. Variations in the latter were accomplished by changing the strength of the oceans' background vertical mixing. While climate sensitivity and aerosol forcing can be varied over rather wide ranges, it is more difficult to create such variation in heat uptake while maintaining a realistic overturning ocean circulation. Therefore, separate ensembles were carried out for a few values of the vertical diffusion coefficient. Joint probability distributions for climate sensitivity and aerosol forcing are constructed by comparing results from 20th century simulations with available observational data. These distributions are then used to generate ensembles of 21st century simulations; results allow us to construct probabilistic distributions for changes in important climate change variables such as surface air temperature, sea level rise, and magnitude of the AMOC. Changes in the rate of ocean and land uptake of CO_2 are also examined.

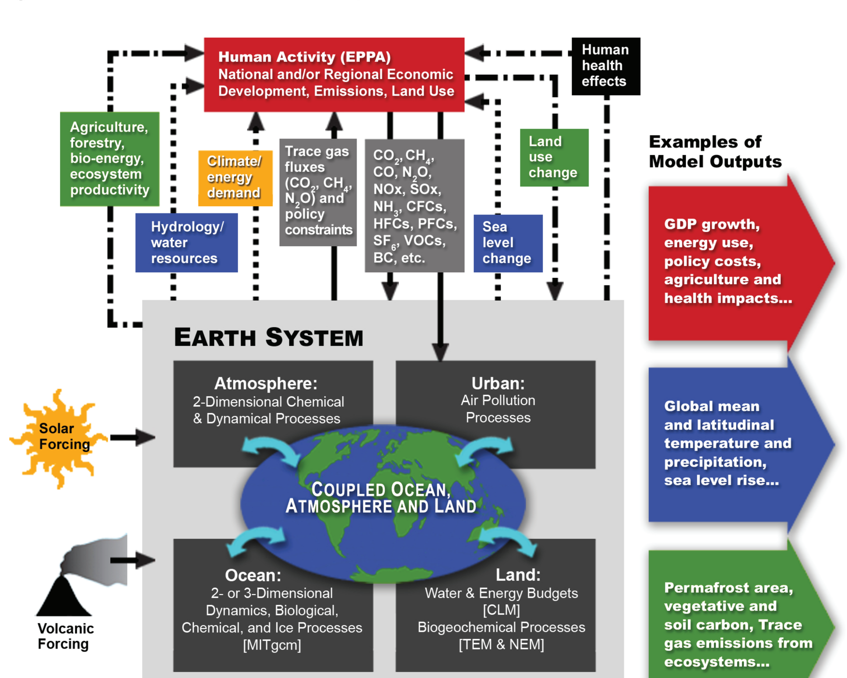
Coupled Model Description

An intermediate complexity model is employed for this work, consisting of the following sub-models:

- Atmospheric Model: a zonally-averaged, statistical-dynamical model based on the GISS GCM (Sokolov and Stone 1998).
- Atmospheric Chemistry Model: transport and chemical reactions of 33 chemical species are included on the zonally-averaged grid (Wang et al. 1998). A business-as-usual emission scenario is used for 21st century simulations.
- Land Model: The Global Land System model is comprised of a zonally-averaged version of the Community Land Model (CLM 2.1) coupled to a terrestrial ecosystem model (TEM) and a natural emissions model (NEM), as described in Schlosser et al. (2007).
- Sea-Ice Model: three-layer thermodynamic model (Winton 2000).
- Ocean Model: MIT ocean general circulation model (Marshall et al. 1997), with the realistic topography at 4°x4° with 15 vertical layers.
- Ocean Carbon Model: includes efficient ocean carbonate chemistry solver (Follows et al. 2006), air-sea exchange of CO_2 (parameterized following Wannikof 1992), physical transport of carbon by ocean circulation, and explicit, though idealized, representation of biological pump including nutrient and light limitation (Dutkiewicz et al. 2005).

The model uses anomaly coupling of wind and freshwater forcing, using observed values as the mean forcing. Additional details about the coupling procedure are described in Dutkiewicz et al. (2005).

This climate model is part of the Integrated Global System Model (IGSM) used by the MIT Joint Program in the Science and Policy of Global Change. The full model is depicted below:

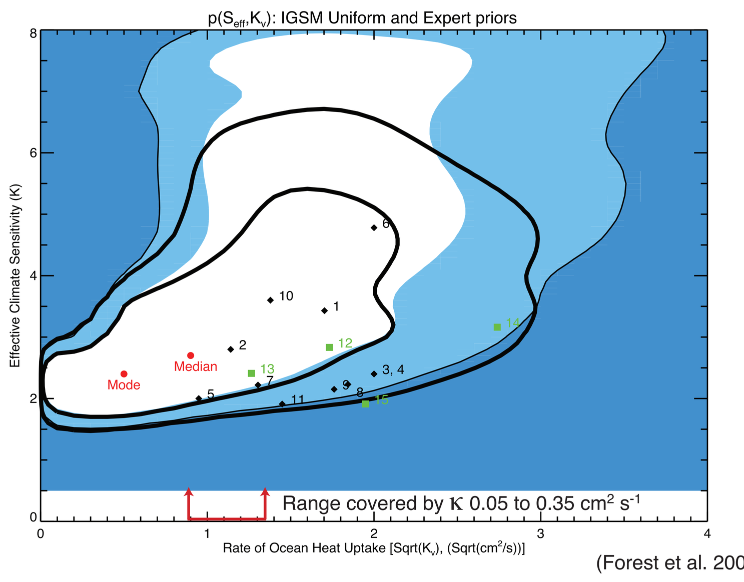


Ensemble Methodology: Uncertain Climate Model Parameters

Ocean Heat Uptake: The rate of deep-ocean heat uptake corresponds to an effective diffusivity with 90% bounds of 0.04-4.1 cm^2/s (Forest et al. 2008) based on matching the observed 20th century climate changes. Unfortunately, no simple "knob" exists in 3D ocean GCMs in order to vary this parameter. Here, different values of ocean heat uptake were achieved by varying the ocean model's background vertical diffusivity (κ_z) using four discrete values (0.05, 0.10, 0.20, and 0.35 cm^2/s) from the onset of the ocean spinup, as described in Dalan et al. (2005). Given the connection between mixing strength and the magnitude of the ocean's MOC, this unavoidably led to somewhat different ocean states for the different values of vertical diffusivity.

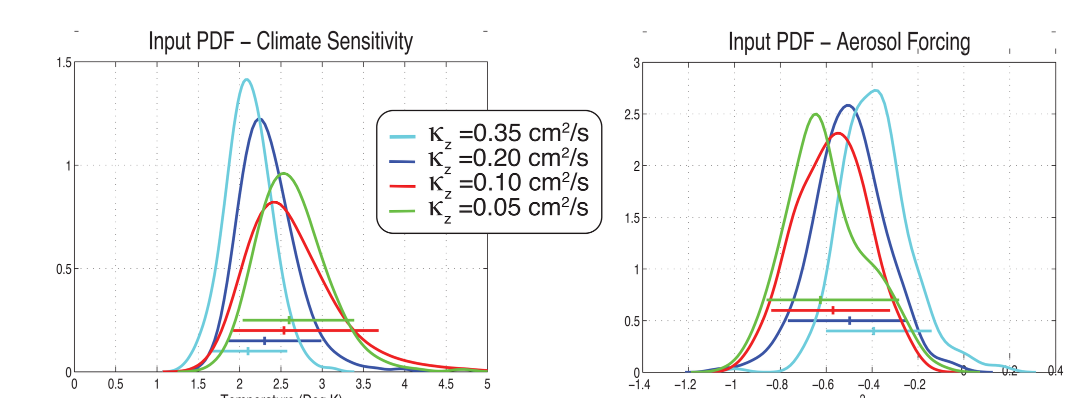
Uncertain Model Parameters, cont.

How well did we cover the range of uncertainty in ocean heat uptake?



Above:The marginal posterior probability density function with uniform (shading) and expert prior on S (thick contours). Shading denotes rejection regions for a given significance level—10%, and 1%, light to dark, respectively. The positions of AOGCMs (diamonds and squares) represent the parameters in the IGSM model that match the transient response in T_{surf} and sea level rise under a common forcing scenario.

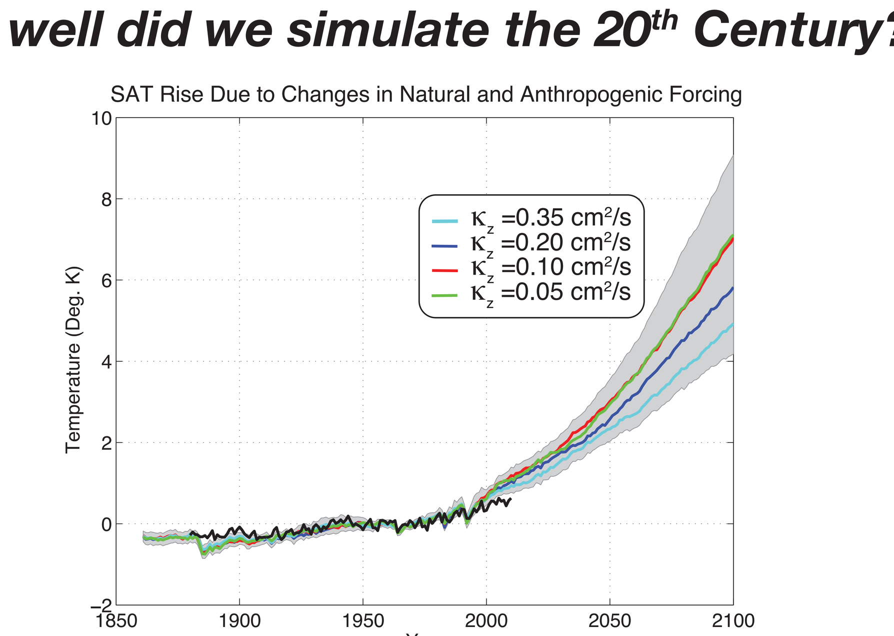
Aerosol Forcing and Climate Sensitivity: PDFs for these uncertain parameters were obtained by comparing model simulations of the 20th century (across a broadly sampled parameter space) with observations using optimal fingerprint diagnostics (Forest et al. 2002). These observations consisted of 1946-1995 decadal mean SAT over four latitudinal bands, and upper air differences between the 1961-1980 and 1986-1995 periods. No observational constraint on deep-ocean heat temperature was employed. Different sensitivities are obtained by varying calculated cloud amount, as a function of ΔT_{surf}.



(5th, Median, and 95th Percentiles also shown above)

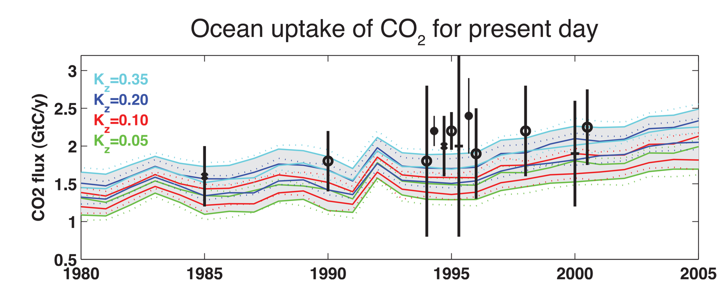
Interpretation: Ocean heat uptake efficiency scales with κ_z (Dalan et al. 2005), so higher κ_z runs require some combination of weaker aerosol cooling and/or higher climate sensitivity in order to match observed 20th century warming. Note however that aerosol cooling, rather than sensitivity, offsets the difference in ocean heat uptake, in fact so much that we see an unexpected *decrease* in sensitivity with ocean heat uptake efficiency. It appears the hemispheric differences in aerosol forcing are such a strong observational constraint that the statistical method requires the sensitivity to compensate for such large differences in aerosol forcing.

How well did we simulate the 20th Century?



The above figure shows the envelope (gray shading: 5th and 95th percentiles; colored lines are median runs) of SAT for the full ensemble of runs. SAT represents the difference as compared to a control run fixed at 1860 conditions. Also shown is the observed global SAT change (heavy black line), normalized to agree with the envelope mean over the period 1951-1980. Note the general agreement in trend over the 20th century. Also note that the post-2000 observations rise more slowly than the envelope; recent work adds an additional decade of observational data to further constrain parameters (Forest, pers. comm.), yet it remains unclear whether the post-2000 disagreement is due to natural variability in the climate system or we have overestimated the 21st century response.

20th Century Simulation, cont.

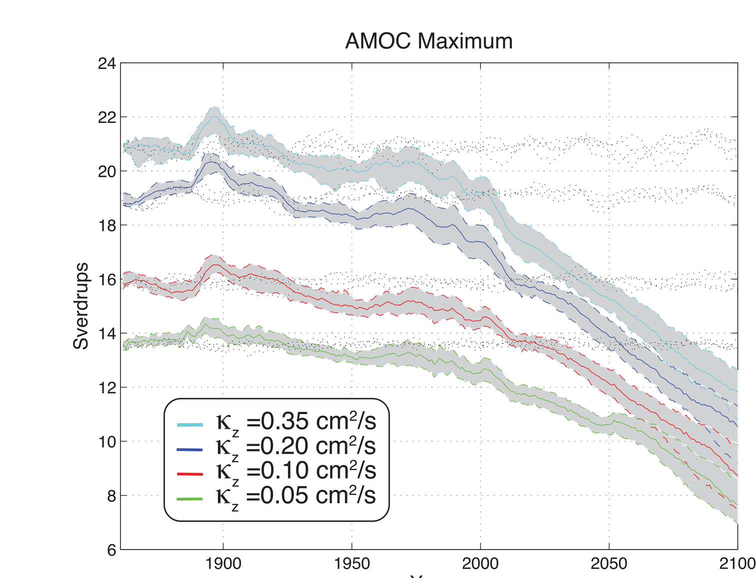


See also poster C44 218B Thursday, for more details on ocean carbon uptake in this ensemble simulation.

Colored lines indicate the 95% confidence interval for each κ_z. Dotted lines indicate the outliers for each κ_z. Symbols indicate other estimates of current day CO_2 uptake by the oceans with error bars: + estimated from shipboard pCO_2 measurements (Takahashi et al. 2002, 2009); o inversion studies (Gloor et al. 2003; Gurney et al. 2004, 2004; Manning and Keeling 2006; Mikaloff Fletcher et al. 2006; Khatiwala et al. 2009); x estimated from CFC's (McNeil et al. 2003); * other model studies (Watson and Orr 2003; Matsumoto et al. 2004).

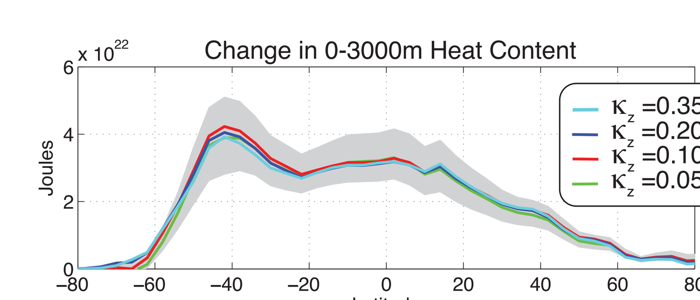
The relative uptake of carbon corresponds to that of heat uptake with the different κ_z. However the carbon uptake of the model is on the low end of that observed, in contrast to the heat uptake which appears above the median of observations; further research is needed.

Ocean Overturning Circulation Change in 20th and 21st Centuries

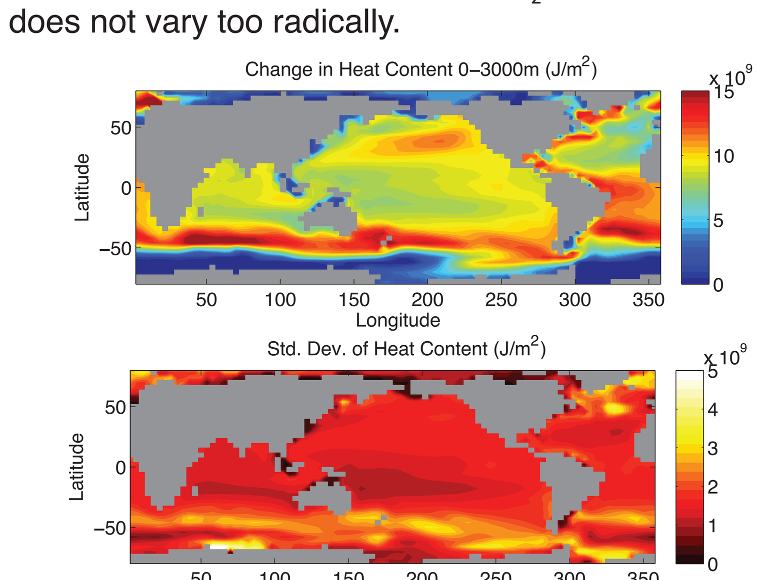


The above figure shows the model's Atlantic meridional overturning streamfunction maximum over 1860-2100 (control runs are plotted as dotted black lines). Unfortunately, there is scant observational data that could be used to assess the model's 20th century behavior. Note that model differences for different κ_z are larger than the envelopes for different aerosol forcing and climate sensitivity. All model runs show significant weakening of the AMOC in the 21st century.

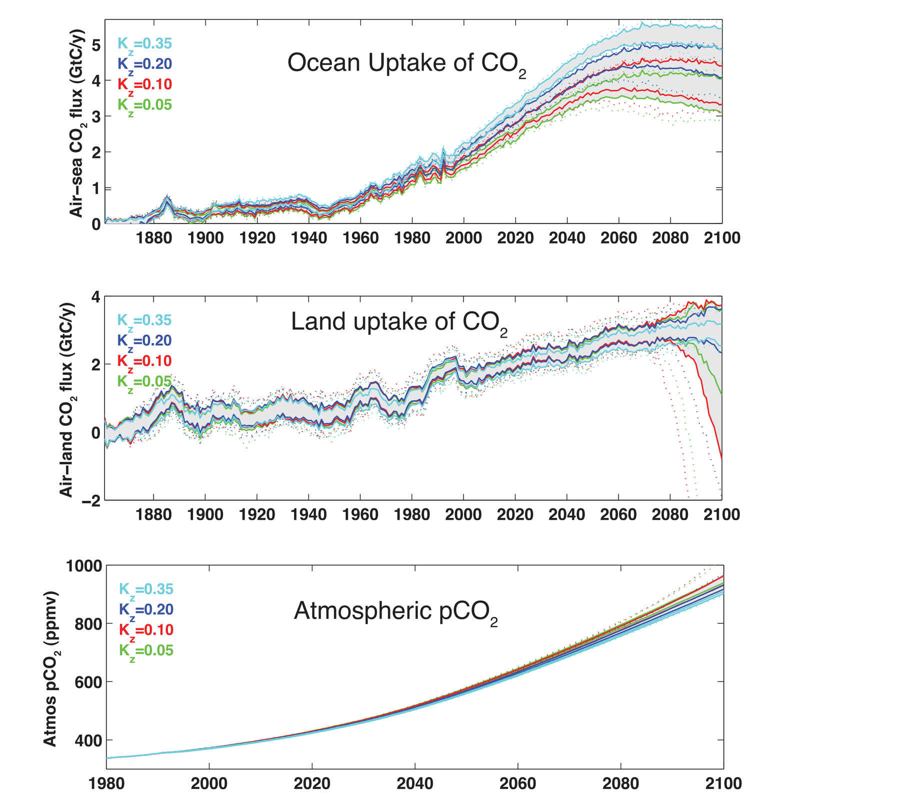
Ocean Heat Content in 21st Century



Above: change in 0-3000m heat content (in Joules, per degree latitude) for mean 2090-2100 minus pre-industrial, shown for the full ensemble and for median κ_z values. Note the asymmetry in warming between the Northern and Southern Hemispheres. This is further illustrated below, showing 0-3000m change in heat content in plan view; note the largest warming in the Southern Ocean and South Atlantic. Also note the regional nature of changes in the Northern Atlantic and Pacific Oceans. The bottom plot shows the standard deviation of the change in heat content across the ensemble. We find the greatest source of uncertainty is in the ocean mean state (i.e., choice of κ_z); otherwise, the large-scale pattern does not vary too radically.



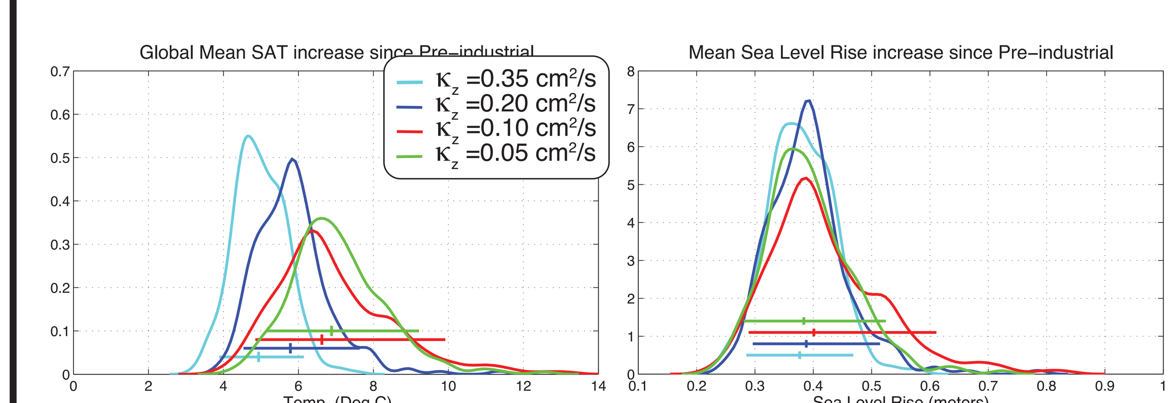
Land and Ocean Carbon Uptake in 20th and 21st Centuries



Above figures show globally integrated results for the ensemble of (top) ocean uptake of CO_2; (middle) land uptake of CO_2; (bottom) change in atmospheric pCO_2. Envelopes show two standard deviations, dotted lines are outliers.

Future projections show a wide range of ocean uptake CO_2 flux (over 2 GtC/y) by 2100. By late 21st century, the ocean uptake rate plateaus: high surface carbon content and warmer water are less capable of taking up additional carbon. The results are strongly dependent on the κ_z values. Land uptake shows a slower, more linear, increase over the late 20st and 21st century. As such, the ocean uptakes an increasingly greater share of carbon in the 21st century. Note that in some ensemble members, a critical temperature threshold is reached and land ecosystems face a massive die-off. The uncertainty in atmospheric pCO_2 in year 2100 is approximately 100 ppm across the ensemble.

Projected SAT and Sea Level Rise



The above figures show 2091-2100 mean PDFs for SAT and sea level rise (thermal expansion only) in relation to the 1860 control run. Note the inverse relationship between heat uptake efficiency and projected increase in SAT; this plot follows very closely with the input PDF for climate sensitivity (second panel), as the aerosol forcing effect is small in the 21st century as compared to changes in greenhouse gases. Note however that the PDFs of projected sea level rise are nearly equivalent for the various κ_z; it is unclear why the compensation between SAT and heat uptake efficiency happens to be so nearly offsetting, nor why the κ_z=0.10 runs in particular exhibit such a long tail.

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