A BAYESIAN SYNTHESIS INVERSION OF CARBON CYCLE OBSERVATIONS: HOW CAN OBSERVATIONS REDUCE UNCERTAINTIES ABOUT FUTURE SINKS?

D.M. Ricciuto[1], K. Keller[2], and K.J. Davis[1]

[1] *Dept. of Meteorology, The Pennsylvania State University, University Park, PA 16802; ricciuto@meteo.psu.edu*

[2] *Dept. of Geosciences, The Pennsylvania State University, University Park, PA 16802*

ABSTRACT

Current predictions of future CO_2 sink strength vary widely as a result of different model representations of the carbon cycle. A sound characterization of these prediction uncertainties is crucial for the design of economically efficient carbon management strategies. We use a mechanistically sound and statistically tractable model of the global carbon cycle to (1) assimilate historical observations of atmospheric CO_2 concentrations and oceanic CO_2 fluxes, (ii) derive probabilistic predictions of future CO_2 concentrations and fluxes, and (iii) compare the utility of terrestrial and oceanic observations to constrain predictive uncertainties. We found that terrestrial and oceanic flux observations have nearly equal ability to constrain these uncertainties, if terrestrial observations include both net primary productivity (NPP) and respiration. Model predictions are dependent on the choice of historical land use emissions dataset. The probability density function (PDFs) of model parameter estimates are not normally distributed, and neglecting autocorrelation in the CO_2 concentration signal during model calibration causes overconfident results.

INTRODUCTION

Recent modeling studies of the coupled climate-carbon system disagree on the question whether terrestrial ecosystems will remain a sink of carbon in the 21st century, and the predicted strength of the ocean carbon sink also varies significantly. One such study [*Cox et al.*, 2000] predicts a a strong positive feedback between climate and the carbon cycle, while another [*Dufresne et al.*, 2002] predicts a much weaker feedback, mainly due to different representations of terrestrial processes. Although the above studies employ state of the art general circulation models (GCMs) and carbon cycle models, they are not calibrated with historical observations in a statistical sense.

With a simple emissions-driven climate-carbon model that runs quickly and contains few parameters, we can use Bayesian techniques in conjunction with observations to derive full parameter PDFs, which can be used in turn to estimate uncertainty in the predicted strength of the carbon sink. We also use this technique to analyze the effect of additional observation systems on parametric uncertainty, and to evaluate the likelihood ratios of land-use emission datasets, which vary significantly but generally do not contain individual uncertainty estimates.

METHODS

Our model contains an impulse-response climate module and 4-box representation of the ocean carbon cycle [*Hooss et al.*, 2001], as well as a 4-box terrestrial carbon cycle model [*Meyer et al.*, 1999]. Calibrating the model with observations is a nonlinear optimization problem, for which both the Bayes Monte Carlo (BMC) and Markov Chain Monte Carlo (MCMC) technique are used. Observational constraints include CO_2 mixing ratio data from Law Dome ice core [*Etheridge et al.*, 1996] and Mauna Loa [*Keeling and Whorf*, 2005], as well as oceanic CO_2 uptake [*McNeil et al.*, 2003; *Sabine et al.*, 2004]. The model is driven by historical fossil fuel and land-use emissions data. Predictions are made using business as usual (BAU) and stabilization (S550) scenarios. Both the BMC and MCMC calibration approaches use a maximum likelihood approach to estimate joint PDFs of carbon cycle parameters and their uncertainties. BMC is a global optimization algorithm, whereas MCMC is a much faster gradient-based approach that can fail for nonconvex problems (multiple maxima in the likelihood function). Resulting PDFs are used to make probabilistic predictions about the future behavior of the carbon cycle

RESULTS

Our analysis suggests five major results. First, the likelihood function is convex, allowing us to employ the faster MCMC algorithm. Despite this convexity, model parameters are not normally distributed. Second, neglecting autocorrelation in the Mauna Loa CO_2 concentration signal causes overconfident parameter uncertainty estimates and overconfident predictions. Conclusions of previous studies that do not account for autocorrelation or assume normally distributed parameters may need to be revisited. Third, driving the model with historical observations of temperature rather than running in coupled climate/carbon mode during the calibration process reduces parametric uncertainty. Because the model cannot reproduce interannually varying global temperature, this implies that the response of CO_2 concentrations to interannual temperature variability contains useful information about the carbon cycle. The fourth result is that given the observational constraints and model structure, one set of land-use emissions data [*Ramankutty and Foley*, 1999] is more than twice as likely than the other [*Houghton and Hackler*, 2003]. The choice of land-use emissions dataset also has a significant impact on model parameters and predictions. Finally, constraints on gross terrestrial fluxes (respiration and NPP) designed to mimic observations from FLUXNET and an additional constraint on oceanic flux designed to mimic a second World Ocean Circulation Experiment (WOCE) both reduce the spread in the predicted CO_2 sink strength by similar amounts, lessening the uncertainty of allowable emissions under a stabilization scenario.

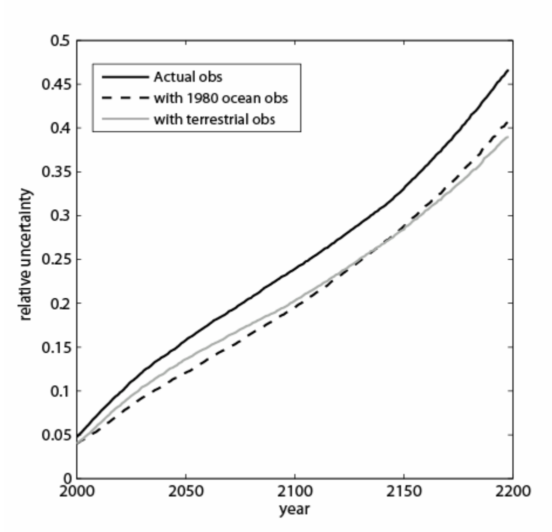

Fig 1. The relative uncertainty of allowable emissions under the S550 stabilization scenario with actual historical observations (black solid line), with the addition of a WOCE-like observation in 1980 (dashed line), and with the addition of NPP and respiration observations in 1980 and 2000 (gray solid line).

FUTURE WORK

Optimal carbon mitigation strategies generally become more costly as the predictive uncertainty of future CO_2 concentrations increases. Therefore, improved information about the carbon cycle can have economic value. By analyzing the reduction of parametric uncertainty resulting from additional carbon cycle observations with integrated assessment models, we can estimate the economic value of information of additional observation systems similar to the World Ocean Circulation Experiment (WOCE) experiment or observations of terrestrial fluxes from FLUXNET.

REFERENCES

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model (vol 408, pg 184, 2000), *Nature*, *408* (6813), 750-750, 2000.

Dufresne, J.L., P. Friedlingstein, M. Berthelot, L. Bopp, P. Ciais, L. Fairhead, H. Le Treut, and P. Monfray, On the magnitude of positive feedback between future climate change and the carbon cycle, *Geophysical Research Letters*, *29* (10), -, 2002.

Etheridge, D.M., L.P. Steele, R.L. Langenfelds, R.J. Francey, J.M. Barnola, and V.I. Morgan, Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn, *Journal of Geophysical Research-Atmospheres*, *101* (D2), 4115-4128, 1996.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer, and F. Joos, A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS), *Climate Dynamics*, *18* (3-4), 189-202, 2001.

Houghton, R.A., and J.L. Hackler, Sources and sinks of carbon from land-use change in China, *Global Biogeochemical Cycles*, *17* (2), -, 2003.

Keeling, C.D., and T.P. Whorf, Atmospheric CO_2 records from sites in the SIO air sampling network, *Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.*, 2005.

McNeil, B.I., R.J. Matear, R.M. Key, J.L. Bullister, and J.L. Sarmiento, Anthropogenic CO2 uptake by the ocean based on the global chlorofluorocarbon data set, *Science*, *299* (5604), 235-239, 2003.

Meyer, R., F. Joos, G. Esser, M. Heimann, G. Hooss, G. Kohlmaier, W. Sauf, R. Voss, and U. Wittenberg, The substitution of high-resolution terrestrial biosphere models and carbon sequestration in response to changing CO2 and climate, *Global Biogeochemical Cycles*, *13* (3), 785-802, 1999.

Ramankutty, N., and J.A. Foley, Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochemical Cycles*, *13* (4), 997-1027, 1999.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.H. Peng, A. Kozyr, T. Ono, and A.F. Rios, The oceanic sink for anthropogenic CO_2, *Science*, *305* (5682), 367-371, 2004.