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Learning about the carbon cycle from global budget data

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[1] Observation-based estimates of the global carbon budget serve as important constraints on carbon cycle models. We test the effect of new budget data on projection uncertainty. Using a simple global model, we find that data for an additional decadal budget have only a marginal effect on projection uncertainty, in the absence of any constraints on decadal variability in carbon fluxes. Even if uncertainty in the global budget were eliminated entirely, uncertainty in the mechanisms governing carbon sinks have a much larger effect on future projections. Results suggest that learning about the carbon cycle will best be facilitated by improved understanding of sink mechanisms and their variability as opposed to better estimates of the magnitudes of fluxes that make up the global carbon budget. **Citation:** Melnikov, N. B., and B. C. O'Neill (2006), Learning about the carbon cycle from global budget data, *Geophys. Res. Lett.*, *33*, L02705, doi:10.1029/2005GL023935.

1. Introduction

[2] Learning can be defined as the acquisition of new information that leads to changes in uncertainty. These changes can include increases or decreases in uncertainty ranges, systematic shifts in ranges, changes in the shape of uncertainty distributions, or changes in the confidence attached to uncertainty characterizations. Understanding the potential for learning about the carbon cycle is important because it can help prioritize research directions and also because learning is a key factor in debates on the optimal timing of emissions reductions [*Webster*, 2002; *Kelly and Kolstad*, 1999]. Learning will occur through a variety of means including observations, theory development, modelling, and experiments, and its overall course is impossible to predict. However, learning by observation is amenable to analysis since we can reasonably expect that some types of data will be collected in the future, and the effect of these data on uncertainty in projections made with carbon cycle models can be simulated.

[3] While many types of global data are important in constraining models [*Knorr and Heimann*, 2001], we focus on global carbon budgets. Decadal budgets are largely observation-based estimates of cumulative changes in atmospheric carbon content, carbon fluxes from fossil fuel and land use, and net ocean-atmosphere and land-atmosphere exchanges [*Prentice et al.*, 2001]. These data have played a key role in the calibration of simple carbon cycle models and provide a logical starting point for learning analysis.

[4] First, we ask what the effect of new estimates of the global budget over time will be on uncertainty in future projections. This projection uncertainty derives from two sources: parameter uncertainty (imprecisely known values of carbon cycle model parameters) and model or structural uncertainty (uncertainty in whether all relevant processes are represented in the model, and in the functional form of their representations). Uncertainty in global budget data bears, in principal, on both parameter and model uncertainty, although for simplicity we examine only its affect on the former. Rather than simulating the learning process into the future, we begin with an historical example: the recent addition of an estimated global budget for the 1990s to existing estimates of a budget for the 1980s.

[5] Next, we ask what the maximum effect that resolving parameter uncertainty entirely (by reducing uncertainty in the carbon budget to zero) would be on projections of future concentrations, and compare it to one example of the effect of structural uncertainty. This question is important because, while one might reasonably anticipate that structural uncertainty will dominate projections in the long-term [*Harvey*, 1989], over the next several decades the relative importance of these different sources of uncertainty is not a priori obvious.

2. Model Calibration and Consistency

[6] We use a simple global-average carbon cycle model consisting of a 1D upwelling-diffusion model of the global ocean with polar overturning, coupled with a well-mixed atmosphere and six-box terrestrial biosphere model [*Jain et al.*, 1995; *Kheshgi et al.*, 1996]. Terrestrial carbon uptake is modelled as consisting solely of CO_2 fertilization, although in reality there are several processes that may affect this flux [*Wigley*, 2000], including temperature feedbacks on respiration. We address the potential effect of structural uncertainty in terrestrial uptake mechanisms in Section 4. To address parameter uncertainty, we treat two key model parameters as uncertain: the β factor controlling terrestrial carbon uptake, and the π parameter governing the carbon content of ocean deep water formed by polar overturning. We focus on these two parameters in order to keep this initial analysis relatively simple and because they have been treated as principle sources of uncertainty in previous analysis with this model [*Kheshgi and Jain*, 2003].

[7] We calibrate the model to reproduce the best estimates of the principal fluxes in the global carbon budget over the 1980s (Table 1) using a procedure employed in many previous studies [*Jain at al.*, 1995; *Kheshgi et al.*,

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Table 1. Global Carbon Budgets for the 1980s and 1990s (GtC yr^{-1})[a]

	Houghton [2003]		
	1980s	1990s	This Study (1990s)[b]
Atmospheric increase	3.3[c]	3.2[c]	3.2
Fossil fuel emissions	5.4[c]	6.3[c]	6.3
Net ocean uptake	−1.7[d]	−2.4[d]	−1.9
Net terrestrial flux	−0.4[d]	−0.7[d]	−1.2
Land use emissions	2.0[e]	2.2[e]	1.6
Residual (terrestrial) sink	−2.4	−2.9	−2.8

[a] Negative values indicate a flux of CO_2 out of the atmosphere.
[b] Based on a model calibrated to the 1980s budget.
[c] From *Prentice et al.* [2001].
[d] From *Plattner et al.* [2002].
[e] From *Houghton* [2003].

1996, 1999; *Wigley*, 2000]. The global carbon budget can be written as

$$\dot{N}_a(t) = E_{ff}(t) + E_{lu}(t) + F_{oc}(t) + F_{res}(t) \qquad (1)$$

where $\dot{N}_a$ is the rate of change of atmospheric carbon mass, E_{ff} is fossil fuel emissions, E_{lu} is net land use emissions (including forest regrowth), F_{oc} is net ocean uptake, and F_{res} is the residual (terrestrial) sink. We first tune the ocean π parameter such that the model's net ocean flux F_{oc} averages 1.7 GtC yr^{-1} over the 1980s [*Plattner et al.*, 2002], using the known atmospheric history N_a over the period 1765–1990 as a boundary condition [*Enting et al.*, 1994; *Keeling and Whorf*, 2002]. This yields the value of $\pi = 0.07$ for the ocean bottom water parameter [cf. *Kheshgi et al.*, 1999]. Next, using the historical record of fossil fuel emissions [*Marland et al.*, 2003], our modelled net ocean uptake, and the atmospheric record, we run the terrestrial model over the period 1765–1990, tuning the CO_2 fertilization factor such that the net land use emissions required to balance the carbon budget (equation (1)) has an average value of 2.0 GtC yr^{-1} in the 1980's [*Houghton*, 2003]. This yields a value of $\beta = 0.7$, which is consistent with previous estimates of 0.2–0.8 derived from empirical data [*Gates*, 1985; *Kohlmaier et al.*, 1987].

[8] A first step in employing new data for the 1990s is to ask whether the model calibrated to the 1980s budget is consistent with the new data. Table 1 shows that recent estimates for the 1990s budget differ substantially from the budget predicted by the 1980s-calibrated model when it is run forward subject to the observed fossil fuel emissions and global atmospheric CO_2 concentration for that decade. However, the difference between net ocean fluxes or residual sink terms in the two budgets does not necessarily imply that the model is incorrect. The difference can be interpreted as decadal variability; i.e., the effect of changes, relative to the 1980s, in processes not represented in the ocean model [*Le Quéré et al.*, 2003] or residual sink term. In this case, the apparently different estimates of net land use emissions also become entirely consistent because this term includes not only land use emissions per se, but also decadal variability in terrestrial and ocean uptake [*Wigley*, 2000].

[9] This example illustrates that, without independent estimates of decadal variability, new observations of decadal global carbon budgets provide no additional constraints on models. Even if in principal the new data contain additional information that should lead to model parameter changes, it will be possible to assign differences between model predictions and new data to unexplained variability. Of course this result only holds if it is not possible independently to constrain decadal variability—an assumption made here for reasons of simplicity but one that is not strictly true. Developing and applying such constraints would be useful future work.

3. Recalibration

[10] Calibrating the model to the 1980s data implicitly assumes that estimated 1980s fluxes are consistent with the long-term trend in ocean and terrestrial uptake, since the model is designed to simulate long-term trends and not decadal (or shorter-term) variability. Rather than using the 1990s data as a test of projections based on a 1980s-calibrated model, an alternative approach is to use it to redefine the long-term trend—i.e., calibrating the model to the 1980s and 1990s data combined. To do this, we calibrate the model to the average net ocean uptake over the 1980–2000 period [*Plattner et al.*, 2002] and average land use emissions over the same period [*Houghton*, 2003]. We find $\pi = 0.45$, and $\beta = 0.73$; Figure 1 shows that compared with results of the model calibrated to the 1980s, the revised calibration implies stronger sinks (primarily a stronger ocean sink) balanced by larger net land use emissions history.

[11] To illustrate the effect of the recalibration on projections of future atmospheric CO_2 concentrations, we use a mid-range scenario from the IPCC Special Report on Emissions Scenarios (SRES) [*Nakićenović et al.*, 2000] for the period 1990–2100 and project concentrations using both calibrations. For clarity, we refer to the model calibrated to the 1980s budget alone as model 1, and to the model calibrated to the 1980s and 1990s data combined as model 2. We first modify the land use component of the SRES scenario (Figure 2) to be consistent with historical land use emissions data (see supporting information of *O'Neill and Oppenheimer* [2004]). All SRES land use

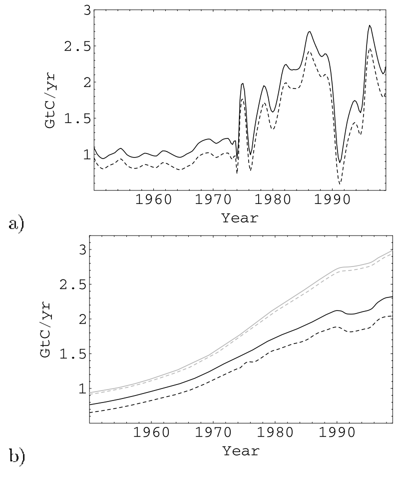

Figure 1. (a) Net land use emissions and (b) net ocean flux (black) and residual sink (gray), GtC yr^{-1}, from a model calibrated to match either the 1980s and 1990s budget data together (solid), or only the 1980s budget (dotted).

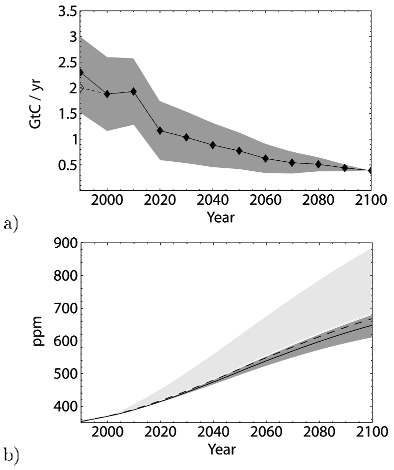

Figure 2. (a) SRES A1 net land use emissions scenario modified for consistency with the model calibration, and (b) projections of atmospheric CO_2 concentration driven by the A1 scenario, using Model 1 (dotted) and Model 2 (solid). The effect of parameter (or budget) uncertainty is indicated in both figures by the gray area, bounded by the strong- and weak-sinks cases. The effect of structural uncertainty is shown as the light-gray area in (b), bounded on top by the capped-fertilization projection.

scenarios start from 1.1 GtC yr^{-1} at 1990, based on older estimates of historical land use emissions. Therefore, we add an "update offset" to the land use scenario so that emissions in 1990 are equal to the assumed 1980s average of 2.0 GtC yr^{-1} [*Houghton*, 2003]. The size of this offset is decreased by 10% of its original value every decade, so that it vanishes in 2100, a procedure that preserves the general shape of the emissions scenario.

[12] Next, we account for the fact that, in model 2, the model-derived land use emissions history averages 2.3 GtC yr^{-1} over the 1980s, rather than the observation-based estimate of 2.0 GtC yr^{-1}. The difference, +0.3 GtC yr^{-1}, is interpreted as decadal variability (see supporting information of *O'Neill and Oppenheimer* [2004]). To be consistent with the land use emissions scenario for model 1, we assume that over the 1990s decade this variability component in model 2 declines linearly to zero.

[13] Figure 2 shows projection results. The projection with model 2 is only slightly lower than the projection with model 1, indicating that the additional decade of information makes little difference to the outlook for future atmospheric CO_2 concentrations over the next 100 years.

4. Parameter Versus Structural Uncertainty

[14] The size of the effect on projected concentrations due to new decadal budget information depends on the nature of that information. The less consistent it is with a model calibrated to the previous decade's information, the larger the effect it will have. To quantify the maximum plausible effect, we consider the bounding cases for new information on decadal budgets, given published uncertainty ranges [*Houghton*, 2003; *Plattner et al.*, 2002]. We define a strong sinks and a weak sinks case for the calibration of model 2. The strong sinks case assumes that new information indicates that historical land use emissions in both the 1980s and 1990s were at the upper bound of their uncertainty range (0.8 GtC yr^{-1} above the best guess values), an assumption that, given the overall carbon budget constraint, requires combined ocean and terrestrial sink strength to be at its maximum plausible value. We assume that ocean uptake was at the upper end of its uncertainty range over both decades (0.6 and 0.7 GtC yr^{-1} above best guess values, respectively), with terrestrial sinks stronger as necessary to balance the historical carbon budgets. Conversely, in the weak sinks case we assume that historical land use emissions were at the lower end of their uncertainty range in both decades (0.8 GtC yr^{-1} below *Houghton* [2003] best guess values), that polar overturning has no effect on bottom-water carbon concentration, and that terrestrial sinks were weaker as necessary to balance the budget. (Alternative mixes of ocean and terrestrial sink strength [e.g., *Kheshgi and Jain*, 2003] are possible but make little quantitative difference to our results in either case.)

[15] The strong sinks case resulted in parameter values $\pi = 1.54$ and $\beta = 0.8$; the weak sinks case resulted in values $\pi = 0$ and $\beta = 0.57$. The two model cases were used to project atmospheric CO_2 concentrations for the same SRES scenario as above, using the method for adjusting the land use emissions scenario described in section 3. Figure 2 shows that the two cases produce a range of CO_2 concentrations in 2050 of ±12 ppm, and in 2100 of ±38 ppm, relative to the reference case. Completely resolving decadal budget uncertainty—and therefore parameter uncertainty in the carbon cycle model—would produce a projection within this range, depending on what the true budget turns out to be.

[16] For comparison, we make one projection that illustrates the possible effect of uncertainty in model structure. Using the model calibration from our weak sinks case, we assume additionally that CO_2 fertilization is capped beyond the year 2000. This case represents the possibility that terrestrial uptake may completely saturate in the near future, and therefore represents structural uncertainty [*Prentice et al.*, 2001]. It can be considered conservative in that we do not consider possible amplifying feedbacks such as from temperature change. Nonetheless, this case yields concentrations in 2050 that are 112 ppm higher, and in 2100 238 ppm higher, than the reference case. Clearly, structural uncertainty has the potential to have a much greater effect on projections than parameter uncertainty, even within the next several decades.

5. Discussion

[17] This study is intended as a first step toward investigating the potential for anticipating how learning about the carbon cycle might take place via future observations. We have therefore focused on global aggregate data, and used a simple global model. Results illustrate how new decadal budget information alone is of limited value in judging the credibility of models calibrated to previous data, since discrepancies can always be explained as being due to decadal variability. Even if the new data are used to recalibrate the model to observations over a longer time period, the effect on projection uncertainty is not large, and in particular is small compared to the effect of uncertainty in model structure.

[18] Several caveats apply, however. First, we have assumed that budget uncertainty affects only parameter uncertainty, but in reality budget information can affect estimates of structural uncertainty as well. For example, the estimated size of the terrestrial or oceanic sink plays a role in constraining plausible explanations of what processes are involved. Second, we have also assumed that there are no constraints on decadal variability. Limiting variability to some plausible maximum value would make additional decadal budget information more influential, especially as a longer time series of budget data accumulates. Given several decadal budget estimates and limits on variability, the time variation of long-term sink processes would be better constrained and could point more clearly toward (or away from) particular processes. In this way, for example, future budget data over time could help support or reject the hypothesis that logarithmic CO_2 fertilization is an accurate description of the terrestrial sink term. Third, budget information also helps determine the effect of structural uncertainty on projections. If, for example, terrestrial sinks are large, then uncertainty in the processes governing them is more important than if those sinks are small. Finally, we have used only a limited set of data in our analysis. Considering other types of data, including ocean carbon tracer data, global average temperature data, and spatially resolved data could improve the value of additional information over time.

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