DOE/SC-CM-15-002

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FY 2015 Second Quarter Performance Metric: Demonstrate in A Climate Model Improved Annual Cycle of Terrestrial Net Ecosystem Carbon Exchange through Comparison with New Experimental and Observational Constraints

March 2015

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1.0 Product Definition

New land model developments improve upon the exchange of carbon between plants and atmosphere, while also accommodating field measurements that are difficult to understand. The timing of plant growth observed in temperate forests does not align well with photosynthetic potentials: leaf-scale measurements indicate that more carbon should be taken up by the forest canopy over the course of the growing season than actually appears as new growth, based on repeat measurements. Based on measurements of the ratios of carbon-to-nutrients, such as nitrogen and phosphorus (vegetation stoichiometry), and measurements of the relative growth of various tissues such as leaves, stems, and roots (vegetation allometry), it appears that availability of nutrients has a strong control on actual growth and accumulation of biomass without having a strong influence on leaf-scale photosynthetic potential. Another newer hypothesis suggests that plant storage of carbohydrates allows high rates of photosynthesis without immediate evidence of growth.

Recent field experimentation in several temperate forest systems supports this idea, and non-structural carbohydrate pools have been measured in many plant types. Terrestrial ecosystem models use a variety of approaches to reconcile the apparent contradiction. Some reduce concentrations or activity of photosynthetic enzymes to match observed growth under conditions of limited nutrient availability. Other models shift allocation toward roots to improve access to limiting resources, while others, including the Community Land Model, assume a down-regulation of photosynthetic rate without imputing a physiological mechanism. A series of fully-coupled climate-biogeochemistry simulations is carried out to investigate the new hypothesis and the influence of a temporary carbon storage mechanism on atmospheric carbon dioxide concentrations ($CO_{2,atm}$) at global and regional scales. In particular, the seasonal cycle of $CO_{2,atm}$ is investigated as an integrative metric of predicted carbon cycle dynamics. Temporary carbon storage by plants is found to have a profound influence on the seasonal cycle amplitude of $CO_{2,atm}$ without necessarily changing other aspects of the coupled climate-biogeochemistry simulation.

2.0 Product Documentation

The influence of various parameterizations of temporary non-structural carbohydrate (NSC) storage on global and regional scale seasonal cycle of $CO_{2,atm}$ was studied and quantified through a series of global-scale fully coupled climate-biogeochemistry simulations using the Community Earth System Model (CESM). Simulations were performed on a nominal 1° x 1° horizontal grid. A global synthesis of observed $CO_{2,atm}$ data for the period 1990-2000 was obtained from the GlobalView data set (GLOBALVIEW-CO_2, 2013). In order to compare simulation results with the GlobalView product, transient historical simulations were performed starting in simulated year 1850 and continuing through 2000, using standard historical forcing data sets for fossil fuel emissions of CO_2 and other greenhouse gases, and observation-based estimates of atmospheric nitrogen deposition and land use and land cover change. Simulations branched at year 1990 with the specification of several different parameterizations for NSC storage, with different turnover times. We also performed a control simulation using the default approach of assumed instantaneous down-regulation of photosynthetic rate in the face of nutrient limitation. Since measurements of $CO_{2,atm}$ are made at many locations and with high precision, it may be possible to place strong constraints on the physiological mechanism of temporary carbon storage by optimizing against existing the observed seasonal cycle in the GLOBALVIEW data set.

3.0 Results

While field experiments point to the presence of a storage pool, the pool size and dynamics are unclear, and may vary considerably among and within plant types and biomes, and over time. The purpose of the simulations described here (see Table 1) was to establish the effectiveness of simple global parameterizations of a storage pool in changing the amplitude and timing of the seasonal cycle of $CO_{2,atm}$ (abbreviated hereafter as SCC). As has been commonly found for CESM and many other coupled climate-biogeochemistry models, the control simulation gives global mean SCC amplitude which is weaker than observed, and with the seasonal peak coming about two months earlier than observed (March instead of May) (Figure 1). While the seasonal concentration minimum for the control simulation is in September, as observed, the simulated period of CO_2 draw-down starts and ends gradually, in contrast to the sharp transitions in the observations.

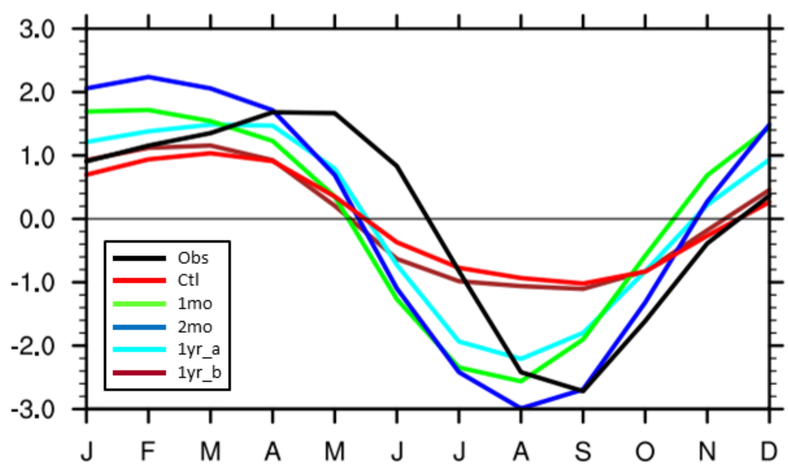

Figure 1. Global mean seasonal cycle of $CO_{2,atm}$ (y-axis units: parts per million), averaged over the period 1992-2000. All data were initially monthly time series, which were first demeaned and detrended (linear trend removal), before calculating the mean value for each month. Observations are shown in black. Simulations are as defined in Table 1.

Table 1. List of simulations

Name	Storage pool turnover period	Notes
Ctl	None	Control (default down-regulation)
1mo	1 month	
2mo	2 month	
1yr_a	1 year	Temperature control on rate of release
1yr_b	1 year	Limited total storage pool to 10% of biomass

Introduction of a simulated NSC pool has a dramatic impact on the amplitude of global mean SCC (Figure 1). In all of these simulations it is assumed that the NSC pool is held temporarily in the plant with a turnover time as indicated in Table 1, and once carbon is turned over from this pool it is released directly back into the atmosphere as CO_2 as though it had been respired by the vegetation. The global mean seasonal SCC is observed to be controlled mainly by the timing of photosynthesis in the northern hemisphere (NH), where most of Earth's vegetated land mass is concentrated. During the NH summer photosynthetic uptake of atmospheric CO_2 causes a draw-down in $CO_{2,atm}$. As photosynthesis slows in the NH fall, respiration by plants and microorganisms returns carbon to the atmosphere in the form of CO_2, causing atmospheric levels to rise again. By assuming a NSC pool with a turnover time of one month extra summer uptake occurs, and is offset by additional release in the fall, driving an increase in the simulated SCC. Because of coincidence with the length of the growing season, a storage pool turnover time of two months causes an even larger increase in SCC amplitude. At longer assumed turnover time of one year the impact on SCC is similar to that for one month, but the timing of peak $CO_{2,atm}$ is in better agreement with observation, as is the timing of the fall minimum (Figure 1).

Short turnover times (one and two months) lead to overestimated amplitude of SCC, while turnover time of one year seems to moderate the amplitude. By introducing assumptions about the maximum size of the storage pool (simulation 1yr_b) the SCC amplitude is constrained to be only slightly higher than the control simulation. Any of these simulations, which include a NSC mechanism, produce results in agreement with available field experiments. This suggests that the combined metrics of field experimentation and global-scale simulation may allow us to constrain the mechanism of NSC turnover time within a physiologically meaningful range. Results presented here are quite preliminary and are mainly indicative of a predictive power. Additional experimentation in the field and a more formal (and expensive in terms of simulation time) optimization exercise is required to further refine our understanding of this mechanism.

As a further test of the efficacy of the NSC mechanism in controlling SCC amplitude and timing, we looked at two additional zonal averages of $CO_{2,atm}$, focusing on the temperate and polar parts of the NH. While observed amplitude of global SCC is on the order of 4-5 polar northern hemisphere (ppm), the observed amplitude is 8-9 ppm in the NH temperate zone (Figure 2) and 12-15 ppm in the NH polar zone (Figure 3). The control simulation underestimates SCC amplitude in both of these zones, but particularly in the temperate zone. The basic pattern of influence of NSC parameterization on predicted SCC amplitude seen at the global scale holds true as well at these regional/zonal scales. In general, the timing and amplitude of the SCC is best approximated by a one-year turnover pool, with some suggestion that a limitation connected with plant biomass may help to correct for overestimation of amplitude.

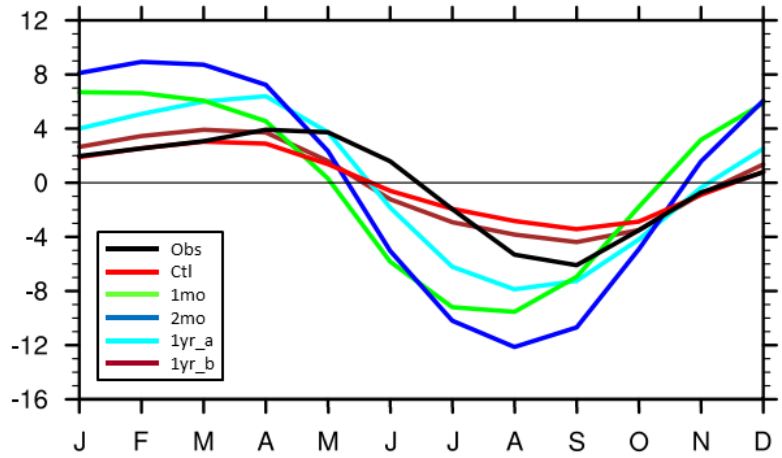

Figure 2. Temperate northern hemisphere (17.5N – 53N) mean SCC. All other details as in Figure 1.

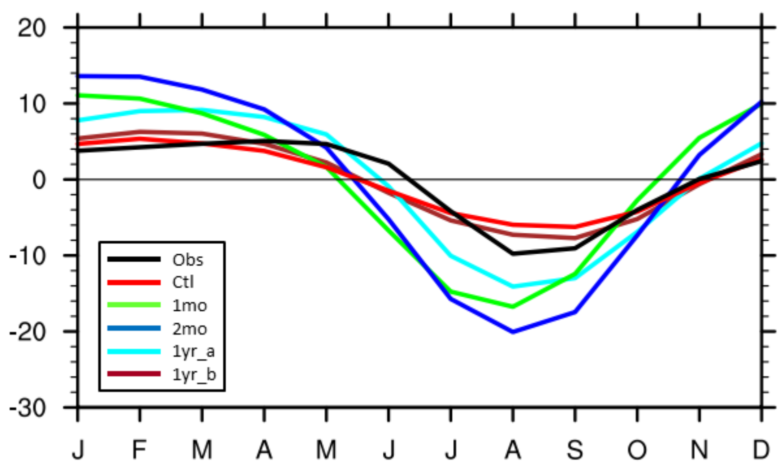

Figure 3. Polar northern hemisphere (53N – 90N) mean SSC. All other details as in Figure 1.

Even in the best-performing simulations, timing of peak $CO_{2,atm}$ is too early and draw-down is not sharp enough. It seems possible from evidence in the field that instead of being directly respired back to the atmosphere, carbon from the NSC pool may be released belowground as root exudate. From there it would be exposed to decomposition within the soil microbial environment, generating complex interactions with nutrient dynamics soil respiration. Simulations to explore these more complex dynamics are underway now, with some early indication that these dynamics have an important impact on both ecosystem productivity, and timing of net carbon fluxes. With continued investigation, we expect this research area to make valuable contributions to global-scale parameterization of fundamental land ecosystem processes with first-order influence on $CO_{2,atm}$, a major driver of global climate variation.

4.0 References

GLOBALVIEW-CO_2: Cooperative Global Atmospheric Data Integration Project. 2013: updated annually. Multi-laboratory compilation of synchronized and gap-filled atmospheric carbon dioxide records for the period 1979-2012 (obspack_co2_1_GLOBALVIEW-CO2_2013_v1.0.4_2013-12-23). Compiled by NOAA Global Monitoring Division: Boulder, Colorado, U.S.A. Data product accessed at http://dx.doi.org/10.3334/OBSPACK/1002

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