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Modeling the effects of snowpack on heterotrophic respiration across northern temperate and high latitude regions: Comparison with measurements of atmospheric carbon dioxide in high latitudes

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Abstract. Simulations by global terrestrial biogeochemical models (TBMs) consistently underestimate the concentration of atmospheric carbon dioxide (CO_2) at high latitude monitoring stations during the nongrowing season. We hypothesized that heterotrophic respiration is underestimated during the nongrowing season primarily because TBMs do not generally consider the insulative effects of snowpack on soil temperature. To evaluate this hypothesis, we compared the performance of baseline and modified versions of three TBMs in simulating the seasonal cycle of atmospheric CO_2 at high latitude CO_2 monitoring stations; the modified version maintained soil temperature at 0 °C when modeled snowpack was present. The three TBMs include the Carnegie-Ames-Stanford Approach (CASA), Century, and the Terrestrial Ecosystem Model (TEM). In comparison with the baseline simulation of each model, the snowpack simulations caused higher releases of CO_2 between November and March and greater uptake of CO_2 between June and August for latitudes north of 30° N. We coupled the monthly estimates of CO_2 exchange, the seasonal carbon dioxide flux fields generated by the HAMOCC3 seasonal ocean carbon cycle model, and fossil fuel source fields derived from standard sources to the three-dimensional atmospheric transport model TM2 forced by observed winds to simulate the seasonal cycle of atmospheric CO_2 at each of seven high latitude monitoring stations. In comparison to the CO_2 concentrations simulated with the baseline fluxes of each TBM, concentrations simulated using the snowpack fluxes are generally in better agreement with observed concentrations between August and March at each of the monitoring stations. Thus, representation of the insulative effects of snowpack in TBMs generally improves simulation of atmospheric CO_2 concentrations in high latitudes during both the late growing season and nongrowing season. These simulations highlight the global importance of biogeochemical processes during the nongrowing season in estimating carbon balance of ecosystems in northern high and temperate latitudes.

Introduction

There is evidence that warming is occurring in some high-latitude areas (Lachenbruch & Marshall 1986; Beltrami & Mareschal 1991; Chapman & Walsh 1993), and that the warming may be impacting both ecosystem function and structure (Oechel et al. 1993, 1995; Chapin et al. 1995). These ecosystems contain approximately 40% of the world's soil carbon inventory that is potentially reactive in the context of near-term climate change (McGuire et al. 1995; Melillo et al. 1995; McGuire & Hobbie 1997). A substantial amount of carbon could be released in inorganic forms from these soils in response to elevated temperature (Nadelhoffer et al. 1992; Oechel et al. 1993, 1995). A large release of CO_2 from these soils has the potential to influence the growth of atmospheric CO_2, which may have consequences for the rate and magnitude of climate change.

During the late 1980's, substantial releases of CO_2 were observed from Alaskan tundra ecosystems in response to declining water tables associated with elevated temperature (Oechel et al. 1993). Recent measurements of CO_2 exchange between tundra ecosystems and the atmosphere indicate that substantial losses of CO_2 from tundra soils may occur during the fall, winter, and spring months (Zimov et al. 1993, 1996; Oechel et al. 1997). Recent measurements at some locations indicate that these losses are currently greater than sink activity in summer months (Oechel and Vourlitis, unpublished). Thus, estimates of carbon balance in high latitude ecosystems are potentially biased if they are based on summer measurements alone (Oechel et al. 1997).

A number of global terrestrial biogeochemical models (TBMs) have been developed to assess the effects of changes in climate and atmospheric carbon dioxide on terrestrial ecosystem processes at large spatial scales (Heimann et al. 1998; Cramer et al. 1999; Kicklighter et al. 1999). For typical global application, TBMs make estimates of monthly CO_2 exchanges between terrestrial ecosystems and the atmosphere for approximately 60,000 grid cells at a spatial resolution of 0.5° by 0.5° (latitude by longitude), with about one-third of these estimates in high latitudes. Heimann et al. (1998) compared the performance of several TBMs by using the monthly estimates of CO_2 exchange by the models to simulate the seasonal cycle of atmospheric CO_2 at a number of CO_2 monitoring stations located throughout the globe. At high latitude monitoring stations, the simulations consistently underestimated the concentration of atmospheric CO_2 during the nongrowing season, which suggests that global TBMs tend to underestimate the release of CO_2 from high latitude soils during the nongrowing season. We hypothesize that decomposition is underestimated during the nongrowing season primarily because the TBMs do not consider the insulative effects of snow on soil temperature. In this study we modify the decomposition formulation of three TBMs to evaluate whether consideration of the insulative effects of snowpack improves the simulation of monthly concentrations of atmospheric CO_2 at CO_2 monitoring stations located in high latitudes.

Modeling the seasonal cycle of atmospheric CO_2

Overview

To model the seasonal cycle of atmospheric CO_2 at a monitoring station requires spatially explicit seasonal estimates of carbon exchange between the atmosphere, the oceans, and the terrestrial surface (Figure 1). In the absence of disturbance and major climatic fluctuations, annual net primary production (NPP) and annual heterotrophic respiration (R_H; i.e., decomposition) of terrestrial ecosystems are approximately in balance. Because photosynthesis and microbial activity are controlled in different ways by environmental and biotic factors, the magnitudes of NPP and R_H are not synchronized throughout the year. Here we adopt the ecological convention that fluxes into the land surface are positive. On a monthly basis, net ecosystem production (NEP), which is the difference between monthly NPP and R_H, can either be positive or negative; positive values indicate sink activity and negative values represent source activity. The seasonal fluctuations of NEP are primarily responsible for the observed seasonal variation in the concentration of atmospheric CO_2, especially at high northern latitudes where these variations have the greatest amplitude (Fung et al. 1983, 1987; Heimann et al. 1989, 1998).

In this study we conducted two simulations with each of three TBMs to evaluate how a representation of the insulative effects of snowpack influences the seasonal cycle of atmospheric CO_2 at high latitude monitoring stations in comparison to the baseline version of each model. For the snowpack version of each model, we modified the R_H formulation in the baseline version so that temperature is maintained at 0 °C when modeled snowpack is present. For each simulation in this study, monthly NPP, R_H, and NEP are estimated for each 0.5° grid cell of the terrestrial biosphere. The spatially explicit monthly NEP estimates are combined with equivalent CO_2 flux fields generated by an ocean biogeochemical model, and fossil fuel source fields; monthly CO_2 emission fields from fossil fuel burning and cement manufac-

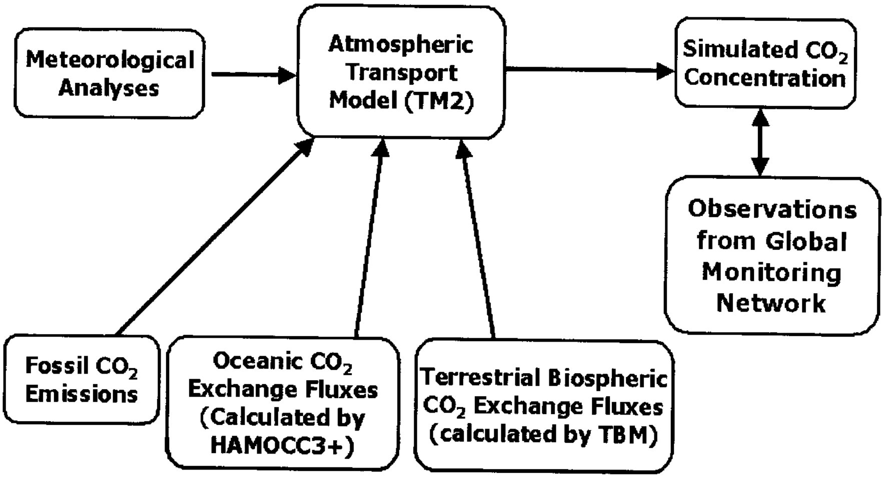

Figure 1. Flowchart of the data flow and model linkages for simulating the seasonal cycle of atmospheric CO_2.

ture are computed based on a global 1° × 1° map compiled by Marland et al. (1989) assuming constant emissions throughout the year. The terrestrial, oceanic, and fossil fuel fields of CO_2 fluxes provide the lower boundary condition for a three-dimensional atmospheric transport model forced by observed winds. To evaluate the simulation of atmospheric CO_2 concentrations, we extracted the monthly estimates of atmospheric CO_2 from locations corresponding to monitoring stations and compared the estimates with the detrended observations at each station.

In a previous study (Heimann et al. 1998), we obtained observed atmospheric CO_2 concentrations for the years 1983–1992 from the monitoring program of the National Oceanographic and Atmospheric Administration (NOAA; Conway et al. 1994a, 1994b). The seasonal cycle of atmospheric CO_2 was extracted from the raw station data at 27 monitoring stations, as described by Heimann et al. (1998). Among the 27 stations, we focus our comparison between simulated and observed concentrations of atmospheric CO_2 on the seven most northern stations (Table 1). Because these stations effectively integrate seasonal CO_2 exchanges across much of the northern hemisphere (Kaminski et al. 1996), we focus our evaluation of the seasonal patterns of CO_2 exchange on northern high latitudes between 60° N and 90° N and on northern temperate latitudes between 30° N and 60° N. To evaluate how well a simulation reproduces the observed seasonal signal of atmospheric CO_2 at a monitoring station, we calculated a normalized mean-squared deviation (NMSD) as

Table 1. Stations from the NOAA station network (Conway et al. 1994b) used in this study.

#	Abbreviation	Station	Country	Latitude	Longitude	Elevation [m]
1	ALT	Alert, N.W.T.	Canada	82°27′ N	62°31′ W	210
2	MBC	Mould Bay, N.W.T.	Canada	76°14'N	119°20′ W	15
3	KTL	Kotelny Island, Siberia	Russia	76°06′ N	137°36′ E	5
4	BRW	Point Barrow, Alaska	U.S.	71°19′ N	156°36′ W	11
5	STM	Ocean Station "M"	Norway	66°00′ N	2°00′ E	6
6	CBA	Cold Bay, Alaska	U.S.	55°12′ N	162°43′W	25
7	SHM	Shemya Island	U.S.	52°43′ N	174°06′ E	40

$$\mathrm{NMSD} = \frac{1}{12}\cdot\sum_{\mathrm{m}=1}^{12}\left(\frac{([\mathrm{TBM}]_\mathrm{m} + [\mathrm{FOS}]_\mathrm{m} + [\mathrm{OCE}]_\mathrm{m} - [\mathrm{OBS}_\mathrm{m}])^2}{\sigma_\mathrm{m}^2}\right),$$

where $[\mathrm{TBM}]_\mathrm{m}$, $[\mathrm{FOS}]_\mathrm{m}$, and $[\mathrm{OCE}]_\mathrm{m}$ are the monthly CO_2 concentrations resulting from the corresponding biospheric, fossil fuel, and ocean flux, respectively, $[\mathrm{OBS}]_\mathrm{m}$ is the mean observed value of CO_2 (from available data in the 1983 to 1992 period) and σ_m is the standard deviation of the observed value for each month (m = 1, 2, ... 12) of the year.

In this study we used the HAMOCC3 ocean biogeochemical model (Maier-Reimer 1993; Six & Maier-Reimer 1996) and the TM2 atmospheric transport model (Heimann 1995). The description and application of these models for purposes of simulating the seasonal cycle of atmospheric CO_2 is documented in Heimann et al. (1998). The three TBMs we applied in this study include the Carnegie-Ames-Stanford Approach (CASA; Randerson et al. 1997), Century (Parton et al. 1993), and the Terrestrial Ecosystem Model (TEM; McGuire et al. 1997; Tian et al. 1999). The data sets used as driving variables for each model are the same as used in the "Potsdam 95" comparison of NPP among global TBMs (Cramer et al. 1999), a comparison which included the three TBMs in this study. Differences in the absolute magnitude of global and regional NPP among the three TBMs have been described in Cramer et al. (1999) and Kicklighter et al. (1999). One important difference among the models concerns controls over the phenology of NPP. In CASA, the phenology of NPP is largely determined from satellite-derived data. In contrast, Century and TEM implement prognostic phenology algorithms. To facilitate evaluation of the seasonality of NPP and R_H among the models in this study, we focus our comparison on the relative proportion of annual NPP and annual R_H that is estimated to occur in each month of the year within