TITLE: AN ANALYSIS OF THE CARBON BALANCE OF THE ARCTIC BASIN FROM 1997 TO 2006

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DATA SET OVERVIEW:

These data sets are the results of a model-data analysis of the contemporary C balance of the Arctic system in which the land and ocean area of the Arctic Basin is treated as a linked system of CO2 and CH4 exchange across terrestrial, marine and atmospheric components. The study area for the terrestrial component of the Arctic Basin is defined as the land area within the watersheds of the major rivers that drain into the Arctic Ocean (Lammers et al., 2001). Several process-based tools were used to conduct this analysis of C dynamics across the Arctic Basin between years 1997 and 2006 through simulations of land-atmosphere CO2 and CH4 exchange, the transfer of land-based C to the Arctic Ocean, and ocean-atmosphere CO2 exchange. CO2 and CH4 exchange between the terrestrial ecosystems of the basin and the atmosphere, along with the export of dissolved organic C (DOC) to the Arctic Ocean, were estimated using the Terrestrial Ecosystem Model (TEM). The TEM considers the effects of a number of factors on its simulations of C dynamics including changes in atmospheric CO2, tropospheric ozone, nitrogen deposition, climate, and disturbance/land use including fire, forest harvest, and agricultural establishment/abandonment. TEM also calculates pyrogenic emissions of CO2, CH4, and CO from the combustion of vegetation and soil carbon in wildfires. The DOC leaching dynamics of TEM are a function of soil C decomposition rate, soil DOC concentration and water flux through the soil. We used the methane dynamics module of TEM (MDM-TEM) to estimate the exchange of CH4 with atmosphere of both wetlands, which generally emit CH4 to the atmosphere, and uplands, which generally consume CH4 from the atmosphere. The MDM-TEM considers the effects of a number of factors on its simulations of CH4 dynamics including the area of wetlands, fluctuations in the water table of wetlands, temperature, and labile carbon inputs into the soil solution derived from the net primary production (NPP) estimates of TEM. The MIT ocean biogeochemistry model simulated the net exchange of CO2 with the atmosphere as driven by changes in sea ice, water temperature, ocean circulation, and DOC inputs from TEM.

The results of these simulations were compared with estimates of CO2 and CH4 exchange from atmospheric inversion models and with observations of terrestrial C export from Arctic watersheds. The simulated transfer of land-based C to the Arctic Ocean was compared against estimates based on a sampling of DOC export from major Arctic rivers (McClelland et al., 2008). The land-atmosphere CO_2 exchange estimate was compared with results from the TransCom3 atmospheric inversion model inter-comparison project (Gurney et al., 2008), and CH_4 to results from atmospheric inversion-estimated surface emissions (Chen and Prinn, 2006). To compare the "bottom-up" results from our model simulations with the "top-down" estimates from these inversion studies, we summarize our estimates of surface-atmosphere CO_2 and CH_4 exchange for the land and ocean area matching the three high-latitude regions defined in the Transcom 3 model experiments (Gurney et al., 2002), namely the Boreal North America, Boreal Asia and Northern Ocean regions.

DATA COLLECTION AND PROCESSING:

Terrestrial CO_2 Fluxes and Pyrogenic CH_4 and CO Emissions

We used the Terrestrial Ecosystem Model (TEM), a coupled carbon-nitrogen cycle process model (Raich et al., 1991), as a "bottom-up" approach to estimate the exchanges of CO_2 with the atmosphere from terrestrial ecosystems of the Arctic Basin. For this study, we used a version of the model (TEM6) that has been modified from Felzer et al. (2004), which simulated ozone pollution effects, to also include the influence of permafrost dynamics (Zhuang et al., 2003; Euskirchen et al., 2006), atmospheric nitrogen deposition, N limitation, dissolved organic carbon (DOC) leaching, wildfire (Balshi et al., 2007), agricultural conversion and abandonment, and timber harvest on terrestrial C dynamics. C pools and associated fluxes are simulated at a monthly time-step for individual æcohortsÆ of unique vegetation types and disturbance history organized within spatially explicit 0.5o latitude x 0.5o longitude grid cells. To initialize the C, N and water pools for the beginning of the analysis period (1997 û 2006), in each model run we simulated dynamics since the year 1000 for each cohort among the 30,169 half-degree grid cells covering the land region north of 45oN. For the Arctic Basin C budget analysis, C fluxes and stock changes are summarized for the basin watersheds (Lammers et al., 2001) and within the Boreal North America and Boreal Asia regions for comparison with the Transcom 3 estimates of land-atmosphere CO_2 flux.

The TEM simulations in this study were driven by temporally- and spatially-explicit data sets on atmospheric carbon dioxide concentration ([CO_2]), tropospheric ozone (O_3), nitrogen deposition (Ndep), climate, and disturbance / land use including fire, forest harvest, and agricultural establishment / abandonment. Global annual atmospheric [CO_2] data are from the Mauna Loa station (Keeling and Whorf, 2005). [CO_2] data for the time period of years 1000 to 1900 were held constant at the year 1901 level (296.3 ppm). Monthly air temperature (oC), precipitation (mm), and incident short-wave solar radiation (Wm-2) data derived from observations for the period 1901û2002, gridded at 0.5o resolution, were obtained from the Climate Research Unit (CRU; University of East Anglia, UK; Mitchell and Jones, 2005). The CRU climate variables were extended to 2006 with NCEP/NCAR Reanalysis 1 data sets (NOAA-ESRL Physical Sciences Division, Boulder CO) using a regression procedure based on data anomalies from a ten-year (1993 û 2002) mean for each variable (see Drobot et al., 2006). These data sets were hind-casted to year 1000 by a repeating 30-year cycle of the 1901 - 1930 monthly data to initialize the carbon pools with climate variability (except for the simulation without climate variability, where 1901 û 1930 monthly means were used to drive the model for each year). The ozone (O_3) pollution data set used in this study, represented by the AOT40 index (a measure of the accumulated hourly ozone levels above a threshold of 40 ppbv), is based on Felzer et al. (2005) and covers the time period from 1860 to 2006. Before 1860, the ozone level in each 0.5o grid cell was assumed to equal the AOT40 of 1860 (which is equal to zero). The atmospheric N deposition data were based on Van Drecht et al. (2003), extended from 2000 to 2006 by adding the difference in annual N deposition rate from 1999 to 2000 to succeeding years, for each 0.5o grid cell (e.g. 2001 N deposition rate = 2000 + (2000-1999), etc.). For years 1000 to 1859, annual N deposition was assumed to equal the per grid cell rates in 1860.

The distribution of potential vegetation types in this study (Figure 1b; Table 1) was derived from the Global Land Cover Characterization (GLCC; Loveland et al., 2000) version 2 Seasonal Land Cover Regions (SLCR) data set available at 1km (equal-area) resolution for North America and Eurasia. The translated vegetation map was aggregated to the 0.5o grid matching the input climate data sets while retaining the area represented by each unique vegetation type within a grid cell as an individual, non-spatial cohort. Wetland cohort areas were assigned to each grid cell based on a 1o x 1o grid cell fraction inundated database (Matthews and Fung, 1987), where wetland area equals the product of fraction inundated and total cell area. To enable the evaluation of different disturbance and land use change events, we have developed a number of spatially-explicit time series data sets to prescribe the timing, area and distribution of historical disturbances and land use change. Historical annual burn areas for North America from 1950 û 2002 were available from the various Alaska and Canada fire databases compiled for the study by Balshi et al. (2007). That studyÆs fire data sets were extended from 2002 to 2006 with updated data from the U.S. Department of the Interior Bureau of Land Management (Alaska) and the Canadian Large Fire Database. The data were extended for Eurasia using the Global Fire Emission Database version 2 (Randerson et al., 2007). Forest harvest and land use (crops or pasture) cohorts were created in the input data set, derived from 1o x 1o gridded, annual land use transitions data for years 1700 through 2000, modeled by Hurtt et al. (2006). For Eurasia, the land use transitions data set was back-casted to the start of the initialization period by linearly ôramping-upö the transitions rates from 0% per year (for each 1o x 1o grid cell) starting in year 1000 to the year 1700 rates. For North America, we assumed land use transition rates of 0% prior to the year 1700. For both regions, the data were extended by simply using the 2000 rates for years 2001 to 2006.

Information about regional carbon sources and sinks can be derived from a “top-down” approach based on variations in observed atmospheric CO2 concentrations via inverse modeling with atmospheric tracer transport models. The land-atmosphere CO2 exchange estimated by the TEM for this study was compared with model mean and spread from the results of the Transcom 3 project, an inter-comparison of atmospheric CO2 inversion models that includes an ensemble of transport models and model variants (Gurney et al., 2002). The fluxes from the two approaches are compared on the basis of the net ecosystem exchange (NEE, see Chapin et al., 2006) for two high-latitude Transcom land regions (Boreal North America and Boreal Asia). NEE, a negative value of which indicates a surface sink, is the net flux that integrates all vertical exchange of CO2 between the atmosphere and the land and ocean. The Transcom 3 NEE estimates are based on the ensemble of models run on observation data from the 104-station network (a 1995-2006 monthly time series), with the long-term model mean subtracted from deseasonalized flux estimates to remove the bias in the estimates (see Gurney et al., 2008). The TEM calculates monthly NEE for terrestrial ecosystems as the net difference between photosynthetic uptake and the release of CO2 through plant respiration, decomposition, the decay of harvested products, and the CO2 emissions associated with biomass burning. Because the TEM estimates total C emissions associated with biomass burning (see Balshi et al. 2007), we partitioned the total emissions into pyrogenic emissions of CO_2, CH_4, and CO. The proportion of flaming versus smoldering emissions were determined using ratios for vegetation (80% flaming : 20% smoldering) and soil (20% : 80%) C converted in fire, based on Kasischke and Bruhwiler (2002). The mean emission factors reported in French et al. (2002) were used to calculate the amount of each gas released in fires. Only the emissions of C as CO_2 are included in the calculation of NEE, while C emitted as CH_4 (fCH_4) and CO (fCO) is included in the net ecosystem C balance (NECB; see Chapin et al., 2006). NEE from the Transcom 3 estimates and the model estimates of this study are compared monthly, annually and as deseasonalized fluxes, the latter calculated as the 13-month trapezoidal mean on monthly NEE (Gurney et al., 2008).

Terrestrial CH_4 Fluxes

We used the Methane Dynamics Module of TEM as a "bottom-up" approach to estimate the biogenic exchanges of CH_4 with the atmosphere from terrestrial ecosystems of the Arctic Basin. The MDM-TEM explicitly simulates the processes of CH_4 production and CH_4 oxidation as well as the transport of the gas between the soil and the atmosphere to estimate net biogenic CH_4 emissions (Zhuang et al., 2004, 2007). The model description and parameterizations for both upland and wetland ecosystems are documented in our previous studies (Zhuang et al., 2004, 2006). To simulate net biogenic CH_4 exchanges in our study area, which is spatially heterogeneous with respect to land ecosystem types, soils, and climate, we apply the module to each 0.5o (latitude x longitude) grid cell within the study area. The regional net CH_4 emissions are estimated as the difference between CH_4 emissions from wetland ecosystems and CH_4 consumption in upland ecosystems. The MDM-TEM in this study was driven with the climate (air temperature, precipitation, vapor pressure, and cloudiness), vegetation, elevation, and soil texture data described earlier for the simulations of CO_2 exchange by TEM. Monthly air temperature, precipitation, and vapor pressure are interpolated into daily time steps following the method described in Zhuang et al. (2004). MDM-TEM was also driven by spatially explicit data on soil water pH (Carter and Scholes, 2000) and leaf area index (LAI). Monthly LAI for our simulation period is organized following Zhuang et al., (2004) with the existing data for the period 1982 to 1999 (Myneni et al., 1997, 2001). During our simulations, LAI is assumed to remain constant within a month, i.e., daily LAI in a particular month is assumed to be the mean monthly value of LAI for that month. The NPP data required for driving MDM-TEM were based on the NPP estimates of TEM, which were aggregated over the cohorts within a grid cell for each month of the simulation.

Similar to CO_2, information of regional CH_4 sources can be derived from a "top-down" approach based on variations in observed atmospheric CH_4 concentrations via inverse modeling with atmospheric tracer transport models. Using an atmospheric inversion approach, Chen & Prinn (2006) estimated methane surface emissions for different methane regional sources and/or processes between 1996 and 2001. Data from 13 high-frequency and 79 low-frequency CH_4 observing sites were averaged into monthly mean values with associated errors arising from instrumental precision, mismatch error, and sampling frequency. Simulated methane mole fractions were generated using the 3-D global chemical transport model (MATCH), driven by NCEP analyzed observed meteorology (T62 resolution), which accounts for the impact of synoptic and inter-annually varying transport on methane observations. They adapted the Kalman filter with monthly emission pulses from each source type to optimally estimate methane flux magnitudes and uncertainties from seven seasonally varying (monthly varying flux) and two aseasonal sources (constant flux). Over the 1996-2001 time period the inversion reduces energy emissions and increases rice and biomass burning emissions relative to the a priori literature-based emissions. The global seasonal emission peak is shifted from August to July because of increased rice and wetland emissions from South-East Asia. The inversion also attributes the large 1998 increase in atmospheric CH_4 to global wetland emissions. Monthly Arctic emissions were estimated separately for the North American and Eurasian sectors and these results are compared with the sum of the pyrogenic and biogenic CH_4 emissions estimated by TEM.

Terrestrial DOC export

We estimate DOC loading to the river networks of the Arctic Basin by simulating DOC production on land and leaching into rivers in TEM. With this approach, we can examine how climate change and disturbance may affect DOC production and loss from land ecosystems. The production of DOC in TEM is assumed to result from the incomplete decomposition of soil organic matter. As a result, the production of DOC depends upon the same factors that influence decomposition: the amount and quality of soil organic matter, soil temperature, and soil moisture (see McGuire et al. 1997). The proportion of DOC produced from decomposition is assumed to vary with vegetation type (Table 2) and is determined from annual NPP estimates of intensively studied field sites and annual DOC export either observed in nearby rivers or estimated from review studies. Under equilibrium conditions, NPP would equal decomposition rates and DOC production would equal DOC leaching rates. However, for some ecosystems, no DOC leaching is assumed to occur because no water is transferred between the soil and the river networks at the model calibration site. The TEM assumes DOC is stored in the soil until it is leached from this pool based on the concentration of DOC in soil water and the flux of water from soil to the neighboring river network.

For linkage to the ocean biogeochemistry model, we use the watershed boundaries defined by Lammers et al. (2001) to determine the land areas of the Arctic Basin that contribute DOC to the Arctic Ocean. This boundary covers 24.2 million km^2 of land in which 2,276 river systems drain into the Arctic Ocean, Hudson Bay and the northern Bering Sea and is represented by 21,025 grid cells (0.5^o latitude x 0.5^o longitude). DOC export is estimated for each of the sixteen sea basins identified by Lammers et al. (2001) by summing the TEM DOC leaching estimates across the grid cells of the appropriate watersheds associated with the sea basins, which represents a conservative estimate of aquatic freshwater processing of DOC.

To evaluate model performance, we compare DOC export estimated by TEM to those obtained by Manizza et al. (2009a) using an empirical approach. Manizza et al. (2009a) estimate DOC export from rivers draining into ten sea basins identified by Lammers et al. (2001): 1) Arctic Archipelago, 2) Barents Sea, 3) Beaufort Sea, 4) Bering Strait, 5) Chukchi Sea, 6) East Siberian Sea, 7) Hudson Bay, 8) Hudson Strait, 9) Kara Sea, and 10) Laptev Sea. The DOC export into other six sea basins is assumed to be negligible.

Ocean CO_2 Fluxes

The MIT ocean biogeochemistry model used in this study was driven by an ocean general circulation model (OGCM) of the MIT General Circulation Model (Marshall et al. 1997) that includes a coupled sea-ice model. The model is configured on a "cubed-sphere" grid in a limited area Arctic domain with open boundaries at ~65o N in the Atlantic and Pacific sectors. Prescribed boundary conditions for potential temperature, salinity, flow and sea-surface elevation are provided from previous integrations of a global configuration of the same model (Menemenlis et al., 2005). The grid is locally orthogonal and has a variable horizontal resolution with an average spacing of ~18 Km, which allows the model to represent eddies. The mesh resolves major Arctic straits, including many of the channels of the Canadian Archipelago. This configuration of the MIT ocean model has also been used to assess the freshwater budget of the Arctic Ocean (Condron et al., 2009).

The atmospheric state (10-m surface winds, 2-m air temperatures and humdities and downward long and short-wave radiation) is taken from the six-hourly datasets of the NCEP reanalysis Kalnay et al. (1996). Monthly mean estuarine fluxes of fresh water are based on the Arctic Runoff database (Lammers et al., 2001; Shiklomanov et al., 2001).

We couple our Arctic OGCM to a simplified ocean biogeochemistry model, which now explicitly represents the transport and cycling of dissolved inorganic carbon, DIC, total alkalinity, phosphate, dissolved organic phosphorus, and dissolved oxygen (Dutkiewicz, et al., 2005). We added an explicit representation of riverine DOC, which has a time-varying riverine source, based on empirical or TEM estimates, as well as and a simple representation of the sink due to microbial respiration, which is a source of DIC to the marine system (Manizza et al., 2009b). We first developed parameterizations of the seasonal and regional delivery of terriginous DOC to the Arctic basin based on an empirical data set (Mannizza et al., 2009a). We implemented this source in the context of an Arctic basin configuration of the MIT ocean circulation model. Using this framework, we demonstrated that the veracity of the modeled sources and transport of terriginous DOC was sufficient to accurately capture the observed relationships between DOC and salinity in the Arctic provided the timescale for respiration of terriginous DOC in the oceans is about 10 years. Hence, we couple the marine and terrestrial carbon cycles by explicitly representing the influence of riverine DOC in estimating the air-sea CO2 fluxes in the Arctic Ocean.

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