3-2006

The impact of a northern peatland on the earth's radiative budget: sustained methane emission versus sustained carbon sequestration

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Recommended Citation
Frolking, S., N. Roulet, and J. Fuglestvedt (2006), How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration, J. Geophys. Res., 111, G01008, doi:10.1029/2005JG000091.

How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration

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Received 18 August 2005; revised 27 October 2005; accepted 25 November 2005; published 7 February 2006.

[1] Northern peatlands sequester carbon and emit methane, and thus have both cooling and warming impacts on the climate system through their influence on atmospheric burdens of CO_2 and CH_4. These competing impacts are usually compared by the global warming potential (GWP) methodology, which determines the equivalent CO_2 annual emission that would have the same integrated radiative forcing impact over a chosen time horizon as the annual CH_4 emission. We use a simple model of CH_4 and CO_2 pools in the atmosphere to extend this analysis to quantify the dynamics, over years to millennia, of the net radiative forcing impact of a peatland that continuously emits CH_4 and sequesters C. We find that for observed ratios of CH_4 emission to C sequestration (roughly 0.1–2 mol mol^{-1}), the radiative forcing impact of a northern peatland begins, at peatland formation, as a net warming that peaks after about 50 years, remains a diminishing net warming for the next several hundred to several thousand years, depending on the rate of C sequestration, and thereafter is or will be an ever increasing net cooling impact. We then use the model to evaluate the radiative forcing impact of various changes in CH_4 and/or CO_2 emissions. In all cases, the impact of a change in CH_4 emissions dominates the radiative forcing impact in the first few decades, and then the impact of the change in CO_2 emissions slowly exerts its influence.

Citation: Frolking, S., N. Roulet, and J. Fuglestvedt (2006), How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration, *J. Geophys. Res.*, *111*, G01008, doi:10.1029/2005JG000091.

1. Introduction

[2] Northern peatlands play a dual role in greenhouse gas radiative forcing of climate, affecting the atmospheric burdens of both methane and carbon dioxide. Most peatlands remove CO_2 from the atmosphere via photosynthesis and sequester a fraction of that carbon in accumulating peat [e.g., *Gorham*, 1991; *Turunen et al.*, 2002]. Most northern peatlands emit methane, though emissions are highly variable, both spatially and temporally; altogether they are a significant source of methane to the atmosphere, currently contributing ~3 to 5% of total global methane emissions [*Prather et al.*, 2001; *Mikaloff Fletcher et al.*, 2004]. C sequestration in peat lowers the atmospheric CO_2 burden, and thus causes a negative radiative forcing of climate (i.e., cooling); methane emissions from peatlands increase the atmospheric CH_4 burden, and thus cause a positive radiative forcing (warming). To evaluate the net result of a peatland's competing impacts on climate radiative forcing (cooling and warming), the effects of both CO_2 removal and CH_4 emission have to be quantified on a comparable basis.

[3] To understand the impact of an individual system's greenhouse gas emissions/uptake on radiative forcing of climate, the system's emissions usually are treated as perturbations to an otherwise constant atmosphere, although it may be argued that the assumption about a nonchanging background is very unrealistic [e.g., *Smith and Wigley*, 2000; *Lashof*, 2000]. A widely adopted approach for comparing climate impacts of different greenhouse gases is the Global Warming Potential (GWP) methodology [e.g., *Ramaswamy et al.*, 2001; *Albritton et al.*, 1995; *Shine et al.*, 1990; *Lashof and Ahuja*, 1990], which can be used to relate radiative forcing, over a specified time horizon, of a pulse emission of CH_4 with a pulse emission of CO_2. For a unit mass pulse input of methane at time $t = 0$, the GWP for a time horizon T is defined as the ratio of integrated radiative forcing due to that pulse relative to the integrated radiative forcing due to a unit pulse of the reference gas CO_2 [*Ramaswamy et al.*, 2001]. An emission of CH_4 can than be converted into a CO_2-equivalent emission by multiplying the CH_4 emission rate by the GWP value.

[4] This equivalent CO_2 emission would produce the same integrated (to time T) radiative forcing as the emission of CH_4. It can be used to compare the climate impacts of CH_4 emissions to CO_2 emission/uptake.

[5] Using the standard GWP methodology assumptions of a constant value for lifetime/adjustment time and for radiative efficiency (i.e., under the assumption of small

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0148-0227/06/2005JG000091

perturbations), the GWP value for methane is a decreasing function of the time horizon chosen, due to the overall slower atmospheric adjustment of CO_2 compared to CH_4. For any pulse emission of CH_4, there is a set of CO_2-equivalent pulse emissions; these values are tabulated for 20-year, 100-year, and 500-year time horizons by *Ramaswamy et al.* [2001]. The choice of a time horizon is often dictated by the specific impact under consideration [*Rodhe*, 1990; *Albritton et al.*, 1995]. Some components of the climate system (e.g., tropospheric temperature) may respond quickly to a change in radiative forcing and a short time horizon might be more appropriate, while others (e.g., ice sheet dynamics) may respond more slowly, and might be better assessed by using a long time horizon [*Albritton et al.*, 1995]. The 100-year time horizon has been adopted in the Kyoto Protocol (UNFCCC/CP/1997/7/Add.1/Decision 2/CP.3) [e.g., *Lashof*, 2000].

[6] *Crill et al.* [2000], *Roulet* [2000], *Whiting and Chanton* [2001], and *Friborg et al.* [2003] used the GWP methodology to assess the climate impact of wetlands, based on the annual exchange of CO_2 and CH_4 at the wetland surface. For any given ratio of CH_4 emission to CO_2 uptake, there is a particular compensation GWP value (or, equivalently, a particular time horizon) that results in the CO_2-equivalent emission of the methane flux exactly offsetting the CO_2 uptake. *Whiting and Chanton* [2001] classified seven sites (subtropical to boreal) where they had concurrently measured CO_2 and CH_4 fluxes as a net greenhouse gas (or CO_2-equivalent) source if either (1) for a given choice of GWP value (or time horizon), the ratio of CH_4 emission to CO_2 uptake was higher than the compensation value; or (2) for a given ratio of CH_4 emission to CO_2 uptake, the chosen GWP value was greater than (or time horizon less than) the compensation value. If neither of these held, the wetland was classified as a net greenhouse gas sink. For a 20-year time horizon, all seven sites were classified as net greenhouse gas sources; for a 500-year time horizon, all seven sites were classified as net greenhouse gas sinks; and for a 100-year time horizon, the boreal sites were classified as sources, and the temperate and subtropical sites as sinks. Similar GWP results were found by *Roulet* [2000] for Canadian peatlands, by *Crill et al.* [2000] for natural and managed peatlands in Finland, if they excluded emissions from storage and combustion of harvested peat, and by *Friborg et al.* [2003] for a site in western Siberia. Note that the meaning of the time horizon here is the impact horizon for a single, annual pulse emission; it is not an assessment of a continuous greenhouse gas source/sink lasting for 20, 100, or 500 years.

[7] However, peatlands do not emit CH_4 or take up CO_2 as an isolated annual pulse; they are temporally and spatially variably persistent sinks for atmospheric CO_2 and persistent sources for atmospheric CH_4. The current and future atmospheric burdens of CO_2 and CH_4, and the radiative forcing they generate, depend on all previous emissions of these gases. The standard GWP methodology does not evaluate the impact of persistent emissions/uptake [e.g., *Smith and Wigley*, 2000; *Fuglestvedt et al.*, 2000; *Berntsen et al.*, 2005]. In the case of a peatland, the climate system is simultaneously experiencing both the short-term dominance of recent CH_4 emissions (which may be well represented by the 20-year time horizon GWP) and the long-term dominance of persistent C sequestration (which may be well represented by the 500-year time horizon GWP). Which has a stronger impact? By how much? Does this vary over the history of the peatland's development? This cannot be quantified in a straightforward manner with GWP calculations, but it can be modeled, in a manner analogous to GWP calculations, as a simple, first-order system of stocks and flows [e.g., *Rodhe*, 2000]. At any time, the instantaneous radiative forcing due to a greenhouse gas is proportional to its concentration in the atmosphere at that time, so the net impact of a peatland on the Earth's current radiation budget (ignoring albedo changes) is determined by the peatland's perturbation of atmospheric composition, which is determined by the combined effect of all past emissions/uptake and the degree to which these have dissipated. The competing impacts of a peatland's CO_2 and CH_4 fluxes can be evaluated as the net radiative forcing impact; this can be quantified at any time and for any emissions scenario.

[8] *Laine et al.* [1996] evaluated the impact of peatland draining/drying on net radiative forcing by driving an atmospheric composition and radiative forcing model (REFUGE [*Savolainen and Sinisalo*, 1994]) with pre- and post-draining fluxes of CO_2, CH_4, and N_2O measured at four sites. Draining decreased CH_4 fluxes, and associated radiative forcing dropped to low values in the first decades following draining. Draining enhanced tree growth (a CO_2 sink) for 120–160 years, but caused an increase in sustained emissions of CO_2 from decomposing peat; the overall dynamics of CO_2 radiative forcing was a decline over ~100 years, then a slower recovery toward pre-draining values. For all sites, the impact of draining on N_2O emissions was small. The overall impact on total radiative forcing was a decrease and then recovery; the magnitude of the changes was a function of the predraining ratio of CH_4 flux to net CO_2 flux. *Minkkinen et al.* [2002] extended these results, estimating the impact of draining of Finnish peatlands for forestry during 1900–1998 on radiative forcing 1900–2100, using the same atmospheric model. In these analyses, *Laine et al.* [1996] and *Minkkinen et al.* [2002] focused on the impacts of management on various carbon pools and the consequences for radiative forcing over 200–500 years, but not on long-term radiative forcing of an unperturbed peatland, nor on the relationship between their methodology and GWP-based analyses.

[9] The characteristics of the GWP methodology are well-understood by the scientific community that is developing and evaluating radiative forcing and climate impact indices, and alternatives are being proposed and debated [e.g., *Hammitt et al.*, 1996; *Wigley*, 1998; *O'Neill*, 2000, 2003; *Lashof*, 2000; *Fuglestvedt et al.*, 2000, 2003; *Manne and Richels*, 2001; *Smith*, 2003; *Godal*, 2003; *Shine et al.*, 2005a, 2005b]. However, the GWP methodology has had widespread direct application in biogeochemical studies [e.g., *Whiting and Chanton*, 2001; *Roulet*, 2000; *Crill et al.*, 2000; *Robertson et al.*, 2000; *Smith et al.*, 2001; *Friborg et al.*, 2003; *Six et al.*, 2004; *Marland et al.*, 2004; *Li et al.*, 2005]; in these situations greenhouse gas emissions are sustained and often variable, which complicates the interpretation.

[10] In this paper we analyze the radiative forcing of climate from sustained emissions of CH_4 and sustained

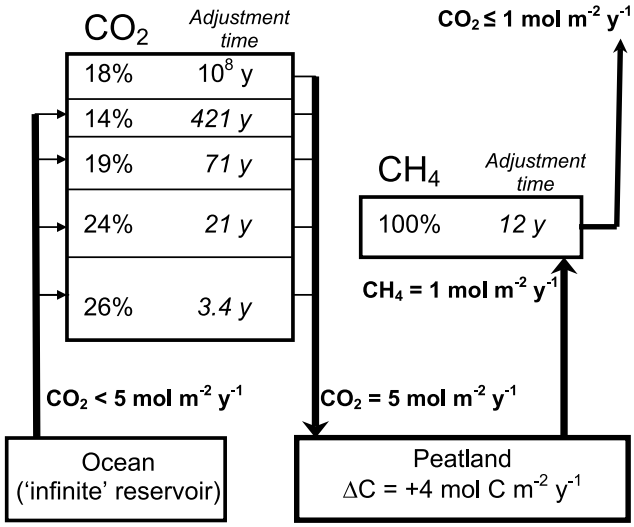

Figure 1. Model atmosphere consisting of 5 noninteracting reservoirs for CO_2, each with a different adjustment time, and a single reservoir for CH_4. The peatland sequesters CO_2 from the atmosphere, taken proportionally from each pool, and emits CH_4 to the atmosphere. In this case, the mole ratio of CH_4 emitted to C sequestered is 0.25. The flux rates shown are generic values, not specific to any site. Four of the five atmospheric CO_2 pools are replenished toward their equilibrium values as first order processes by an "infinite" reservoir, which could be considered to be the ocean for the timescale of this model (millennia or less). The fifth pool is not significantly replenished during a 2000-year simulation, so peatland carbon sequestration represents a permanent removal from that pool. CO_2 fraction values (α_i in equation (2)) and lifetimes/adjustment times (τ_i in equation (2)) are from *Joos et al.* [1996]. The atmospheric methane pool loses methane by a first-order process, with a turnover time of 12 years [*Prather et al.*, 2001].

uptake of CO_2 by a peatland. We use a simple atmospheric model and assume that net emissions of CO_2 and CH_4 are small perturbations to the global atmosphere, so that we can use the simplifying assumptions of constant lifetime and constant radiative efficiency, as is done in the GWP methodology. This approach does not require the choice of a single fixed time horizon, and goes beyond standard GWP-based calculations by (1) allowing for a time series of gas flux input instead of only a single pulse input, and (2) providing the instantaneous radiative forcing for each year of the simulation instead the equivalent amount of CO_2 that would give an equal radiative forcing when accumulated up to a specified time horizon. By calculating radiative forcing (e.g., W m^{-2}) the two gases can be compared in common units at any time, and the dynamics of total radiative forcing impact can be quantified when the emissions are continuous (either constant or variable), as is the case with peatlands and all other ecosystems. We first demonstrate that the model has behavior that is equivalent to the GWP methodology for pulse emissions, then apply it to evaluate the impact of sustained peatland CO_2 and CH_4 fluxes in terms of radiative forcing as function of time, then consider the impact of changing CO_2 and CH_4 emissions for simple scenarios, and finally discuss the difference in interpretation of the climate impact between this and the GWP methodologies.

2. Methods

[11] The behavior of a small pulse input of CH_4 into an otherwise constant atmosphere is adequately represented by a first-order decay in concentration with a constant lifetime/adjustment time, τ_{CH4}, so the time evolution of an atmospheric burden pulse perturbation can be represented as

$$r_{CH_4}(t) = r_o \exp(-t/\tau_{CH4}), \tag{1}$$

where r_o is the initial CH_4 perturbation. Accurately portraying CO_2's lifetime/adjustment time in the atmosphere is more complicated, and can be approximated as the linear superposition of several first-order decay pools with different time constants, τ_i, and fractional contributions, α_i, so the time evolution of an atmospheric burden pulse perturbation can be represented as [*Joos et al.*, 1996; *Shine et al.*, 2005a]

$$r_{CO_2}(t) \sim \sum_{i=0}^{4} \alpha_i \exp(-t/\tau_i). \tag{2}$$

[12] We modeled the atmospheric burden of CH_4 as a single reservoir with an annual input and a first-order loss equal to reservoir mass divided by constant reservoir lifetime/adjustment time, and the atmospheric burden of CO_2 as a collection of five noninteracting global reservoirs, each with an annual removal equal to the annual CO_2 flux multiplied by the reservoir fraction and a first-order recovery determined by the reservoir lifetime (Figure 1) [*Joos et al.*, 1996; *Shine et al.*, 2005a]. The model integration used a second-order Runga–Kutta method, applied at an annual time step, resulting in annual CO_2 and CH_4 burden differences from background, or burden perturbations. Radiative forcing (again, positive or negative) due to the flux perturbations was then calculated for each year as the product of the burden perturbation times the gas's radiative forcing factor, A. The total radiative forcing, RF_{total}, was calculated as the sum of the individual gas contributions, and can be written as

$$RF_{\text{total}}(t) = \sum_{i=0}^{5} \left(\xi_i A_i f_i \cdot \int_0^t \Phi_i(t') e^{(t'-t)/\tau_i} dt' \right), \tag{3}$$

where ξ_i is a multiplier for indirect effects (1.3 for CH_4 and 1.0 for CO_2 [*Ramaswamy et al.*, 2001]), A_i is radiative efficiency of greenhouse gas i ($A_{CH4} = 1.30 \times 10^{-13}$ W m^{-2} kg^{-1} CH_4; $A_{CO2} = 0.0198 \times 10^{-13}$ W m^{-2} kg^{-1} CO_2 [*Ramaswamy et al.*, 2001]), f_i is the fractional multiplier for the flux of greenhouse gas i (1.0 for CH_4; see Figure 1 for CO_2 values), and $\Phi_i(t')$ is the flux of greenhouse gas i into the atmosphere at time t'. The integral term in equation (3), $\int_0^t \Phi_i(t') e^{(t'-t)/\tau_i} dt'$, is the current (time t) concentration of gas i due to all previouss emissions (since $t = 0$) and their partial to nearly complete

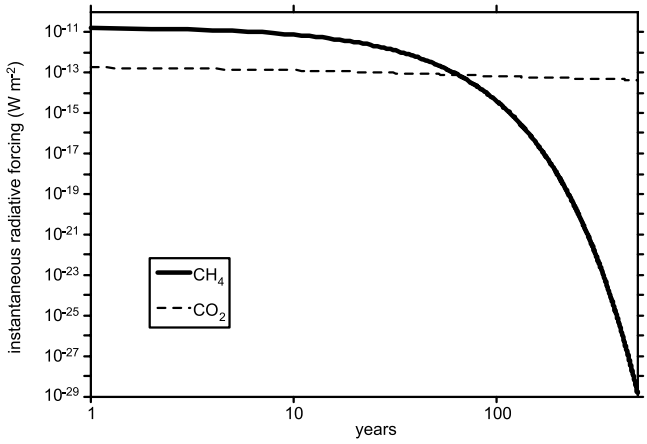

Figure 2. Temporal evolution of instantaneous radiative forcing (W m^{-2}) caused by a pulse emission in year 0 of 100 kg CH_4 (solid line) and 100 kg CO_2 (dashed line). CH_4 radiative forcing (including indirect effects) is initially higher because of its stronger radiative efficiency per unit mass. Eventually, CO_2 radiative forcing is stronger because of its longer effective lifetime/adjustment time in the atmosphere.

removal from the atmosphere. Note that CO_2 is the greenhouse gas for $i = 0-4$, and CH_4 is $i = 5$.

[13] We estimate the instantaneous perturbation to radiative forcing by this CO_2 and CH_4 over a 4000-year simulation to quantify the impact of a peatland on the Earth's climate system. We ignore the behavior of CO_2 and CH_4 in the background atmosphere, and assume that a linear radiative forcing response to the perturbations is a good approximation, even over long time periods. This simplifying assumption could be relaxed with more sophisticated and complete process modeling of atmospheric burden sources and sinks of CO_2 and CH_4, but this simple approach will nevertheless enable us to explore and illustrate some key characteristics of the system.

[14] We calculated the peatland impact on radiative forcing per mole of CH_4 emitted; northern peatlands emit <0.1 to ~4 mol CH_4 m^{-2} yr^{-1} [*Bartlett and Harriss*, 1993; *Alm et al.*, 1997; *Roulet*, 2000; *Whiting and Chanton*, 2001; *Minkkinen et al.*, 2002; *Christensen et al.*, 2004]. Our only emissions parameter is the ratio of C sequestered as peat to CH_4 emitted. We considered three sets of emissions scenarios: (1) pulse emissions for direct comparison with the GWP methodology: 100 kg CH_4 and 6200, 2300, and 700 kg CO_2 to match the 20 year, 100-year, and 500-year GWP values for methane [*Ramaswamy et al.*, 2001], and also 100 kg CO_2 to directly compare the two gases; (2) sustained constant CH_4 emission and CO_2 uptake to determine the impact on current climate of long-term peatland development for various CH_4:CO_2 flux ratios, as would be the case for a comparison of the relative importance of different wetland types; and (3) sustained emission/uptake (2000 years) with step-function function transitions to new emission/uptake values (higher and lower) for 500 years, to evaluate possible impacts of environmental change. In this case we used a CH_4:CO_2 flux ratio of 0.25; this is roughly equivalent to ratio of total northern peatland CH_4 flux (~20 Tg CH_4 yr^{-1} [*Mikaloff Fletcher et al.*, 2004; *Wang et al.*, 2004]) to C-sequestration (~0.07 Pg C yr^{-1} [*Gorham*, 1991; *Turunen et al.*, 2002]). We considered various combinations of changes in CH_4 emission and/or CO_2 uptake: doubling, reducing to half, reducing to zero, as well as a change in CO_2 flux from net uptake to net emission.

[15] Observed CO_2 and CH_4 fluxes generally show significant temporal variability [e.g., *Christensen et al.*, 2003; *Friborg et al.*, 2000, 2003; *Lafleur et al.*, 2003; *Aurela et al.*, 2002; *Heikkinen et al.*, 2002; *Waddington and Roulet*, 1996; *Edwards et al.*, 1994; *Shurpali et al.*, 1993], but flux variability is smoothed in the atmospheric response for relatively long-lived and well-mixed gases like CO_2 and CH_4. Thus, for decadal to millennial scale analyses, the temporal variability on timescales shorter than their atmospheric lifetimes, particularly the seasonal cycle but also interannual variability, can be ignored. To simplify our analysis, we also considered CH_4 emissions and C sequestration to be constant over millennial timescales, ignoring possible century-scale to millennial scale variations in C sequestration rates and CH_4 emissions that could be driven by climatic shifts and natural peatland successional development [*Belyea and Malmer*, 2004].

[16] We consider carbon sequestered as peat to represent the only carbon removed from the atmospheric CO_2 pool by the peatland. Net ecosystem exchange of CO_2, as measured in the field by flux towers and chambers, will include uptake of CO_2 that is subsequently lost from the peatland, either as CH_4 or dissolved organic carbon (DOC), or through episodic disturbance (e.g., fire); thus the net ecosystem uptake of CO_2 should be greater than the peat accumulation or C sequestration rate. Most carbon emitted from the peat as CH_4 eventually returns to the atmospheric CO_2 pool via oxidation in the atmosphere, so this carbon is only temporarily removed from the atmospheric CO_2 pool. The GWP methodology does not include this oxidation-generated CO_2 as a component of the direct or indirect radiative forcing impact of methane emissions [*Ramaswamy et al.*, 2001]. The fate of DOC drained from a peatland is less certain; a portion is transported to downstream aquatic systems and some is oxidized and lost to the atmosphere as CO_2 through evasion from the outlet streams [e.g., *Billett et al.*, 2004; *Dawson et al.*, 2004].

3. Results

3.1. Pulse Emissions

[17] Two factors influence a gas's accumulated radiative forcing for a chosen time horizon: its radiative efficiency per molecule or unit mass, and its lifetime in the atmosphere [*Albritton et al.*, 1995]. Because CH_4 has a higher radiative efficiency per unit mass than CO_2, for equal mass pulse emissions CH_4 will initially generate a stronger instantaneous radiative forcing (including indirect forcing) than CO_2 (Figure 2). Because CH_4 has a shorter atmospheric lifetime than CO_2, for all time after about 65 years following equal mass pulse emissions the remaining CO_2 in the atmosphere will generate a stronger instantaneous radiative forcing than the remaining CH_4 (Figure 2). The accumulated annual radiative forcing for 700 kg CO_2 (or 2300 kg or 6200 kg CO_2) equaled the accumulated annual radiative

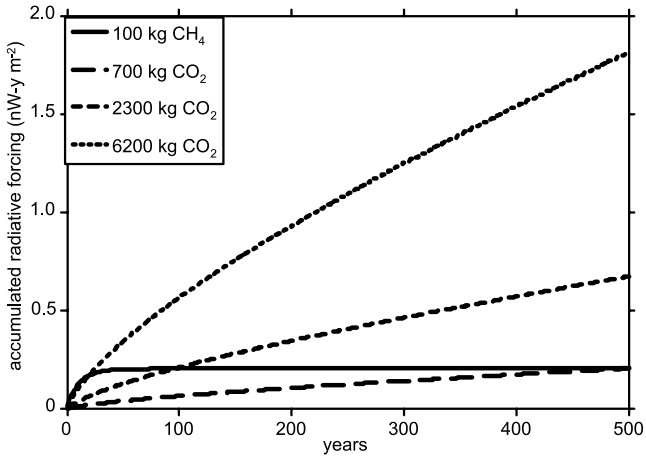

Figure 3. Annually accumulated radiative forcing (nW-yr m^{-2}; 1 nanowatt-year = 0.032 J) for pulse emissions in year 0 of 100 kg CH_4 (solid line), 700 kg CO_2 (long-dashed line), 2300 kg CO_2 (short-dashed line), and 6200 kg CO_2 (dotted line). The accumulated radiative forcing for 100 kg CH_4 equals the accumulated radiative forcing for CO_2 after 20 years for the 6200 kg pulse, 100 years for the 2300 kg pulse, and 500 years for the 700 kg pulse; these correspond to CH_4 GWP values of 62 (20 years), 23 (100 years), and 7 (500 years) [*Ramaswamy et al.*, 2001]. Note that the slope of these curves represents the instantaneous radiative forcing in any year.

forcing of 100 kg CH_4 after 500 years (or 100 years or 20 years) (Figure 3), establishing that this atmospheric model (equation (3)) is consistent with the GWP values given by the IPCC. Note, however, that for times beyond the specified horizon of 20, 100, or 500 years, the accumulated radiative forcing for CO_2 will be greater than the accumulated radiative forcing for CH_4 in all three cases, while for times shorter than the specified horizon, CO_2's accumulated radiative forcing will be less (Figure 3). The GWP methodology only specifies the time at which the accumulated radiative forcings are equal; by itself it does not indicate which gas has a stronger accumulating impact earlier or later than the other, nor which has the strongest instantaneous impact at any specific time.

3.2. Sustained Constant Methane Emission and Carbon Dioxide Uptake

[18] Because the atmospheric CH_4 burden perturbation is modeled as a single pool with a first-order loss, for a constant perturbation input (i.e., the peatland CH_4 flux), atmospheric CH_4 is within a few percent of equilibrium within about 50 years ($\sim 4\tau_{CH4}$). The radiative forcing perturbation is also approximately constant after about 50 years at about 25×10^{-15} W m^{-2} per mol CH_4 emitted (Figure 4a). The behavior of CO_2 differs from CH_4 because it is modeled as five separate pools with different lifetimes (see Figure 1). In particular, a pool with effectively infinite lifetime (i.e., very long relative to the timescales of the simulation due to slow cycling of C through the deep ocean, sediments, including peatlands, and rocks) causes a fraction of the CO_2 sequestered as peat carbon in the peatland to not be replaced in the atmosphere. Therefore as long as the peatland accumulates carbon the atmospheric CO_2 burden perturbation will become more negative and the radiative forcing perturbation due to the CO_2 perturbation will become more negative (Figure 4a).

[19] The total or net radiative forcing equals the sum of the impacts of CO_2 and CH_4. Initially, CH_4 dominates the impact and the net effect is a positive radiative forcing (warming), which peaks in about year 50 (Figure 4b). After this, as the methane impact has stabilized and the negative radiative forcing impact of CO_2 continues to increase, the net impact declines toward zero. We refer to the time when the net radiative forcing reaches zero as the switchover time. After switchover, the magnitude of the CO_2 impact on radiative forcing continues to grow larger than the constant methane impact, and the net radiative forcing becomes increasingly negative (cooling). The switchover time is a function only of the ratio of CH_4 emission to CO_2 removal, increasing as the mole ratio increases (Figure 5). For mole ratios of CH_4 emission to CO_2 removal less than about

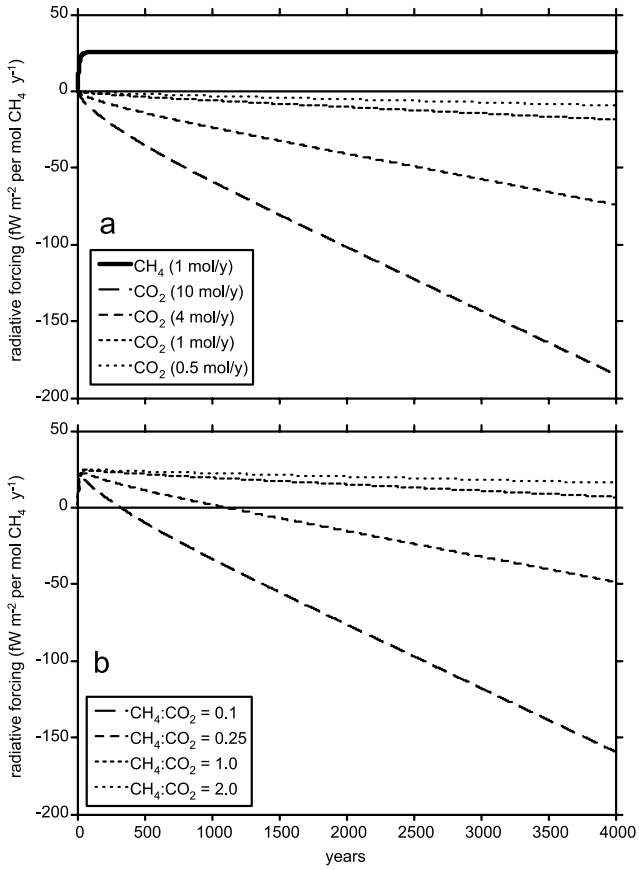

Figure 4. Instantaneous radiative forcing (a) by CH_4 (solid line) and CO_2 (dashed lines) and (b) total forcing due to perturbations in atmospheric burdens of CO_2 and CH_4 resulting from constant emission of 1 mol CH_4 yr^{-1} and removal of CO_2, at 10, 4, 1, and 0.5 mol yr^{-1}, and both beginning in year 0. The CH_4 and CO_2 radiative forcings are equal to the size of the perturbed CH_4 and total CO_2 atmospheric pools times each gas's radiative efficiency; 1 fW = 10^{-15} Watts.

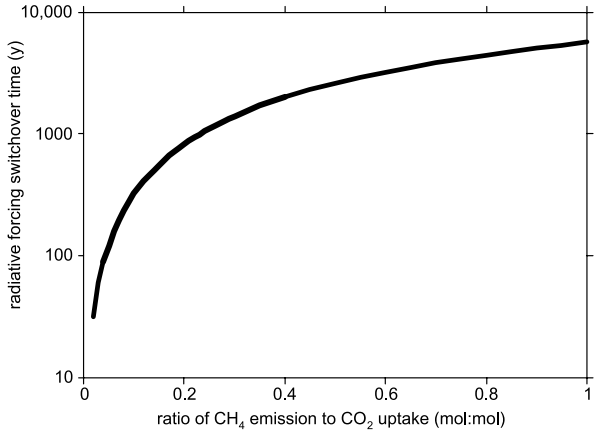

Figure 5. Timing of the instantaneous radiative forcing switchover from net warming to net cooling as a function of the ratio of CH_4 emission to CO_2 removal for constant fluxes (see Figure 4). As CH_4 emissions increase relative to CO_2 removal, the time to switchover increases. For ratios of CH_4 emission to CO_2 removal less than about 0.012, net radiative forcing is always dominated by CO_2 and no switchover occurs. The switchover timing is independent of the magnitude of emissions, and depends only on the CH_4:CO_2 ratio, as long as emissions are small perturbations to the global atmosphere.

0.012 mol mol^{-1}, net radiative forcing is always dominated by CO_2 and no switchover occurs.

3.3. Sustained Methane and Carbon Dioxide Fluxes With Abrupt Changes to New Values

[20] Just before step change in emissions (i.e., simulation year 2000), the radiative forcing due to the sustained CH_4 emissions is constant and positive (Figure 6a), as it has been since ~50 years after emissions began (Figure 4a). At this time the radiative forcing due to sustained CO_2 uptake is slowly becoming more negative (Figure 6a), as it has since sequestration began (Figure 4a), due to the system's inability over a few millennia to fully replenish CO_2 removals from pools with long adjustment times. Atmospheric composition and radiative forcing respond rapidly to a step change in CH_4 emission (increase or decrease), reaching a new steady state in several decades (Figure 6a). The steady state atmospheric methane concentration perturbation is linearly proportional to the perturbation flux rate, so abruptly doubling (halving) the flux rate leads after ~50 years to a doubling (halving) of the radiative forcing perturbation (Figure 6a). Atmospheric composition responds slowly to a step change in CO_2 flux rate (increased or decreased uptake, or a switch to net emission), not reaching a new steady state within 500 years, even for cessation of CO_2 flux; the impact on perturbation radiative forcing tracks that response (Figure 6a).

[21] When these CO_2 and CH_4 flux scenarios are combined, a variety of results emerge (Figure 6b). Scenarios with the same CO_2 flux (e.g., 1xCO_2 & 1xCH_4, 1xCO_2 & 2xCH_4, and 1xCO_2 & 0.5xCH_4; or 2xCO_2 & 1xCH_4, 2xCO_2 & 2xCH_4, and 2xCO_2 & 0.5xCH_4) all have parallel perturbation radiative forcing trajectories after year 2050, with the different CH_4 fluxes generating offsets during the first 50 years (see sets of black, purple, and dark blue lines in Figure 6b). We also conducted simulations for all of these scenarios with a linear ramp change over 50 years from the original to the new flux (results not shown). The change in

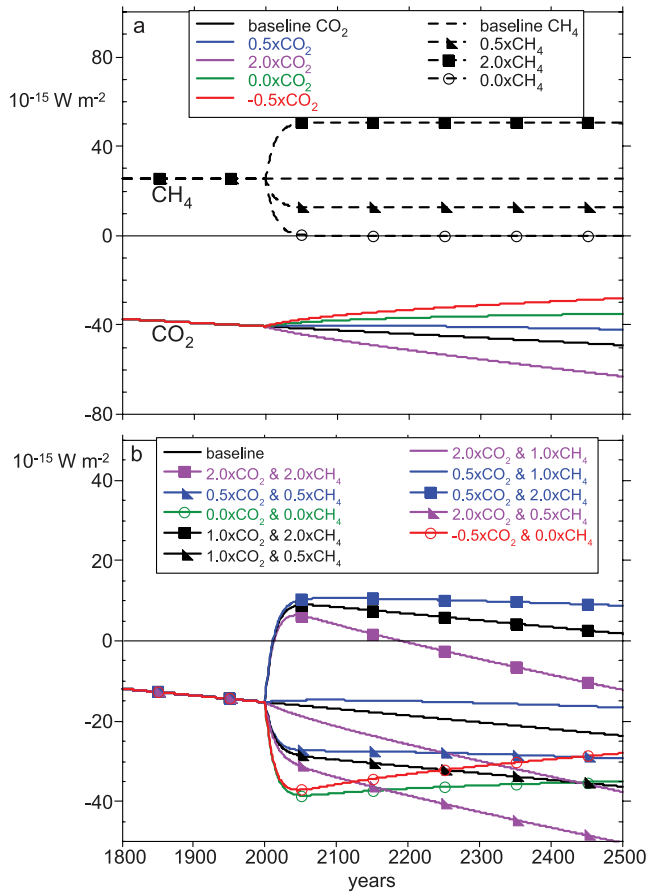

Figure 6. (a) Instantaneous radiative forcing by CH_4 (dashed lines) and CO_2 (solid lines) for constant emissions ("baseline"), fluxes reduced to half (CO_2, blue; CH_4, decreasing triangles), fluxes doubled (CO_2, purple; CH_4, solid squares), fluxes reduced to zero (CO_2, green; CH_4, open circles), and CO_2 flux changed from uptake to emission at half the rate (red). In all cases, there was constant baseline CH_4 emission of 1 mol m^{-2} yr^{-1} and net CO_2 uptake of 4 mol m^{-2} yr^{-1} for 2000 years (as in Figure 4a), then a step change to the new emission/uptake rates in year 2001. All radiative forcing values are per mol CH_4 emitted per year prior to year 2000. The panel shows perturbation radiative forcing for years 1800 to 2500 (200 years before change to 500 years after); for years 0–1800, see Figure 4a. (b) Total perturbation instantaneous radiative forcing in simulation years 1800–2500 for the baseline constant flux case (thick black line; see also Figure 4b) and 10 scenarios of change: both fluxes double, drop to half, or drop to zero; CH_4 emission only doubles or drops to half; CO_2 uptake only doubles or drops to half; CH_4 emission doubles and CO_2 uptake drops to half; CH_4 emission drops to half and CO_2 uptake doubles; and CH_4 emission stops and CO_2 flux switches from uptake to emission at half the baseline rate. In Figure 6b, colors match CO_2 scenarios and symbols match CH_4 scenarios in Figure 6a.

radiative forcing due to CH_4 and CO_2 and combined net forcing were more gradual, but were very similar in overall pattern to Figure 6. Methane forcing still reached a new equilibrium within 100 years, and all trajectories beyond that time were nearly identical to the step change results in Figure 6. In all cases, the impact of a step or ramp change in methane emissions dominates the perturbation radiative forcing over the first few decades, and then the impact of the step or ramp change in CO_2 emissions slowly modifies the methane impact. This parallels GWP calculations, where CH_4 has a higher CO_2-equivalent for shorter time horizons.

4. Discussion

[22] The fundamental difference between the radiative forcing impacts of CO_2 and CH_4 fluxes is due to their different adjustment times in the atmosphere and their different radiative efficiencies. The different adjustment times accounts for the declining GWP value for CH_4 as the time horizon increases, and it determines how the current state of the atmosphere and overall radiative forcing depends emissions in previous years to millennia. CH_4 has a relatively short lifetime: long enough to be well mixed in the global atmosphere, but short enough that within several decades a pulse input is almost completely removed from the atmosphere, and the atmosphere can come into approximate equilibrium with a new constant source or sink. A constant methane source (or sink) will thus cause a temporary dynamic period (~50 years) before stabilizing as a constant radiative forcing perturbation; continued constant flux only maintains this new, constant state [*Laine et al.*, 1996]. CO_2 uptake (or emission) leaves a persistent negative (or positive) residual in the atmosphere, on timescales of up to millennia or longer [e.g., *Maier-Reimer and Hasselmann*, 1987; *Caldeira and Kasting*, 1993; *Archer et al.*, 1997; *O'Neill*, 2000]. Therefore the atmosphere cannot come into equilibrium with a constant CO_2 source or sink over the timescales we are considering, as the magnitude this residual offset continually increases.

[23] In the case of a peatland that emits CH_4 and takes up CO_2 (sequesters C), its overall instantaneous impact on the atmosphere must eventually be dominated by C sequestration and will be a net cooling. After 4000 years of constant fluxes, only 0.3% of the total emitted methane is still in the atmosphere, while ~20% of the CO_2 sequestered as peat has not been restored to the atmosphere from the other components of the carbon cycle (see Figure 1). The time after which the cooling effect of C sequestration dominates is a function of the relative strengths of the two fluxes. Owing to the different behaviors of CO_2 and CH_4 in the atmosphere, even constant fluxes cause a temporally dynamic response in the net radiative forcing impact of a peatland, which changes in both magnitude and sign (Figure 4). A single GWP application cannot capture this dynamic behavior, though evaluating GWP impacts for several time horizons gives an indication of this; longer time horizons give less weight to methane and are more likely to result in classifying a peatland as a net greenhouse gas sink [e.g., *Whiting and Chanton*, 2001; *Roulet*, 2000].

[24] Most northern peatlands are at least several thousand years old [e.g., *Smith et al.*, 2004; *Clymo et al.*, 1998; *Kuhry et al.*, 1993; *Gorham*, 1991]. *Turunen et al.* [2002] estimated the area-weighted mean age of ~2600 peatlands in Finland to be about 4200 years. The current radiative forcing impact of a peatland 4200 years old that has been an approximately constant source of methane and sink for carbon will be a net cooling if the mole ratio of CH_4 emission to C sequestration is less than 0.75, and a net warming if the ratio is greater than 0.75 (Figure 5). Peatlands with flux ratios less than and greater than 0.75 exist in Finland [*Laine et al.*, 1996; *Alm et al.*, 1997; *Minkkinen et al.*, 1999, 2002].

[25] Northern peatland carbon cycling is likely to change as climate changes [e.g., *Roulet*, 2000], though predicting just how rates of carbon sequestration and methane flux will change will not be easy [*Belyea and Malmer*, 2004; *Moore et al.*, 1998]. To evaluate the impact of any change in fluxes with the methodology outlined above, the model can use a projected emissions time series as input and generate a time series of the instantaneous radiative forcing perturbation. To evaluate the impact with the GWP methodology, one first has to decide what is the appropriate pulse emission to consider: the new flux rate (if a single new value can be specified) or the change in the flux rate. Consider a simple case that could represent a slight drying of a peatland: A peatland initially has a constant CH_4 emission of 1 mol m^{-2} yr^{-1} and a constant C uptake of 4 mol m^{-2} yr^{-1} (i.e., CH_4:CO_2 = 0.25 in Figure 4b), but after drying the CH_4 emission drops to 0.5 mol m^{-2} yr^{-1}, and C uptake remains at 4 mol m^{-2} yr^{-1}. Using the new "equilibrium" fluxes for a GWP calculation, the CO_2 plus CO_2-equivalent fluxes are +7.3 mol m^{-2} yr^{-1} (20-year time horizon), +0.2 mol m^{-2} yr^{-1} (100-year horizon), and −2.7 mol m^{-2} yr^{-1} (500-year horizon). Using the change in fluxes (ΔCH_4 = −0.5 mol m^{-2} yr^{-1}, ΔCO_2 = 0) the CO_2-equivalent flux would be −11.3 mol m^{-2} yr^{-1} (20-year horizon), −4.2 mol m^{-2} yr^{-1} (100-year horizon), or −1.3 mol m^{-2} yr^{-1} (500-year horizon).

[26] The actual trajectory in radiative forcing is an initial drop by about 10×10^{-15} W m^{-2} per m^2 peatland over the first few decades, and then a continuing slow decline (parallel to the baseline or no-change trajectory) of another 5×10^{-15} W m^{-2} in the subsequent few hundred years (see baseline and 1.0xCO2 & 0.5xCH4 curves in Figure 6b). The GWP calculations based on the change in fluxes give this same general picture, i.e., large negative CO_2-equivalent flux in the short term and small negative CO_2-equivalent flux in the long term. However, if GWP calculations should be based on the change in flux to give a reliable portrayal of impact, then if fluxes do not change the GWP-based impact would be zero. This has not been the standard GWP-based interpretation of peatland climate impact [e.g., *Friborg et al.*, 2003; *Whiting and Chanton*, 2001; *Crill et al.*, 2000; *Roulet*, 2000].

[27] One assumption of both the GWP methodology and the model presented here is that the atmospheric perturbations are small and the atmosphere is otherwise constant over the duration of the simulation. Since both a gas's radiative efficiency and its lifetime/adjustment time depend on its atmospheric concentration [*Ramaswamy et al.*, 2001; *Myhre et al.*, 1998], this assumption allows these parameters to be held constant, simplifying the calculations. However, the assumption becomes problematic for a long time horizon and/or a large perturbation. Both CO_2 and CH_4

had lower atmospheric burdens during the preindustrial era [*Prentice et al.*, 2001; *Prather et al.*, 2001], and thus higher radiative efficiencies. *Caldeira and Kasting* [1993] determined that for CO_2 changes in radiative efficiency and lifetime had approximately offsetting impacts on its global warming potential. *Osborn and Wigley* [1994] estimated that the current methane lifetime is ~25% longer than the preindustrial lifetime; this increased lifetime would offset the climate impact of the decline in radiative efficiency to some degree. In this study we ignored these factors, as they would require a more complex atmospheric model and revised GWP values, and because these factors will have a similar impact on both methodologies.

[28] A second simplifying assumption is long periods of constant CH_4 and CO_2 fluxes. We conducted simulations with variable CO_2 and CH_4; each had a sinusoidal oscillation about the mean flux, with an amplitude equal to half the mean, a period of a few to several hundred years, and a phase shift between the CH_4 and CO_2 oscillations of zero to 0.5 cycles. This led to oscillations in the radiative forcing about the means (results not shown), but overall trends were the same as for constant emissions shown in Figure 4. The oscillations were stronger for CH_4, with a single atmospheric pool and a relatively short lifetime, than for CO_2, whose multiple pools, some with longer lifetimes, led to damped oscillations. A more realistic characterization of long-term variability or trends in emissions/uptake would require realistic modeling of peatland development and associated CO_2 and CH_4 fluxes. The specific details of the long-term history of fluxes may not be very important, however, since the atmosphere comes into equilibrium with CH_4 fluxes in a few decades at a burden perturbation of about 12 times of the annual flux, and ~20% of C sequestered is not restored to the atmosphere on millennial timescales. Given this, to first order the current radiative impact of long-term peatland development can be approximated by the net radiative forcing of a negative CO_2 burden perturbation equal to 20% of the total accumulated peat carbon and a positive CH_4 burden perturbation equal to 10 times the recent annual CH_4 flux.

[29] In assessing the impact of a system that is a source and/or sink of one or more greenhouse gases, there is a cause-effect sequence of considerations: (1) emissions of the various greenhouse gases; (2) changes in atmospheric greenhouse gas concentrations; (3) changes in net radiative forcing; (4) climate change; (5) climate change impacts on ecosystems and human society; and (6) damages/benefits due to these changes [*Smith and Wigley*, 2000; *Fuglestvedt et al.*, 2003]. Proceeding from consideration 1 to 6, there is increasing societal relevance, increasing uncertainty, and increasing interdisciplinarity. The GWP methodology provides a simple mechanism for comparing emissions of different greenhouse gases (level 1) by quantifying their radiative forcing impacts (level 3), but only for a very specific outcome, the integrated radiative forcing impact (a proxy for level 4), over a specified time horizon, of a single pulse emission representing current year emissions, or a change in emissions. It determines the CO_2 equivalent of a pulse emission of CH_4 or other radiatively active gas, which can be directly compared to a pulse emission of CO_2 or the CO_2 equivalent of another gas (i.e., back to level 1). The model presented above brings the analysis to dynamic radiative forcing impacts (level 3), including the temporal dynamics of the forcing, for a pulse, sustained or varying emission scenario.

[30] Recently proposed alternatives to the standard GWP methodology include a GWP for sustained emissions (step function rather than pulse) [*Berntsen et al.*, 2005], and a global temperature change potential or GTP for pulse or sustained emissions [*Shine et al.*, 2005a]. *Berntsen et al.* [2005] show that the ratio of sustained GWP to pulse GWP is a function of a gas's atmospheric lifetime/adjustment time; for a gas with a lifetime/adjustment time of 10 years ($\sim\tau_{CH4}$), the ratio is a nonlinear function of the time horizon, and is roughly 1.2 (20-year time horizon), 1.5 (100-year time horizon), and 1.7 (500-year time horizon). The GTP is based on a simple, mean global temperature response to radiative forcing from greenhouse gas emissions [*Shine et al.*, 2005a]; the temperature change at 20, 100, and 500 years after a pulse or sustained emissions of CH_4 and other gases, relative to the temperature change caused by a unit emission of CO_2, as in GWP calculations. *Shine et al.* [2005a] show that pulse emission GWP values for CH_4 are very similar to sustained emission GTP values for 20-, 100-, and 500-year time horizons, differing by <10%.

5. Conclusions

[31] *Albritton et al.* [1995] noted that the intended application of the GWP methodology is to assess the relative climate impacts of anthropogenic emissions of greenhouse gases. The role of the GWP methodology in the Kyoto Protocol process is to provide a mechanism for "trading" among gases in a multigas "basket" approach [*Fuglestvedt et al.*, 2003]. The ease and transparency of the GWP methodology (two features that are important for its usefulness as a policy tool), along with its IPCC imprimatur, have led its to widespread application. In the field of biogeochemistry, it has become common to apply the GWP methodology to compare climate impacts of ecosystem-atmosphere fluxes of greenhouse gases, treating a single year's fluxes as isolated pulse emissions.

[32] While the GWP methodology puts time-integrated radiative impacts of CH_4 and CO_2 pulses into common units (CO_2-equivalent emissions), providing a mechanism for evaluating trade-offs between the climate impacts of different gases, it does not assess the impact of sustained or variable greenhouse gas emissions on radiative forcing and the climate system at any given time. Our analysis, which does assess the impact of sustained greenhouse gas emissions on radiative forcing, leads to several conclusions about peatland impact on radiative forcing that do not emerge from a GWP analysis.

[33] 1. Relatively constant methane emissions from northern peatlands maintain the atmospheric methane perturbation burden and the associated perturbation to radiative forcing at relatively constant levels.

[34] 2. Relatively constant C sequestration causes an increasingly negative (or cooling) perturbation to radiative forcing.

[35] 3. The current radiative forcing impact of a peatland is determined primarily by a trade-off between the total C sequestered since the peatland's formation and the recent (decades) methane fluxes. For many northern peatlands that

would be characterized as net greenhouse gas emitters by a 20-year or 100-year GWP analysis, the current radiative forcing perturbation due to past and present methane emissions and C sequestration is negative (i.e., cooling). This is a direct consequence of their persistence as a C sink over millennia.

[36] 4. If peatland CH_4 and CO_2 fluxes change, the atmosphere and radiative forcing will respond rapidly to changes in CH_4 fluxes, and more slowly to changes in CO_2 fluxes. If the methane flux stabilizes at a new value, the atmosphere burden and radiative forcing due to methane will also stabilize within a few decades.

[37] Although we conclude that the overall current climate impact of northern peatlands is likely to be a net cooling, this does not mean that their CH_4 emissions are not important. Peatland greenhouse gas fluxes will inevitably involve a competition between the quick, strong warming from CH_4 emissions and the slow cooling from CO_2 uptake, and the methods used to evaluate this competition can obscure or highlight the dynamics. These dynamics are important for our understanding of past changes, and for the assessment of possible future paths for emissions and uptake from peatlands. If the methane flux from northern peatlands (or another source) changes significantly and rapidly, the atmospheric methane burden and associated radiative forcing will respond in decades, possibly stabilizing at a new level (e.g., Figure 6). *Dlugokencky et al.* [1998, 2003] have argued that the reduction in the growth rate of atmospheric CH_4 observed in the 1990s may be just such a burden stabilization following an increase in flux over the past few hundred years due to rapid growth of the dominant anthropogenic sources (agriculture and energy production).

[38] These conclusions do not invalidate the results of GWP calculations. However, they provide a more comprehensive and informative set of results for analysis and assessment, and identify some limitations of the GWP methodology. To evaluate how the impact of climate change on peatlands will feed back to impact climate through greenhouse gas emissions and radiative forcing, it is important that the analysis account for possible dynamic behavior of peatlands and sustained but likely variable CO_2 and CH_4 emissions trajectories, such as would be generated by a peatland ecosystem gas flux model driven by climate change scenarios [e.g., *Valdes et al.*, 2005; *Gedney et al.*, 2004]. As a policy tool, dynamic model results may be too complex for easy negotiations (i.e., no single value for comparison), but, for a scientific assessment of impacts of realistic scenarios, we believe they are an improvement on the GWP methodology. Finally, we note that both methods, unlike the GTP index, refer only to radiative forcing impact, and not to actual climate change.

[39] **Acknowledgments.** This work was supported by a grant to the University of New Hampshire from the NASA EOS Interdisciplinary Science project (NAG5-10135); and grants to McGill University from the NSERC Discovery Grants Program and from the Canadian Foundation for Climate and Atmosphere Science (CFCAS) for the Canadian Global Coupled Climate–Carbon Model network. We thank Kari Minkkinen and an anonymous reviewer for their comments and suggestions.

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