Climate feedback from wetland methane emissions

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[1] The potential for wetland emissions to feedback on climate change has been previously hypothesised [*Houghton et al.*, 2001]. We assess this hypothesis using an interactive wetlands scheme radiatively coupled to an integrated climate change effects model. The scheme predicts wetland area and methane (CH_4) emissions from soil temperature and water table depth, and is constrained by optimising its ability to reproduce the observed inter-annual variability in atmospheric CH_4. In transient climate change simulations the wetland response amplifies the total anthropogenic radiative forcing at 2100 by about 3.5–5%. The modelled increase in global CH_4 flux from wetland is comparable to the projected increase in anthropogenic CH_4 emissions over the 21st century under the IS92a scenario. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Gedney, N., P. M. Cox, and C. Huntingford (2004), Climate feedback from wetland methane emissions, *Geophys. Res. Lett.*, *31*, L20503, doi:10.1029/2004GL020919.

1. Introduction

[2] Methane is a strong greenhouse gas and currently the second largest contributor to the anthropogenic greenhouse effect. Of all the natural and anthropogenic sources of methane, wetland emission is thought to be the single largest [*Houghton et al.*, 2001]. Moreover, methane emissions from wetlands have the potential to produce a significant positive feedback on climate change. (Changes in soil temperature and moisture are likely to modify CH_4 emissions [*Cao et al.*, 1998; *Moore et al.*, 1998]). In spite of their importance, there is considerable uncertainty in the magnitude of present day natural wetland emissions, with estimates varying from 115 [*Fung et al.*, 1991] to 237 Tg CH_4 yr^{-1} [*Hein et al.*, 1997]. In addition, emissions from rice paddies are also a significant but highly uncertain CH_4 source (25–100 Tg CH_4 yr^{-1} [*Houghton et al.*, 2001]).

[3] The three major controls of methane emissions from wetlands are soil temperature (through microbial process rates) [*Christensen et al.*, 1996, 2003], water table depth (by determining the depth of the methane generating and oxidising zones) [*Moore et al.*, 1998] and the amount and quality of decomposable substrate [*Christensen et al.*, 2003]. Methane can be transported to the atmosphere through various pathways: molecular diffusion, ebullition and via vascular plant stems [see *Walter and Heimann*, 2000]. A number of models exist which include a detailed description of CH_4 generation, transport and oxidation [e.g., *Walter and Heimann*, 2000]. However as well as the large uncertainty in the current total wetland emissions, the sensitivity of emissions to these controls is not well known or understood.

[4] The temperature sensitivity is normally characterised in terms of a Q_{10} factor, i.e., the factor by which a reaction rate increases with a 10 K increase in temperature. Small-scale observational studies derive values of Q_{10} for wetland emissions varying from 1.7–16 [*Walter and Heimann*, 2000.] Part of the discrepancy amongst these estimates is likely to be due to the difficulty of separating environmental drivers which co-vary [*Khalil et al.*, 1998]. However temperature is often found to exert the dominant control over wetland methane emissions. For example, over a number of northern wetland sites, soil temperature variations accounted for 84% of the CH_4 emission variance [*Christensen et al.*, 2003], with $Q_{10} \sim 5$. Also *Khalil et al.* [1998] obtained a $Q_{10} \sim 1.5$–3 over rice paddies in China using a methodology which isolated the flux rate temperature dependence.

[5] Given these uncertainties, and those associated with methane production and oxidation processes as a function of water table depth, we opt here for a deliberately simplistic modelling approach which allows us to make use of data on the observed interannual variability in global mean CH_4 atmospheric concentration as a large-scale constraint on the temperature sensitivity.

2. Wetlands Emission Model

[6] We develop a simple methane emission scheme which can be run within the Met Office climate model [*Gordon et al.*, 2000]. It is coupled to the land-surface scheme MOSES-LSH [*Gedney and Cox*, 2003] which predicts the distribution of sub-grid scale water table depth and wetland fraction (f_w) from the overall soil moisture content and the sub-grid scale topography. We parameterize the methane flux from wetlands F^w_{CH4}, by including the basic controls of temperature, water table height and soil carbon C_s, as follows:

$$F^w_{CH4} = k_{CH4} f_w C_s Q_{10}(T_{soil})^{(T_{soil}-T_0)/10} \quad (1)$$

where T_{soil} is the soil temperature in Kelvin averaged over the top 10cm and k_{CH4} is a global constant which is calibrated to give the required global methane flux. T_0 is defined as 273.15 K. (We use soil carbon content as there is a lack of global data on substrate availability).

[7] We assume that only the fraction of the grid box where the water table is at or above the surface (i.e., f_w) is a net emitter of CH_4, otherwise methanotrophic bacteria in the aerobic soil completely oxidise all the CH_4 produced from the methanogenic bacteria. In reality a net CH_4 flux is often observed when the water table is within about 20 cm of the surface so this approximation may underestimate the extent of CH_4-emitting wetlands. We tested for this against a more realistic empirical relationship of the net CH_4 flux dependence on water table height [*Roulet et al.*, 1992] and found that our approximation had a negligible impact on the results, so it is retained here for simplicity. Paddy field emissions are dealt with in a similar manner, although the geographical pattern of rice cultivation is held fixed.

[8] The Arrhenius equation, which describes the temperature dependence of a single biological process (such as methanogenesis), can be mathematically approximated by a temperature-independent Q_{10} factor [*Thornley and Johnson*, 1990]. However this approximation is only valid over a limited temperature range. We retain an effective Q_{10} as it offers a useful metric for comparison with literature. However, since we are applying a single parameterisation globally, we generalise Q_{10} so that it fits the Arrhenius equation exactly and can therefore be applied over the whole physical temperature range. (Note that, as mentioned earlier, Q_{10} values inferred from observations of net CH_4 emissions are due to a combination of processes, and therefore even the Arrhenius equation should be seen as a semi-empirical fit). We allow the effective Q_{10} to vary with temperature such that:

$$Q_{10}(T) = Q_{10}(T_0)^{T_0/T} \tag{2}$$

where $Q_{10}(T_0)$ is a constant. The resulting reduction in Q_{10} with increasing temperature is in line with the different temperature sensitivities of *Christensen et al.* [2003] and *Khalil et al.* [1998] (see above).

3. Constraining the Model Parameters

[9] Using a methodology similar to *Dlugokencky et al.* [2001] we now use the observed inter-annual variability of atmospheric CH_4 to constrain the wetland emissions scheme in equation (1). A simple lifetime model can be used to predict the global atmospheric methane burden $[CH_4]$ such that:

$$\frac{d[CH_4]}{dt} = \sum F^{w}_{CH4} + \sum F^{nw}_{CH4} - \frac{[CH_4]}{\tau} \tag{3}$$

where $\sum F^{w}_{CH4}$ and $\sum F^{nw}_{CH4}$ are the global fluxes due to wetland plus rice paddy fluxes and non-wetlands emissions (e.g., biomass burning, anthropogenic etc.) respectively. Using the annual observed global mean atmospheric CH_4 concentration from *Dlugokencky et al.* [2001] and assuming a constant atmospheric methane lifetime τ (8.9 yrs) *Houghton et al.* [2001], we can infer the inter-annual variability in the total source ($\sum F^{w}_{CH4} + \sum F^{nw}_{CH4}$).

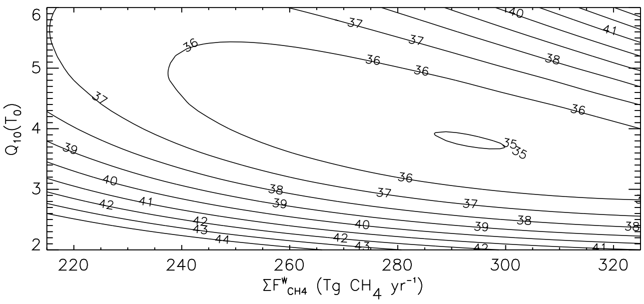

Figure 1. RMS errors (CH_4 yr^{-1}) when fitting modelled wetland methane emissions against those inferred from the observed atmospheric concentrations. (See Table 1 S1 for experimental setup details.)

[10] We assume that the variability due to anthropogenic sources can be neglected. However we do include the effect of biomass burning in this study as some of the observed CH_4 variability is thought to be due to forest fires, particularly the large fires in Siberia and Indonesia in 1997–1998 [*Dlugokencky et al.*, 2001]. We combine the mid-range estimates of CO and CH_4 emissions (3.8 Tg CH_4) for the 1998 boreal fires [*Kasischke and Bruhwiler*, 2003] with the observed relationship between CO anomalies and boreal fire extent between 1991–1999 [*Wotawa et al.*, 2001] to estimate the CH_4 inter-annual variability due to high latitude fires. We use an estimate of 2.5 Tg CH_4 for the 1997–98 Indonesian fires [*Levine*, 1999].

[11] In order to estimate the wetland flux from equation (1) we force a stand-alone version of MOSES-LSH with observations/analyses at the standard Met Office climate model resolution of 2.5° latitude by 3.75° longitude. The model is spun up by repeatedly forcing it with monthly mean data from the Global Soil Wetness Project (GSWP) [*Dirmeyer et al.*, 1999] until equilibrium is reached. Observed monthly mean anomalies in the primary atmospheric drivers for wetland methane emissions: surface air temperature and precipitation [*Jones et al.*, 2001; *Xie and Arkin*, 1998] are added to this baseline climatology and the model is run from 1990–1999. The simulation is repeated for a range of specified $Q_{10}(T_0)$ and k_{CH4} values. The resulting time series of global fluxes are then compared to ''truth'' which we obtain by combining the annual observed global CH_4 anomalies [*Dlugokencky et al.*, 2001] with equation (3).

[12] Given that detailed inversion atmospheric chemistry studies have estimated the annual mean total wetland flux (i.e., including paddy fields) to be in the range 215–325 Tg CH_4 yr^{-1} [*Fung et al.*, 1991; *Hein et al.*, 1997] and the Q_{10} value is also highly uncertain, we calculate the RMS error in the annual anomaly time series predicted over the likely range of these two parameters. (We ignore the 1990 and 1991 anomalies because the Mount Pinatubo eruption distorts the results). Figure 1 shows how the RMS error varies over the parameter ranges using the seasonally varying wetland extent and our best estimate of the CH_4 contribution from biomass burning. The figure shows that a $Q_{10}(T_0)$ value of 3.7 and global mean flux of 297 Tg CH_4 yr^{-1} produce the lowest errors. However, there are not significantly larger errors over a fairly wide range of values.

[13] We repeat this calibration for a number of studies (S1-4). Table 1 gives the best estimates of the parameter

Table 1. Results of Off-Line Simulations of Annual CH_4 Flux Anomalies From Wetlands (1992–1999): Minimum RMS Error in the Fit, and $Q_{10}(T_0)$ and $\sum F^w_{CH4}$ (Tg CH_4 yr^{-1}) Values Required for This Best Fit[a]

	Min. RMS	$\sum F^w_{CH4}$	$Q_{10}(T_0)$
S1 Varying f_w	35	297	3.7
S2 Mean f_w	28	325	3.2
S3 Varying f_w, τ = 8.4yr	36	305	3.7
S4 Varying f_w	31	287	3.4

[a]S1-3 and S4 use Indonesian biomass burning emissions derived from *Levine* [1999] and *Duncan et al.* [2003] resp.

values for each study. Removal of wetland temporal variation (S2) results in a slightly lower temperature sensitivity. Including a sink term due to methanotrophic soil bacteria *Houghton et al.* [2001] via setting τ = 8.4 yrs (S3) produce little change in the optimised model parameters. We also consider a higher estimate for the Indonesian fires (S4: 4.0 Tg CH_4) which is derived from satellite and aircraft measurements [*Duncan et al.*, 2003]. Overall there is little variation in the implied temperature sensitivities, which given the uncertainties, are in the region of those inferred from the high-latitude field campaigns [*Christensen et al.*, 2003; *Khalil et al.*, 1998].

[14] Figure 2 shows (a) observed surface air temperature and precipitation anomalies, and (b) best estimates of modelled wetland flux temporal anomalies for simulations S1 and S2. There is a clear correlation between observed temperature and "observed" methane anomalies inferred by inverting the observed atmospheric concentrations (equation (3)). This demonstrates the importance of the temperature dependence of methanogenesis. This is picked up in the general ability of the simple model (equation (1)) to reproduce the phase of the atmospheric CH_4 anomaly regardless of whether or not wetland seasonality is included.

4. 21st Century Projections

[15] We now incorporate the wetlands model into an "Integrated Model of Global Effects of climatic aNomalies" (IMOGEN) [*Huntingford et al.*, 2004] to carry out an

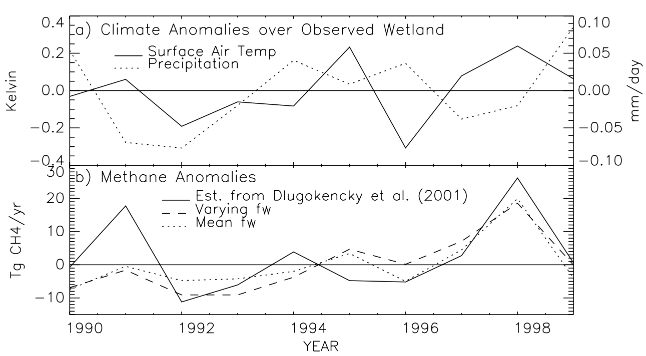

Figure 2. Inter-annual variability of a) climatology over the observed wetland area and b) the simulated surface methane emission anomalies as inferred by: inverting the variability in observed atmospheric concentration (solid line) and fluxes estimated from equation (1). Dashed and dotted lines refer to varying and fixed wetlands (Table 1 S1, S2).

ensemble of simple climate change experiments. IMOGEN simulates the land-surface aspects of climate change driven by climate anomalies representative of those from a full General Circulation Model (GCM). It takes patterns of climate change anomalies simulated by a GCM and scales their magnitude according to the global mean temperature change due to greenhouse gas concentrations [*Huntingford and Cox*, 2000]. IMOGEN incorporates the MOSES-LSH land surface scheme and now additionally includes the wetland CH_4 emission model described above and a simple lifetime model of atmospheric CH_4 (see equation (3)). Using mathematical expressions given by *Houghton et al.* [2001] we allow the CH_4 lifetime to vary with atmospheric CH_4 concentration and calculate the additional radiative forcing due to the wetlands CH_4 flux-climate feedback. This additional radiative forcing from the interactive wetlands then feeds back on the surface climate through the scaling of the surface climate change anomalies by the global mean temperature change due to greenhouse gases.

[16] A number of runs of IMOGEN are carried out from 1990 with the baseline climate taken from GSWP (as described above). The model is run to 2100 using patterns of climate change from a HadCM3 simulation [*Gordon et al.*, 2000] using the IS92a emissions scenario. We consider a number of simulations with interactive modelled wetland area (see Figure 3 for details) which cover the parameter range with the lowest RMS errors in Figure 1 ($\sim$36 Tg CH_4 yr^{-1}). (In each case we recalculate k_{CH4} such that it produces the required initial global flux for the specified Q_{10}.) In an additional experiment we fix the wetland extent throughout the simulation to present day observations [*Aselmann and Crutzen*, 1989] to investigate the significance of any changes in wetland coverage. A control experiment (CTL) is also carried out where changes in wetland emissions do not feedback radiatively onto the climate.

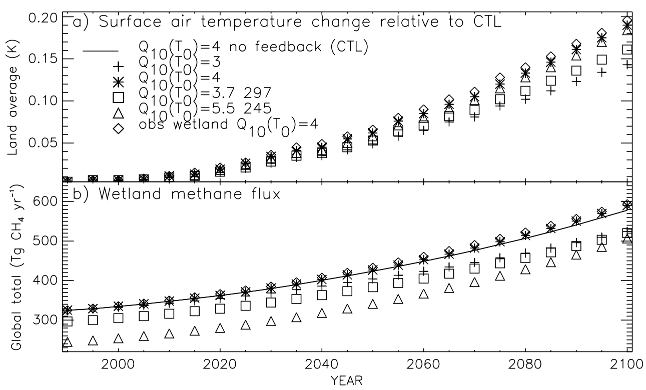

Figure 3. Climate change predictions of enhanced land averaged temperature and total wetland CH_4 emissions from IMOGEN using different wetland temperature responses. The control experiment has $Q_{10}(T_0)$ = 4.0, $\sum F^w_{CH4}$ = 325 Tg CH_4 yr^{-1} with no CH_4 radiative feedback (CTL) (solid line). The following scenarios include CH_4 radiative feedback and modelled, interactive wetland area, with $Q_{10}(T_0)$ and $\sum F^w_{CH4}$(Tg CH_4 yr^{-1}) pairs as follows: 3.0; 325 ('+'), 4.0; 325 ('*'), 3.7; 297 (squares) and 5.5; 245 (triangles). The simulation using observed wetland extent and including radiative feedback has $Q_{10}(T_0)$ = 4.0, $\sum F^w_{CH4}$ = 325 Tg $CH_4 yr^{-1}$ (diamonds).

[17] Figure 3 shows the predicted changes in average land climate from the scenarios described above. The projected temperature change from 1990–2100 in the CTL case is 4.2 K (not shown), compared to 4.4 K in the highest scenario considered. There is a considerable increase in predicted CH_4 emissions by 2100, with the most likely scenarios predicting between $\sim$500–600 Tg CH_4 yr^{-1}. This is equivalent to a 3.7–4.9% increase in radiative forcing (not shown). The total wetland area decreases only slightly by 2100, suggesting that it is the wetland temperature response and not the change in wetlands extent that will dominate the change in natural CH_4 emissions.

5. Conclusions

[18] Our optimised wetlands model yields an approximate doubling of CH_4 emissions from wetlands by 2100, which is comparable to the projected increase in "anthropogenic" CH_4 emissions under the IS92a scenario. When coupled to a simple pattern-scaling climate model, this very significant increase in CH_4 results in an increase in global mean temperature of 0.14–0.20 K, which is 3.7–4.9% of the total projected warming by 2100. The simulated wetland CH_4-climate feedback is therefore relatively small in the context of climate change under most scenarios of increasing anthropogenic CO_2 emissions, but large compared to projected increases in CH_4 emissions from human-activities. More significant climate feedbacks are possible if climate change and CO_2 increase lead to a loss of peatland carbon, but an assessment of this risk requires a better mechanistic understanding of wetland carbon cycling including both CH_4 and CO_2 fluxes [*Moore et al.*, 1998] and possible losses as dissolved organic carbon [*Freeman et al.*, 2004].

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