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 [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 $F_{CH4}^w$ by including the basic controls of temperature, water table height and soil carbon $C_s$, as follows:

$$F_{CH4}^w = k_{CH4} f_w C_s Q_{10} (T_{soil} - T_0)^{10}$$

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where $T_{\text{soil}}$ is the soil temperature in Kelvin averaged over the top 10 cm and $k_{\text{CH}_4}$ 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 [Thorley 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:

$$Q_{10}(T) = Q_{10}(T_0) \frac{T_0}{T}$$

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:

$$\frac{d[\text{CH}_4]}{dt} = \sum F_{\text{CH}_4}^w + \sum F_{\text{CH}_4}^n - \frac{[\text{CH}_4]}{\tau}$$

where $\sum F_{\text{CH}_4}^w$ and $\sum F_{\text{CH}_4}^n$ 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 $\tau$ (8.9 yrs) Houghton et al. [2001], we can infer the inter-annual variability in the total source ($\sum F_{\text{CH}_4}^w + \sum F_{\text{CH}_4}^n$).

[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 $k_{\text{CH}_4}$ 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 geographical pattern of rice cultivation is held fixed.

Figure 1. RMS errors (CH$_4$ yr$^{-1}$) when fitting modelled wetland methane emissions against those inferred from the observed atmospheric concentrations. (See Table S1 for experimental setup details.)

[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 CH4 Flux Anomalies From Wetlands (1992–1999): Minimum RMS Error in the Fit, and $Q_{10}(T_0)$ and $\sum F_{CH4}$ (Tg CH4 yr$^{-1}$) Values Required for This Best Fit$^a$

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$^a$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 $\tau = 8.4$ yrs (S3) produce little change in the optimised model parameters. We also consider a higher estimate for the Indonesian fires (S4: 4.0 Tg CH4) 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 CH4 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 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 CH4 emission model described above and a simple lifetime model of atmospheric CH4 (see equation (3)). Using mathematical expressions given by Houghton et al. [2001] we allow the CH4 lifetime to vary with atmospheric CH4 concentration and calculate the additional radiative forcing due to the wetlands CH4 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 (~36 Tg CH4 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 feed back radiatively onto the climate.

![Figure 2](image-url)  
**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).

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

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![Figure 3](image-url)  
**Figure 3.** Climate change predictions of enhanced land averaged temperature and total wetland CH4 emissions from IMOGEN using different wetland temperature responses. The control experiment has $Q_{10}(T_0) = 4.0$, $\sum F_{CH4} = 325$ Tg CH4 yr$^{-1}$ with no CH4 radiative feedback (CTL) (solid line). The following scenarios include CH4 radiative feedback and modelled, interactive wetland area, with $Q_{10}(T_0)$ and $\sum F_{CH4}$ (Tg CH4 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 $Q_{10}(T_0) = 4.0$, $\sum F_{CH4} = 325$ Tg CH4 yr$^{-1}$ (diamonds).
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 ~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

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 project increase, but an assessment of this risk requires a better mechanistic understanding of 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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References


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