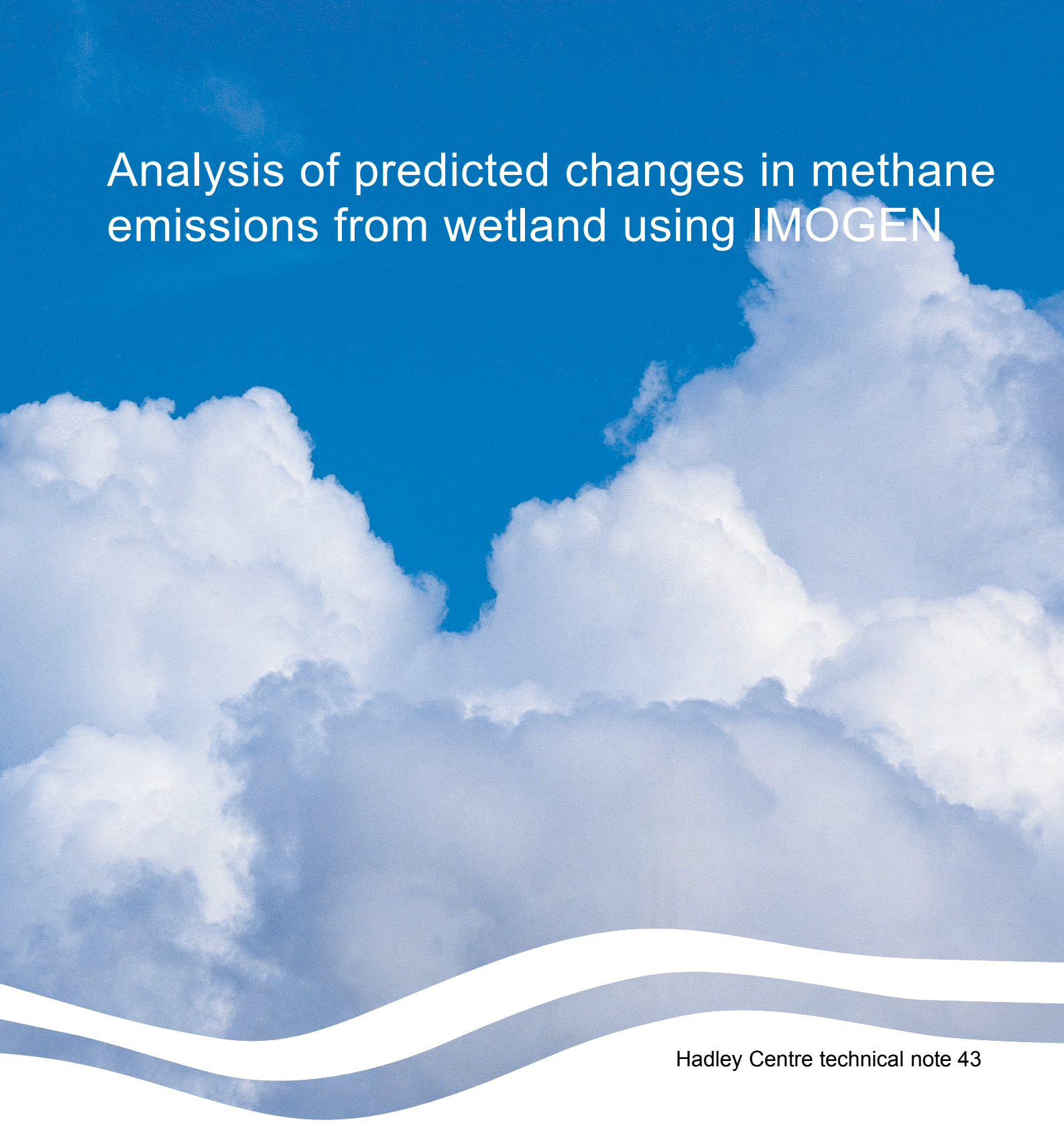
Analysis of predicted changes in methane emissions from wetland using IMOGEN



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Abstract

The wetlands model is constrained by investigating its ability to predict the interannual variability in methane (CH_4) concentration offline between 1984-1999. Model parameters are varied such that the global annual methane flux and the model's sensitivity to temperature are within the current estimated uncertainty. An integrated climate change effects model "IMOGEN" is used to simulate the effects of transient climate on methane emissions. It is adapted further to include the interactive radiative effects of changes in natural methane emission, to investigate their possible feedbacks on climate change. A number of IMOGEN runs are carried out from present day to 2100. The wetlands model is modified such that the bounds of uncertainty in biogenic methane emissions are covered. Under the most extreme wetland response considered the feedback is as large as the anticipated increase in anthropogenic CH_4 emissions, but it still contributes only of the order of 6% of the total anthropogenic climate change by 2100 under the IS92a scenario.

1 Introduction

Work under Annex 13 of the DEFRA Climate Prediction Programme ("Physical, Chemical and Biological Effects of Climate Change") is motivated in part by the need to provide consistent interactive estimates of processes which may produce significant climate feedback.

The ultimate aim is to calculate these effects "online" within the GCM to ensure consistency with the predicted climate change. Prior to this, "IMOGEN" (Integrated Model of Global Effects of climatic aNomalies) provides an environment for examining sensitivities to climate forcing and feedback.

Methane emission from wetlands can potentially produce such a feedback. The tundra ecosystems are a huge soil carbon store, which could be released through enhanced anaerobic decomposition under anthropogenic climate change. Methane is currently the second largest contributor to the anthopogenic greenhouse effect (IPCC (2001)). Even though wetlands are currently the largest single source of CH_4 emissions, there is considerable uncertainty in their magnitude. Table 1 lists the estimates of CH_4 emissions from wetlands and rice paddies made in preious budget studies (based on table 4.2 of the IPCC TAR). Present day estimates from inverse models vary 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 significant and highly uncertain (25-100 Tg CH_4 yr^{-1} (IPCC (2001))).

Two general methods are employed for estimating global wetland emissions: "top-down" and "bottom-up" approaches. "Top-down" methodologies use an inverse model to derive the emission

Study	**Wetland Emissions** Tg CH_4 yr^{-1}	**Rice Paddy Emissions** Tg CH_4 yr^{-1}	Total CH_4 Emissions Tg CH_4 yr^{-1}
Fung et al. (1991)	115	100	500
Hein et al. (1997)	237	88	587
Lelieveld et al. (1998)	225		600
Mosier et al. (1998)		25-54	
Olivier et al. (1999)		60	

Table 1: Previous estimates of methane emissions from wetlands and rice paddies (based on IPCC TAR table 4.2). Estimates of the total methane flux (natural plus anthropogenic) are shown for comparison.

estimates by best reproducing the observed atmospheric concentration (including seasonal, annual and geographical variations). "Bottom-up" approaches extrapolate small-scale measurements/models upto the global scale.

The three major controls of net methane emissions from wetlands are soil temperature (through micro-biological process rates), water table height (by determining the depth the methane generating and oxidising zones) and the amount and quality of the decomposable substrate.

a Uncertainty in the sensitivity of wetland emissions

As well as the large uncertainty in the current total wetland emissions, the sensitivity to temperature is also not well known. Table 2 lists the assumptions made in previous large-scale modelling studies. Walter and Heinmann (2000) cite observed values of Q_{10} varying from 1.7-16. (Q_{10} is the factor by which a reaction rate increases with a 10^o increase in temperature). The inverse modelling study of Fung *et al* (1991) use a Q_{10} value of 2 for natural wetlands and prescribes a constant value per rice harvest. However they have a very simplistic emission model, using monthly surface air temperature rather than soil temperature, and assuming that emission occurs when monthly mean precipitation exceeds potential evaporation. (In addition wetland area is held constant and taken from the Matthews and Fung (1987) observational dataset).

The inverse modelling study of Hein *et al* (1997) sets Q_{10} to 1.5. A value of 2 gives an unrealistic seasonal variation in the high northern latitudes. However, they again use a simple model based on air temperature.

The process-based model of Walter *et al* (2001a) has a Q_{10} =6, which agrees well with their four site studies in the high latitudes. However, in the tropical field study, Q_{10} was difficult to ascertain due to the small seasonal amplitude in temperature. (Walter *et al* (2001b) also run their model globally with a simple atmospheric box model. They force it with ECMWF reanalysis for the period 1982-93. It shows good agreement with the observed CH_4 interannual variability, whereas a Q_{10} value of 2 underestimates this).

In spite of these major differences in temperature sensitivity in the different approaches of Hein *et al* (1997) and Walter *et al* (2001a), they both estimate about 25% of the flux originating from the high-latitudes (>30^oN) in their global studies. This large discrepancy between the results of top-down (using a very simple emission model, but with complex atmospheric chemistry), and bottom-up approaches (with a physically based wetland emission model, but relatively simple atmospheric chemistry), needs to be resolved.

The Q_{10} factor commonly used to describe the temperature dependence of plant processes, is

Study	Q_{10} (0 ^{o}C)	Q_{10} (30 ^{o}C)
Fung et al. (1991)	2.0	2.0
Hein et al. (1997)	1.5	1.5
Walter and Heimann (2000)	1.7 - 16	
Walter et al. (2001a)	6.0	6.0
This study (best estimate, figure 2)	5.5	4.0

Table 2: Estimates of the temperature sensitivity of methane emissions from wetland at 0^oC and 30^oC. The Q_{10} value is the factor by which the emission rate is assumed to increase for each 10^oC warming.

only strictly valid over limited temperature ranges, and is a simplification of the Arrhenius equation. Thornley and Johnson (1990) (Chapter 5) describe the Arrhenius theory in detail. It is based on the fact that for an irreversible, exothermic chemical reaction to occur, a molecule must have a high enough energy to reach a higher transient energy state E_a. From the Boltzmann distribution, the proportion of molecules with this energy increases with temperature. Arrhenius' equation is derived from this, giving a rate constant k for the reaction as:

$$k \propto \exp(\frac{-E_a}{RT}) \tag{1}$$

The commonly used Q_{10} factor is based on the observation that a given temperature increment often increases the reaction rate by the constant factor such that:

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

where k_r is the rate constant at the reference temperature T_0. Using a Taylor expansion about the reference temperature, it can be shown that equations 1 and 2 are in good agreement over a limited temperature range. Hence:

$$\exp(\frac{-E_a}{RT}) \propto Q_{10}^{T/10} \tag{3}$$

and therefore Q_{10} is actually dependent on temperature:

$$Q_{10}(T) = Q_{10}(0)^{T_0^2/T^2} \tag{4}$$

For a value of Q_{10} of about 2 at 275K, Q_{10} varies little (1.8 at 305K), whereas a Q_{10} value of 12 at 275K reduces to 7.5 at 305K. However in most global wetland methane studies the temperature dependency of Q_{10} is ignored.

b Interannual Variability

Global methane emissions have remained nearly constant during 1984-96. The observed long-term decrease in growth rate is consistent with constant CH_4 emissions and lifetime in a system approaching chemical steady state (Dlugokencky *et al* (1998)). An anomaly in atmospheric CH_4 concentration occurs in 1998 during the observational period of 1984-1999, with the following year seeing the return to values more typical to the rest of the observation period (Dlugokencky *et al* (2001)). The source-sink imbalance rose from 11 Tg CH_4 (1995-1997) to 35 TgCH_4 in 1998. Biomass burning (large fires in Siberia and Indonesia) is likely to have made a only small contribution to this anomaly ($\sim$ 5.7 Tg

CH_4). A major likely cause is the enhancement on wetland emissions, as 1998 is the warmest year in this period.

To investigate this Dlugokencky *et al* (2001) adapts the global processed-based model [Walter (1998), Walter *et al* (2001b)] and forces it with the NCEP anomalies in soil temperature and precipitation for 1998 and 1999, based on the 1980-1999 climate mean. In common with the studies to date, the model also uses a non-interactive definition of wetland distribution (usually Matthews and Fung (1987)). The model reproduces the 1998 anomaly well, but the authors caution that the global mean estimate is higher than many other current estimates.

2 Methodology

a Wetlands emission model

We have developed a simple methane emission model which can be run within IMOGEN and the GCM (see Gedney and Cox (2001)). It is run in conjunction with MOSES II, and an improved large-scale hydrology model (Gedney and Cox (1999)) which predicts wetland area interactively. In brief, we parameterise the methane flux from wetlands as follows:

$$F_{CH4} = f(T_{soil}) k_{CH4} f_{wetl} C_s Q_{10}(T)^{(T_{soil})/10} \tag{5}$$

where f_{wetl} is the wetland fraction, k_{CH4} is a global constant, C_s is the soil carbon in kgC m^{-2}, Q_{10} (T) is taken from equation 4, T_{soil} is the soil temperature in Kelvin meaned over the top metre, and $f(T_{soil})$ is the step function taking the value of 1 when $T_{soil} > 273.15K$ and 0 for $T_{soil} \leq 273.15K$. k_{CH4} is calibrated to give the required global methane flux.

b Constraining the model parameters

If we assume that the atmospheric CH_4 variability is dominated by natural variability in the source (rather than atmospheric lifetime or anthropogenic emissions), then we can investigate how well our wetlands model fits the observations. A simple lifetime model can be used to predict the atmospheric CH_4 concentration such that:

$$\frac{dCH_4}{dt} = F_{CH4} + F_{CH4}^{anthr} - \frac{CH_4}{\tau} \tag{6}$$

where F_{CH4}^{anthr} is the flux due to anthropogenic emissions and τ is the atmospheric lifetime of methane which is set to 8.9yrs (Prinn *et al* (1995)). We invert this to infer the F_{CH4} flux variability.

The observed monthly surface air temperature anomalies for the period 1984-1999 (as a surrogate for the top 1m soil temperature) are added to the current climatology to predict wetland emissions and used to force the methane model (equation 5) offline. The observed wetland area of Aselmann and Crutzen (1989) is used to estimate the wetland fraction required for equation 5.

The Q_{10} values for the field of seasonal temperature over the wetland, for a given Q_{10} at 273.15K value are then calculated. (We assume natural wetlands and paddy fields have the same behaviour for simplicity). The modelled time series of global wetland emission is then obtained by rescaling k_{CH4} to give the required long-term global mean.

Figure 1 shows an example of the predicted deviations in atmospheric concentration from the multi-annual mean. This analysis assumes a Q_{10} value of 8 at 273.15K and a long term mean total wetland emission of 325Tg CH4 yr^{-1}. The figure shows a correlation between the observed globally averaged surface air temperature anomalies and atmospheric methane anomalies, demonstrating the

importance of the temperature dependence of methanogenesis. This is picked up in the general ability of the simple model to reproduce the phase of the atmospheric CH_4 anomaly. As mentioned earlier not all the atmospheric variation can be attributed to wetland emission changes. The largest discrepancy between the model and observation is in 1991 and 1992.

The significant increase in atmospheric CH_4 in 1991 can be attributed to the reduction in OH radicals due to the large amount of dust released from the Mount Pinatubo eruption. The CH_4 decrease in the following year, could be related to reduced fossil fuel emissions in the former Soviet Union, and/or decreased emissions in the boreal regions from the cooler temperatures which followed after the eruption.

A GCM run with prescribed SSTs over this period is also analysed in a similar manner (but using the actual soil temperature). The model actually predicts wetland fraction thereby including the potential influence of seasonal and interannual variability in wetland extent on the atmospheric concentration. The GCM tends to reproduce the temperature trends reasonably well, particularly the 1998 El Nino. As expected the predicted methane fluxes, are less in phase with the observations. Fixing the wetland fraction to the multi-annual, annual mean (not shown) does not significantly alter the amplitude of the flux variability, indicating that at least in this model, the temperature is the primary driver of interannual variability.

Given the annual mean total wetland area (i.e. including paddy fields) CH_4 flux has been estimated to be between 215-325 Tg CH_4 /yr [Hein *et al* (1997), Walter *et al* (2001a), see table 1] and the Q_{10} value is also highly uncertain, we calculate the RMS error in the time series predicted using the observed surface temperatures for the likely range of these values.

Figure 2 shows this from the period of 1993-99. We ignore earlier years because the Mount Pinatubo eruption distorts the results. The figure shows that the highest global wetland emissions and a Q_{10} value of between 5-6 at 273.15K produce the lowest errors. However, there are not significantly larger errors over a fairly wide range of values.

c Future Predictions using IMOGEN

IMOGEN simulates the land-surface aspects of climate change driven by climate anomalies representative of those from a full General Circulation Model (GCM). Based on the "GCM Analogue Model" (Huntingford and Cox (2000), IMOGEN takes patterns of surface climate anomalies from a GCM and scales their magnitude according to greenhouse gas concentrations.

IMOGEN incorporates the MOSES II land surface scheme which is also a component of the coupled climate-carbon cycle GCM (Cox *et al* (2000)). IMOGEN now additionally includes a new large-scale hydrology module (Gedney and Cox (1999) which produces a diagnostic wetland area, which is required for CH_4 estimates.

We have further adapted IMOGEN by including a simple lifetime model of atmospheric CH_4 (see equation 5) so that any changes in wetland methane emissions feedback on the climate. A number of runs of IMOGEN are carried out from 1984 to 2100 using patterns of climate change from a HadCM3 simulation using the IS92a emissions scenario. The wetland model is tuned so that the total wetland emission in the first year of the run is set to the lowest and highest of the present day estimates (215 and 325 Tg CH_4 yr^{-1} respectively). We also investigate the effect of fixing Q_{10} and allowing it to vary with temperature (as defined in equation 4).

Figure 3 shows the predicted climate change using a number of different Q_{10} values and initial wetland emission values. The wetland emissions scenarios vary from Q_{10} =2 with no natural CH_4 radiative feedback (control) to the highest feedback potential considered (F_{CH4}=325 Tg CH_4 yr^{-1} and

a Q_{10} value fixed at 8). The temperature differences between the control and the other experiments are directly due to the wetland emissions radiative feedback. There is considerable difference in the predicted emissions by 2100, with the highest scenario predicting ~950Tg CH_4 yr^{-1}. The related increase of ~ 600Tg CH_4 in wetland emissions is similar in magnitude to the anticipated increase in anthropogenic CH_4 emissions. However even such a large increases in CH_4 emissions only corresponds to an enhancement of a land average surface air temperature of 0.25K, which is ~6% of the total predicted climate change. (There is only a small predicted increase in global wetland area of ~6% (not shown)).

3 Conclusions

We have applied our model of wetland methane emissions (Gedney and Cox (2001)), to estimate the importance of these emissions for 21st century climate change. The CH_4 emissions model was adapted to use a temperature-dependent Q_{10} value, based on the Arrhenius equation. The observed interannual variability in atmospheric CH_4 concentrations was used to provide a joint constraint on the present-day globally integrated methane emissions, and the temperature sensitivity of the wetland component (i.e. its Q_{10} value at 0°C). High values for both Q_{10} and the global CH_4 flux are most consistent with the observations, but there is still considerable uncertainty in both.

Transient climate change experiments were carried out using IMOGEN and a range of CH_4 parameters consistent with the observed interannual variability. These suggest that it is the temperature response and not the change in wetlands that will dominate the change in natural CH_4 emissions. The strongest possible wetlands response provides an increase in CH_4 emissions which is similar to that predicted to occur directly from anthropogenic activities (for example in the IS92A scenario total methane emissions go from 540 Tg CH_4 /yr in 2000 to 916 Tg CH_4 /yr in 2100). However, the corresponding radiative feedback is relatively small (~6%) when compared to the total anthropogenic GHG forcing anticipated for the 21st century.

We plan to constrain these estimates further using local measurement of wetland/tundra CH_4 emissions, and past climatic variations (e.g. the lower CH_4 concentration during the last glacial period).

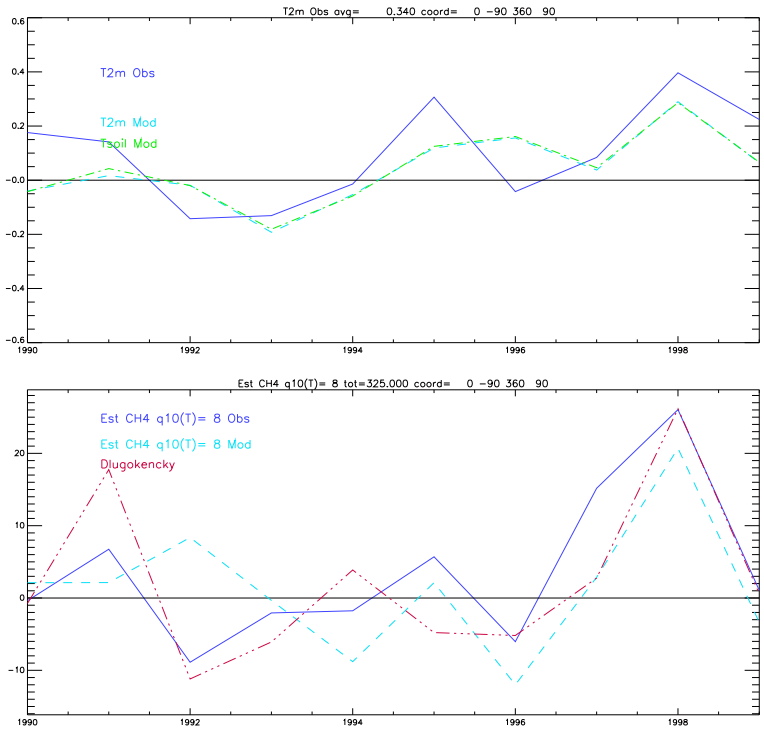

Figure 1: interannual variability of temperature and estimated methane emissions. The top figure shows the observed anomalies in surface air temperature (dark blue), those simulated in a GCM run (light blue) and the top 1m soil temperature anomalies simulated in the GCM run (green). The bottom figure shows the simulated surface methane emission anomalies as predicted by: inverting the variability in atmospheric concentration (red), the observed surface air temperature anomalies (dark blue) and surface air temperature anomalies simulated by the GCM (light blue).

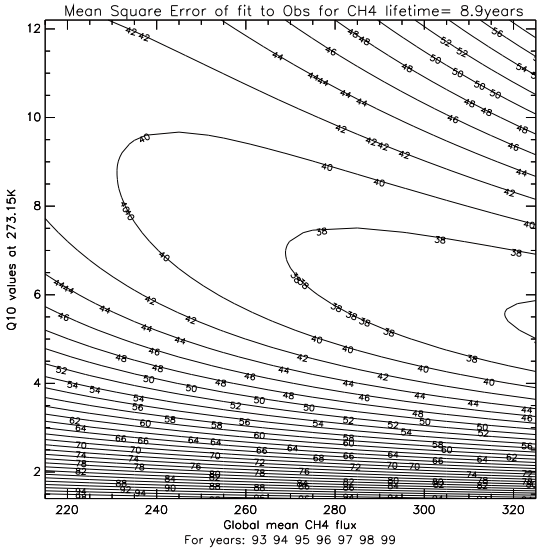

Figure 2: RMS errors when fitting estimated CH4 emissions against those infered from the observed atmospheric concentrations, with Q_{10} a function of temperature. (Values shown refer to those set at 273.15K).

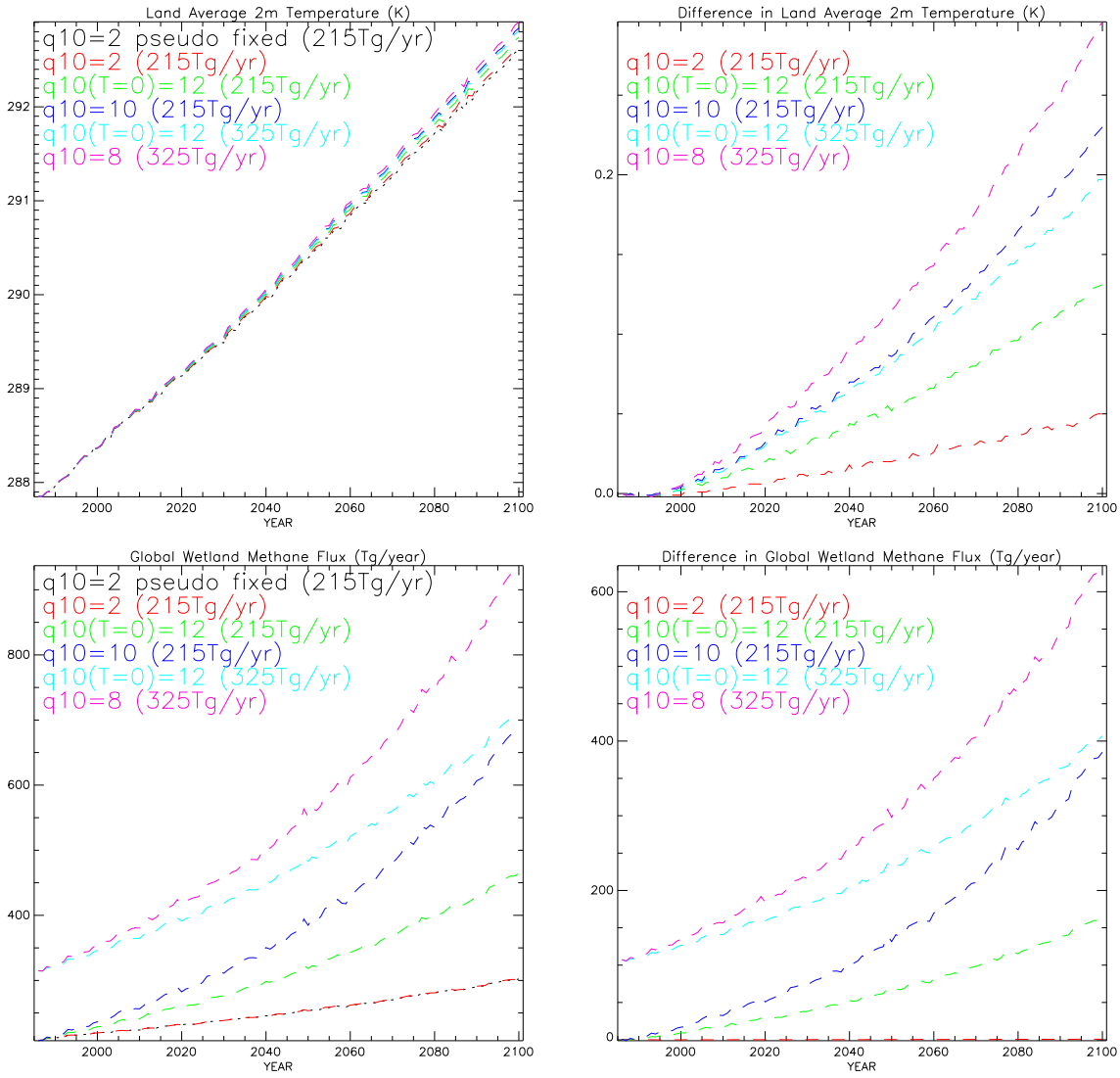

Figure 3: Climate change predictions of land averaged temperature and wetlands CH_4 emissions from IMOGEN using different wetlands model responses. The scenarios considered are: Q_{10} =2 with no radiative feedback (the control) (black line), Q_{10} =2 with radiative feedback and initial annual mean of 215Tg/yr (red line), Q_{10} (0)=12 at 273.15K with radiative feedback and initial annual mean of 215Tg/yr (green line), Q_{10} =10 with radiative feedback and initial annual mean of 215Tg/yr (dark blue line), Q_{10} (0)=12 at 273.15K with radiative feedback and initial annual mean of 325Tg/yr (light blue line) and the Q_{10} =8 with radiative feedback and initial annual mean of 325Tg/yr (red line). (The left hand graphs show all the scenarios considered. The right hand graphs show the difference between each scenario and control).

4 Acknowledgements

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