

Response of methane emission from arctic tundra to climatic change: results from a model simulation

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ABSTRACT

Methane is an important greenhouse gas contributing approximately 15% to the present greenhouse warming. Tundra ecosystems between 50°N and 70°N are estimated to contain 14% of the global soil carbon and account for between 20 and 25% of the natural methane emissions. Consequently, enhanced anaerobic decomposition of tundra soil carbon and the associated increase in methane production could provide a significant positive feedback on the anthropogenic greenhouse effect. This work is an attempt to quantify this feedback for arctic tundra. A model of permafrost thermodynamics and methane emission has been developed for inclusion in the UK Meteorological Office land surface scheme. This improved scheme was tested by driving it directly with surface meteorological observations and comparing the simulated methane emission to those observed during a field study on the North Slope of Alaska. Results are also presented from simulations carried out with the single column version of the Hadley Centre climate model, for both current conditions and a simple doubled carbon dioxide warming scenario. The latter shows a significantly enhanced methane emission. In order to assess the dependence of this result on the particular scenario chosen, offline sensitivity studies were carried out using meteorological observations and a range of perturbations to air temperature and rainfall.

1. Introduction

Although climate simulations carried out using the current generation of General Circulation Models (GCM's) differ in detail, there is general agreement that; (a) increasing atmospheric concentrations of greenhouse gases will cause a global climate warming and (b) that this warming will be especially pronounced in northern high latitudes (IPCC, 1992). Terrestrial ecosystems have the potential to provide a feedback on this warming by associated changes in the natural emissions of greenhouse gases. Of particular significance are the tundra ecosystems between 50°N and 70°N which contain about 14% of global soil carbon

(Post et al., 1982) and are estimated to contribute 20%–25% of the global natural methane emissions (Fung et al., 1991). It has been suggested that the enhancement of methane emission from tundra could lead to a significant positive climatic feedback (Guthrie, 1986; IPCC, 1990), but this depends largely on the soil moisture regime continuing to favour anaerobic rather than aerobic decomposition.

There is qualitative agreement in the literature on the relationship between tundra trace gas fluxes and the soil climate (Fig. 1). A warmer-wetter soil will probably increase methane emissions, whilst a warmer-drier soil might decrease methane emission and possibly change the tundra from a carbon sink to a net source of CO₂. However, given the range of factors which appear to determine methane emission from tundra (Bartlett et al., 1992; Morrissey and Livingston, 1992; Whalen

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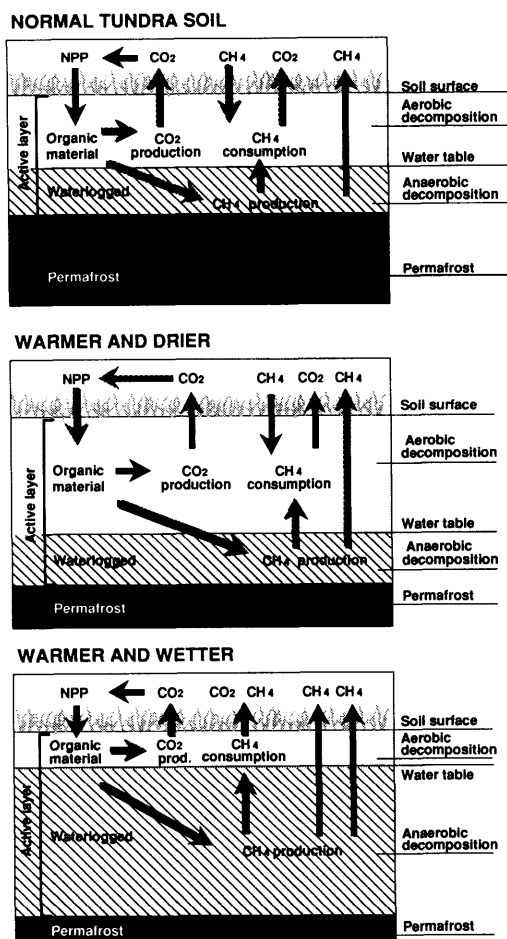


Fig. 1. General hypothesis for the response of tundra exchange with the atmosphere of methane and carbon dioxide, following two scenarios of climate change. A black arrow indicates a surplus relative to a hatched arrow in the opposite direction (modified from Christensen, 1991).

and Reeburgh, 1992; Christensen, 1993), few predictive models have been developed. This paper describes one attempt to model observed methane emissions, and explores the response of the modelled methane fluxes to various climate change scenarios.

2. The permafrost model

For investigations of climate change due to increased greenhouse gas concentrations, GCM's

have generally been run with simple representations of the upper ocean and recently with more detailed dynamical models of the ocean to its full depth (IPCC, 1992). Relatively simple schemes for interactive land surface temperature and soil moisture are also included. Representations of other elements of the climate system like land-ice and biosphere have usually been included as non-interactive components. The UK Meteorological Office land surface scheme has recently undergone improvements by the inclusion of multi- rather than single-layer soil hydrology and also, as part of the present project, by the introduction of permafrost thermodynamics and soil water phase changes (manuscript in preparation).

The model's hydrology and thermodynamics are based on vertically discretised forms of Richards' equation of fluid flow in a porous medium and Fick's law of heat diffusion. Soil-water phase changes are parametrised in terms of a simple dependence of maximum unfrozen water on temperature (Williams and Smith, 1989), thereby simulating the observed phenomenon of unfrozen water existing at temperatures below 0°C (Williams and Smith, 1989). Latent heat effects are included through an effective (temperature dependent) heat capacity. The hydraulic conductivity and soil water suction are parametrised in terms of the unfrozen soil water only (Black and Tice, 1988). In this way, the simulated frozen soils exhibit the observed properties of low hydraulic conductivity and strong water suction. The model can be used with an arbitrary number of soil layers, but the results below were produced using four soil layers with thicknesses (from the surface downwards) of 3.5 cm, 13.5 cm, 48.5 cm and 154.2 cm. These layer thicknesses were originally chosen so as to optimise the response of the soil temperature model to sinusoidal forcing with periods ranging from half a day to ten years. They are retained for consistency with the current UK Meteorological Office land surface scheme. The total depth (of about 2.2 m) should be interpreted as an "effective" soil depth, which must be sufficient to ensure negligible heat fluxes from the base of the model.

3. The methane model

Although methane emission from tundra is undoubtedly determined by a number of inter-

acting factors, recent studies suggest that soil temperature, soil moisture and thaw depth are the dominant controls (Christensen, 1993; Dise et al., 1993; Christensen and Cox, 1994). In order to incorporate these effects into a predictive model a simple mechanistic approach was taken.

Production and consumption were assumed to have the same standard microbial " Q_{10} " temperature dependencies. This is inaccurate from a microbiological point of view since most studies of methanogenic bacteria show higher Q_{10} dependencies than those of methanotrophic (Dunfield et al., 1993). However, large variations in Q_{10} values have been found depending on temperature, moisture (Svensson, 1980) and substrate quality (Valentine et al., 1994), and no specific studies of the microbial populations concerned are available from the area where the emission data used as validation was obtained. Also, rather than attempting to produce a specific microbiological model for a particular site, the aim of this work was to make a broader ecosystem-type model. The most simple and general temperature dependencies mentioned above were therefore adopted.

Fractional saturation was used as the moisture constraint on methane production and consumption. The maximum thaw depth was considered a lower limit for microbial activity in the soil. All unfrozen soil layers were given the same potential for decay, which is probably unrealistic considering the different decay potentials with depth shown in comparable environments (Hogg et al., 1992; Hogg, 1993). A higher methane production potential is normally associated with the upper soil layers which have a larger density of root biomass (Svensson and Sundh, 1992). The UK Meteorological Office land surface scheme defines a "root-depth" which represents the depth of soil from which water can be extracted by plants. In the future it may also be interpreted as a zone of increased decay potential ("productivity").

The parametrisation developed for this study is based on the assumption that each soil layer can behave as a methane-producing or methane-consuming unit depending on its temperature and moisture content. Layers which contain more than half the saturation soil moisture are treated as net emitters, whilst those with less than half are net consumers. As mentioned above, the microbial temperature dependence is the commonly used " Q_{10} " for layers which are unfrozen, while par-

tially-frozen layers ($T < 0^{\circ}\text{C}$) are assumed to be passive (zero net emission). Thus the model of net soil methane flux, F_{CH_4} , takes the simple form:

$$F_{\text{CH}_4} = \sum_{i=1}^N f(T_i) \{2\Theta_i - 1\} (k_i \Delta z_i) Q_{10}^{(T_i - 2)/10},$$

where Θ_i is the fractional saturation of the i th soil layer, T_i is the temperature in $^{\circ}\text{C}$ of the i th soil layer, N is the total number of soil layers (4 in this case), and $f(T_i)$ is the step function taking the value 1 for $T_i > 0^{\circ}\text{C}$ and 0 for $T_i < 0^{\circ}\text{C}$. k_i and Δz_i are the methane productivity and depth of the i th layer respectively. In the simulations presented here $Q_{10} = 2.0$. As discussed above, the choice of Q_{10} is a necessary generalisation but not out of line with observations in comparable environments (Svensson, 1983; Valentine et al., 1994). Note that decomposition is allowed to occur in all layers which have temperatures exceeding the freezing point of water. This restricts application of the model to areas where the organic layer depth always exceeds the maximum thaw depth (i.e., organic wet/moist tundra).

As shown by Christensen (1993) the methane emission increases during the thaw season as a function of degree days. Similarly, in this model the productivity, k_i , has a simple linear dependence on degree days:

$$k_i(\tau) = 50 \left\{ \alpha_i + \beta_i \int_0^{\tau} T_i dt \right\},$$

where $\alpha_i = 0.85 \text{ mg CH}_4 \text{ m}^{-3} \text{ day}^{-1}$ and $\beta_i = 0.00075 \text{ mg CH}_4 \text{ m}^{-3} \text{ day}^{-1} \text{ }^{\circ}\text{C}^{-1}$. The productivity is set at $50 \text{ mg/m}^3/\text{day}$ based on mean emission in the observations under "standard" conditions. Those conditions were the mean values of soil temperature, water table position, and thaw depth, at the sites and during the period where the methane flux data used for comparison with the model were obtained. With the chosen productivity and the mean environmental parameters the model produces a methane flux similar to the observed mean. Again, the productivity should ideally vary with depth. Also the similar conditions given to production and consumption could theoretically under extremely dry conditions give rise to unrealistic high rates of consumption. In order to avoid this, account would have to be taken of physical limitations on gas transport in the soil.

The field sites used for the comparison with the model are named "elevations" and details of how flux data were obtained at these and other sites are reported in Christensen (1993). The elevations consist of a variety of tundra plants including species of *Sphagnum*, *Carex*, *Eriophorum*, and small shrubs all characteristic of moist/wet tundra in the area. They possess physical characteristics similar to the idealised tundra soil in the model, i.e., a deep organic layer with water table fluctuating between the maximum thaw depth and the soil surface. The elevations represents a general tundra vegetation type which is widespread in most tundra environments as opposed to other tundra sub-units surveyed by Christensen (1993). Those other units were mostly associated with tussock tundra which in distribution is limited to western North America and eastern Siberia (Aleksandrova, 1980). Furthermore, during two seasons of flux measurements the elevations showed a mean emission of $31 \text{ mg/m}^2/\text{day}$ (Christensen, 1993) which is in accordance with emission measured in other recent studies of moist/wet tundra environments (Svensson and Roswall, 1984; Sebachner et al., 1986; Whalen and Reeburgh, 1990, 1992; Bartlett et al., 1992; Morrissey and Livingston, 1992).

4. Overview of model experiments

The following experiments have been carried out with the model.

(1) A local simulation of variations in methane flux between 15 June and 5 August 1991 using hourly weather observations of air temperature, precipitation, net radiation and wind speed obtained by the Long Term Ecological Research (LTER) Programme near Toolik Lake on the North Slope of Alaska. Results were compared with in situ observations of methane flux over the same period near Toolik Lake (Christensen, 1993). Unfortunately the length of the period of this validation run was constrained by the availability of consistent LTER weather data.

(2) A number of sensitivity experiments where the LTER weather data were manipulated with respect to input parameters air temperature and rainfall, creating warmer, colder, wetter and drier summers in various combinations.

(3) A regional 5-year simulation where the UK Meteorological Office single column model (SCM) (Dolman and Gregory, 1992) was forced with climatology for the North Slope of Alaska (68°N , 149°W) derived from UK Meteorological Office operational analyses (R. E. Essery, personal communication, 1993).

(4) As (3) but for $2 \times \text{CO}_2$ with an assumed warming in the climatological forcing.

5. Results

5.1. Stand-alone tests with LTER data

Fig. 2a shows a comparison between measured and simulated methane fluxes from model experiment (1). The measured soil environment (soil temperature, water table and thaw depth) was reproduced to within an error of about 10% by the model. Fig. 2b shows measured and modelled soil temperatures.

Fig. 2a shows a reasonable agreement between modelled and real data with a slightly more extreme variation in the observations. Most of the model run falls within the standard error of the observations. A linear regression analysis of the two data sets based on the days of observations show $r^2 = 0.75$ ($p = 0.0001$; $n = 15$). The mean values are very similar, 24.5 and $25.7 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ for the observed and modelled data respectively. This similarity is obviously influenced by the fact that the chosen productivity was based on the data used for validation. However, if the model did not reproduce the temporal fluctuations in methane flux satisfactorily, the similarity in mean fluxes would be hindered. Still, the validation of the model lies mostly in the modelled temporal fluctuations rather than in the scale of emission. The model run presented in Fig. 2 provided some confidence that despite the simple approach taken the model does seem to integrate the main controlling factors in a realistic way.

The stand-alone version of the model was then manipulated with respect to air temperature and precipitation. Air temperature was increased and decreased by 4°C . Versions with unchanged and warmer air temperatures were combined with changes in precipitation varying from a 50% decrease to a 50% increase in rainfall.

With a 4°C increase in air temperature the thaw depth increased by 11%. This effect varied

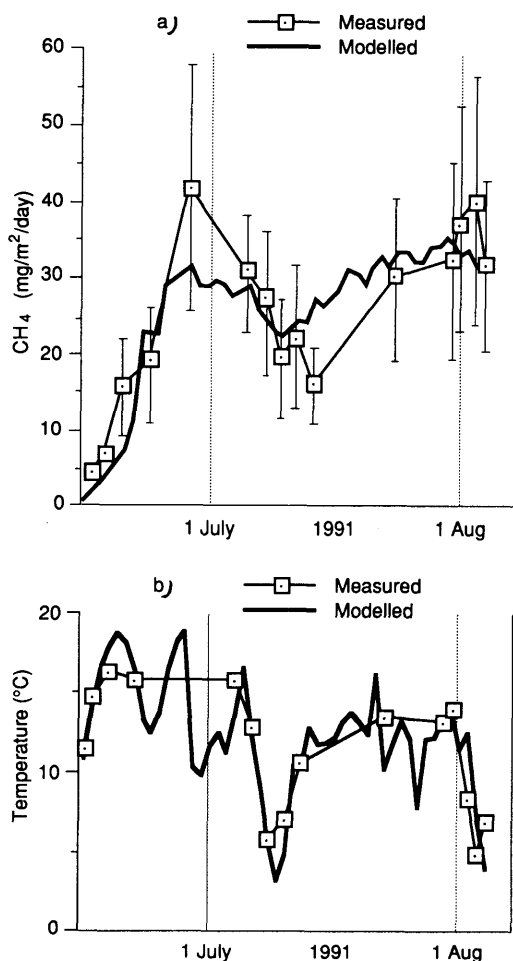


Fig. 2. Methane flux (a) and soil temperature at 5 cm depth (b) at arctic tundra sites near Toolik Lake on the North Slope of Alaska between 15 June and 5 August 1991 as measured in the field and simulated by the model (bold line). The bars indicate the standard error in the mean of flux observations ($n = 3$).

little with different precipitation changes. A 4°C decrease in air temperature caused a 23% shallower active layer and periodical surface freezing during the cold period in early July. The fluctuating water table was directly correlated with the varying precipitation. The model did not produce significant variations in the thaw depth as a consequence of precipitation changes, which caused methane emission to be linearly correlated with fractional precipitation (Fig. 3). Fig. 3 shows the mean methane emission in two temperature

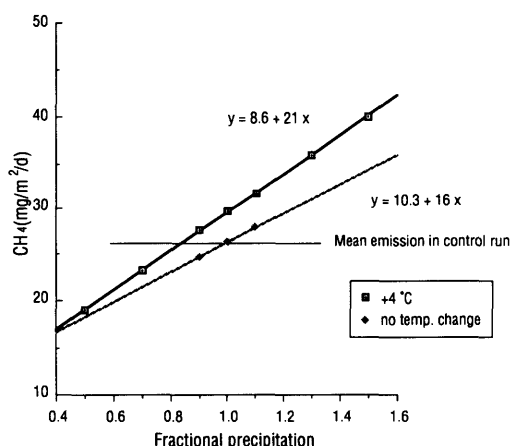


Fig. 3. Mean methane emission output from the stand-alone model driven with manipulated LTER weather data (see text).

scenarios (0 and $+4^{\circ}\text{C}$ changes) as a function of fractional precipitation.

Fig. 3 illustrates how the stand-alone version of the model predicts a 13% increase in methane emission with a 4°C temperature increase and no change in precipitation. Correspondingly, approximately 13% decrease in precipitation is needed for drying to outweigh the effect of air warming and result in zero change in net emission. The model seems slightly more sensitive to precipitation changes under the warming scenario. With a 50% reduction in rainfall there is little difference in flux between the two temperature scenarios while at a 50% increase in precipitation warming produces about 17% higher flux. According to this version of the model a mean 4°C increase and 10% increase in precipitation would cause a 21% increase in methane emission. A similar warming but with a 10% decrease in precipitation would result in a 5% increase in emission.

5.2. 1-D atmosphere-permafrost simulations

Selected model variables from experiments 3 and 4 are shown in Fig. 4. It should be noted here that the thaw depth, active layer temperature and active layer soil moisture were not explicitly modelled, but diagnosed from the layer temperatures and moisture contents. Details are given in the figure caption. In experiment 3 ($1 \times \text{CO}_2$) the thaw depth reaches approximately 1 m which is slightly deeper than what is normally found in

tundra environments. The annual mean methane flux of $17 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ is within range of most recent field studies of tundra methane emission (Svensson, 1983; Bartlett et al., 1992; Whalen and Reeburgh, 1992; Christensen, 1993). The significant interannual variability in these experiments is produced by the random forcing of the single column model using the variances of temperature and dewpoint depression derived from the operational analyses (Dolman and

Gregory, 1992; R. E. Essery, personal communication, 1993). Years 2 and 5 (Fig. 4) show a relatively large mid-summer drying (i.e., lower active layer soil moisture) and a correspondingly reduced methane emission.

In the $2 \times \text{CO}_2$ experiment the mean air temperature used to force the single column model was increased by 4°C in the winter and 2°C in the summer (IPCC, 1990; IPCC, 1992). The resulting five year simulation is also shown in Fig. 4.

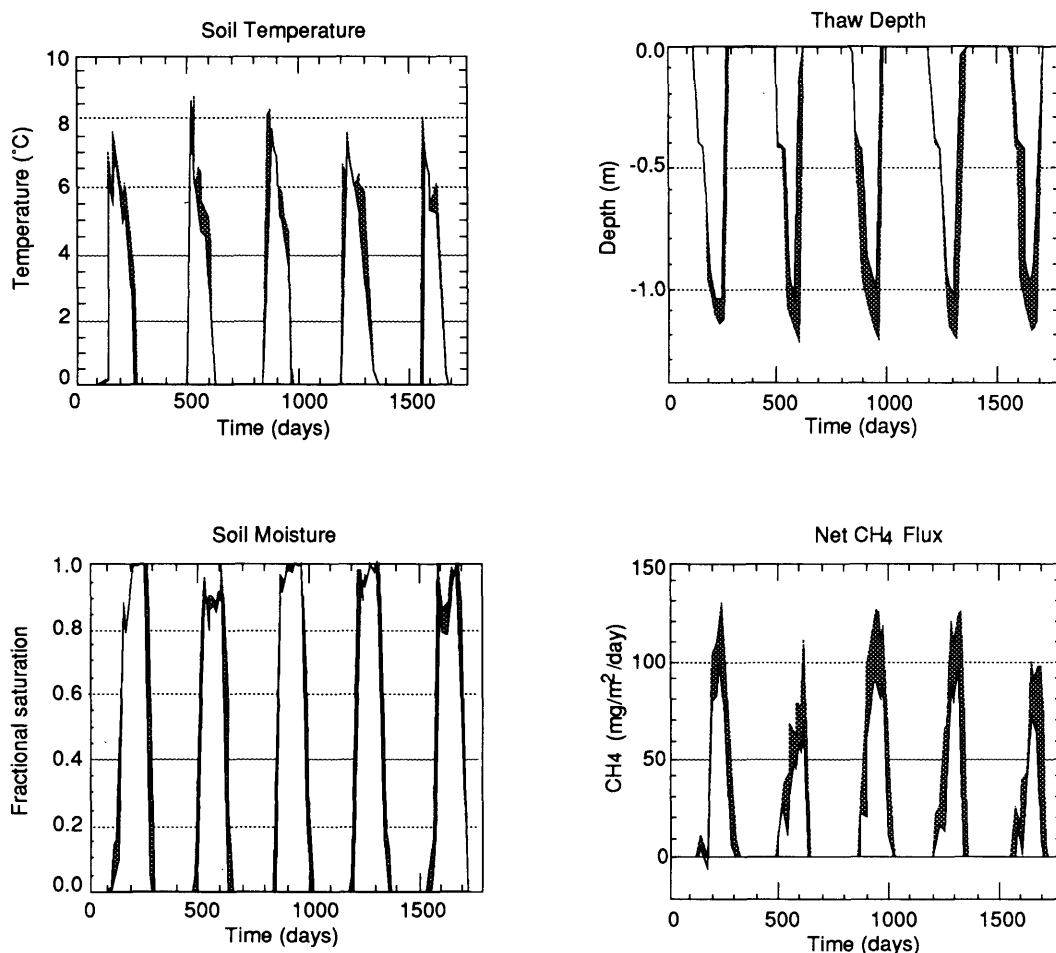


Fig. 4. Active layer temperature, thaw depth, active layer soil moisture (as a fraction of saturation) and net CH_4 flux from 5-year model runs using forcing data from the Meteorological Office operational analyses. Results from both the $2 \times \text{CO}_2$ and control ($1 \times \text{CO}_2$) experiments are shown, with the black lines encompassing white areas representing the control simulation and the stippled areas the increases which occur in the $2 \times \text{CO}_2$ experiment. The thaw depth is defined as the depth of the 0°C isotherm, whilst the soil temperature and soil moisture represent the (vertically integrated) mean values for the active layer, i.e., the layer from the surface to the 0°C level. All three take the value zero if the 0°C isotherm reaches the surface.

Table 1. 5-year means from the $1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ simulations

	$1 \times \text{CO}_2$	$2 \times \text{CO}_2$	$2 \times \text{CO}_2 - 1 \times \text{CO}_2$
precipitation (mm day ⁻¹)	1.63	1.93	0.30 (+18%)
surface temperature (°C)	-11.1	-7.1	4.0
active layer temperature (°C)	1.55	1.87	0.32 (+21%)
thaw depth (cm)	22.5	31.9	9.4 (+42%)
active layer soil moisture	0.298	0.349	0.051 (+17%)
methane emission (mg CH ₄ m ⁻² day ⁻¹)	17.1	26.6	9.5 (+56%)

The active layer soil moisture is expressed as a fraction of saturation and is the annual average, which means it includes the winter where very little unfrozen soil moisture is present.

Table 1 compares the 5-year means from model experiments (3) and (4). The increase in precipitation is largely due to the simple warming scenario assumed, i.e., a warming of the climatological temperature profile but no change in the profile of dew point depression. However, the resulting precipitation change is within the range of GCM predictions (IPCC, 1990; IPCC, 1992). The most striking difference occurs in the mean thaw depth which increases by 42% in the $2 \times \text{CO}_2$ experiment. This reflects both a deeper maximum thaw and a longer thaw season (Fig. 4). The latter is only partly responsible for the increases in active layer soil moisture and temperature. The combination of slightly warmer and moister soils with increased active soil volume leads to a 56% enhancement of methane emission in the $2 \times \text{CO}_2$ experiment.

6. Discussion

There are very few published models attempting to predict tundra methane emission response to climate change available for comparison. Roulet et al. (1992) used simple and separate hydrological and thermodynamical models for floating and non-floating northern fens to arrive at estimates for soil temperature and water table response to a warmer climate. They linked the responses to methane flux by separate relationships and estimated that temperature increase alone would increase fluxes by between 5% and 40% which is in accordance with the results presented in the sensitivity study above. Their model predicted a falling water table level following climate warming, and methane flux was highly sensitive to this, with a decrease in flux of up to 81% following a water

table that dropped from 8 to 22 cm below the peat surface. We did not see such dramatic changes in water table in our scenarios and thus not such extreme changes in flux. This may be due to our model being adapted to a permafrost environment with no vertical drainage and limited surface runoff.

Harriss et al. (1993) related methane emission to past temperature records for various northern wetland sites in an attempt to show the sensitivity to climatic anomalies. They mostly found rather modest interannual variations of 0–2 Tg/yr or 0%–12% of the total model flux. They note how these variations are unlikely to have influenced changing atmospheric concentration of methane over the past century and that climatic change will have to produce uniform increases in soil moisture over all northern wetland regions if these are to produce any significant feedback effect on greenhouse warming. During initial stages of such warming Harriss et al. postulate that regional differences in changes of the soil moisture regime will outweigh any significant contribution to further warming.

The SCM runs carried out in this study are probably more reliable than the stand-alone sensitivity tests. The stand-alone runs showed some sensitivity to the initial conditions which in some cases were difficult to estimate. Moreover, the SCM runs incorporate the effect of warming on the annual cycles, including those of a longer thaw season. However, the SCM only produced one warming scenario which makes the sensitivity of the model difficult to compare with other models. The results of the stand-alone version were therefore used in the following comparison.

The sensitivity results presented here disagree with the conclusions of Harriss et al. (1993)

and Roulet et al. (1992) in that a warming and (modest) drying in our model still produces a higher output of methane. Say that the tundra at present emits 35 Tg CH_4/yr as estimated by Fung et al. (1991). If 50% of the tundra experiences warming and a 10% increase in precipitation, and the other half warming and a 10% decrease in precipitation, then according to our model, total flux increase would be $17.5 \times 13\% = 20 \text{ Tg}$ plus $17.5 \times 5\% = 18 \text{ Tg}$ yielding a total of 38 Tg. Although this is a sizeable increase in global tundra flux, 3 Tg/yr represents less than 1% of the total atmospheric input. Such cavalier extrapolation can at best provide a framework in which to understand the magnitude of the predicted changes in local methane flux. Obvious limitations in this case are the assumption of uniform fractional changes in precipitation and temperature, and the failure to take account of different tundra types (see below). However, it does seem to support the general conclusion drawn by Harriss et al. (1993) that a significant feedback on global warming from increased methane emission can only be expected if soil moisture increases uniformly across the tundra region.

As mentioned earlier the modelled changes in emission following a changing climate are influenced heavily by the increasing thaw depth. This means the results derived from our model are sensitive to the assumption of uniform decay potential with depth. As discussed above, in reality the magnitude of the response may be limited by a reduction of decay potential in the deeper soil layers. This may account for part of the discrepancy between our results and those of Harriss et al. (1993) and Roulet et al. (1992).

In conclusion, we have developed a simple model of methane emissions from arctic tundra. Simplifications in the model imply that it is only strictly applicable to wet/moist tundra, which account for about one third of all tundra areas (Miller et al., 1983; Oechel and Billings, 1992).

When driven offline with meteorological data this model reproduces the variability in observed fluxes with reasonable accuracy. Sensitivity studies carried out using a range of climate change scenarios, suggest enhanced methane emissions from arctic tundra as a consequence of anthropogenic climatic warming. However, the magnitude of this enhancement is dependent on the local changes in soil water availability, as expected from various field and modelling studies (Svensson, 1983; Sebacher et al., 1986; Crill et al., 1988; Moore et al., 1990; Bartlett et al., 1992; Morrissey and Livingston, 1992; Whalen and Reeburgh, 1992; Christensen, 1993; Roulet et al., 1992, 1993; Harriss et al., 1993). Unfortunately, predictions of the geographical distribution of changes in soil moisture remain uncertain, implying that the increase in methane emission could amount to anywhere between 0 and 5% of the current global emission. A figure towards the upper bound would represent a significant positive feedback on anthropogenic climatic warming.

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REFERENCES

- Aleksandrova, V. D. 1980. *The Arctic and Antarctic: their division into geobotanical areas*. Cambridge University Press, Cambridge.
- Bartlett, K. B., Crill, P., Sass, R. C., Harriss, R. S. and Dise, N. B. 1992. Methane emissions from tundra environments in the Yukon-Kuskokwim Delta, Alaska. *J. Geophys. Res.* **97**, 16645–16660.
- Black, P. B. and Tice, A. R. 1988. *Comparison of soil freezing curve and soil water curve data for Windsor sandy loam*. US Army Cold Regions Research and

- Engineering Laboratory Report 88-16, Hanover, NH, US.
- Christensen, T. 1991. Arctic and sub-arctic soil emissions: possible implications for global climate change. *Polar Record* **27**, 205–210.
- Christensen, T. R. 1993. Methane emission from Arctic tundra. *Biogeochemistry* **21**, 117–139.
- Christensen, T. R. and Cox, P. 1994. Modelling response of methane emission from arctic tundra to climatic change: an overview of relevant controlling factors. In: *Proceedings of the Global Change and Arctic Terrestrial Ecosystems Conference*, Oppdal, Norway, August 1993 (ed. Callaghan, T.). Ecosystems Research Report, Commission of the European Community, in press.
- Crill, P. M., Bartlett, K. B., Harriss, R. C., Gorham, E., Verry, E. S., Sebach, D. I., Madzar, L. and Sanner, W. 1988. Methane flux from Minnesota peatlands. *Global Biogeochem. Cycles* **2**, 371–384.
- Dise, N. B., Gorham, E. and Verry, E. S. 1993. Environmental factors controlling methane emissions from peatlands in Northern Minnesota. *J. Geophysic. Res.* **98**, 10583–10594.
- Dolman, A. J. and Gregory, D. 1992. The parametrization of rainfall interception in GCMs. *Quart. J. R. Met. S.* **118**, 455–467.
- Dunfield, P., Knowles, R., Dumont, R. and Moore, T. R. 1993. Methane production and consumption in temperate and subarctic peat soils: response to temperature and pH. *Soil Biol. Biochem.* **25**, 321–326.
- Fung, I., John, J., Lerner, J., Matthews, E., Prather, M., Steele, L. P. and Fraser, P. J. 1991. Three-dimensional model synthesis of the Global methane cycle. *J. Geophysic. Res.* **96**, 13033–13065.
- Guthrie, P. D. 1986. Biological Methanogenesis and the CO₂ greenhouse effect. *J. Geophysic. Res.* **91**, 10847–10851.
- Harriss, R., Bartlett, K., Froking, S. and Crill, P. 1993. Methane emissions from northern high-latitude wetlands. In: *Biogeochemistry of global change: radiatively active trace gases* (ed. Oremland, R. S.). Chapman & Hall, New York.
- Hogg, E. H. 1993. Decay potential of hummock and hollow Sphagnum peats at different depths in a Swedish raised bog. *Oikos* **66**, 269–278.
- Hogg, E. H., Lieffers, V. J. and Wein, R. W. 1992. Potential carbon losses from peat profiles: effects of temperature, drought cycles, and fire. *Ecol. Appl.* **2**, 298–306.
- IPCC, 1990. *Climate change*. The Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment. Cambridge University Press, Cambridge.
- IPCC, 1992. *Climate change 1992*. The supplementary Report to The IPCC Scientific Assessment. Cambridge University Press, Cambridge.
- Miller, P. C., Kendall, R. and Oechel, W. C. 1983. Simulating carbon accumulation in northern ecosystems. *Simulation* **40**, 119–131.
- Moore, T. R., Roulet, N. and Knowles, R. 1990. Spatial and temporal variations of methane flux from subarctic/northern boreal fens. *Global Biogeochem. Cycles* **4**, 29–46.
- Morrissey, L. A. and Livingston, G. P. 1992. Methane Emission from Alaska Arctic Tundra: An Assessment of Local Spatial Variability. *J. Geophysic. Res.* **97**, 16661–16670.
- Oechel, W. C. and Billings, W. D. 1992. Effects of Global Change on the Carbon Balance of Arctic Plants and Ecosystems. In: *Arctic ecosystems in a changing climate. An ecophysiological perspective* (ed. Chapin, F. S., Jefferies, R. L., Reynolds, J. F., Shaver, G. R., and Svoboda, J.). Academic Press, San Diego.
- Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G. 1982. Soil carbon pools and world life zones. *Nature* **298**, 156–159.
- Roulet, N., Moore, T., Bubier, J. and Lafleur, P. 1992. Northern fens: methane flux and climatic change. *Tellus* **44B**, 100–105.
- Roulet, N. T., Jano, A., Kelly, C. A., Klinger, L., Moore, T. R., Protz, R., Ritter, J. A. and Rouse, W. R. 1993. Role of the Hudson Bay lowland as a source of atmospheric methane. *J. Geophysic. Res.* **99**, 1439–1454.
- Sebach, D. I., Harriss, R. C., Bartlett, K. B., Sebach, S. M. and Grice, S. S. 1986. Atmospheric methane sources: Alaskan tundra bogs, an alpine fen, and a subarctic boreal marsh. *Tellus* **38B**, 1–10.
- Svensson, B. H. 1980. Carbon dioxide and methane fluxes from the ombrotrophic parts of a subarctic mire. In: *Ecology of a subarctic mire* (ed. Sonesson, M.). Swedish Natural Science Research Council, Stockholm.
- Svensson, B. H. 1983. *Carbon fluxes from acid peat of a subarctic mire with emphasis on methane*. Department of Microbiology, Swedish University of Agricultural Sciences, Uppsala. Report no. 20.
- Svensson, B. H. and Roswall, T. 1984. In situ methane production from acid peat in plant communities with different moisture regimes in a subarctic mire. *Oikos* **43**, 341–350.
- Svensson, B. H. and Sundh, I. 1992. Factors affecting methane production in peat soils. *Suo* **43**, 183–190.
- Valentine, D. W., Holland, E. A. and Schimel, D. S. 1994. Ecosystem and physiological controls over methane production in northern wetlands. *J. Geophysic. Res.* **99**, 1563–1571.
- Whalen, S. C. and Reeburgh, W. S. 1990. A methane flux transect along the Trans-Alaska Pipeline Haul Road. *Tellus* **42B**, 237–249.
- Whalen, S. C. and Reeburgh, W. S. 1992. Interannual variations in tundra methane emissions: A four-year time-series at fixed sites. *Global Biogeochem. Cycles* **6**, 139–159.
- Williams, P. J. and Smith, M. W. 1989. *The frozen earth*. Cambridge University Press, Cambridge.