

## Climate-CH<sub>4</sub> feedback from wetlands and its interaction with the climate-CO<sub>2</sub> feedback

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**Abstract.** The existence of a feedback between climate and methane (CH<sub>4</sub>) emissions from wetlands has previously been hypothesized, but both its sign and amplitude remain unknown. Moreover, this feedback could interact with the climate-CO<sub>2</sub> cycle feedback, which has not yet been accounted for at the global scale. These interactions relate to (i) the effect of atmospheric CO<sub>2</sub> on methanogenic substrates by virtue of its fertilizing effect on plant productivity and (ii) the fact that a climate perturbation due to CO<sub>2</sub> (respectively CH<sub>4</sub>) radiative forcing has an effect on wetland CH<sub>4</sub> emissions (respectively CO<sub>2</sub> fluxes at the surface/atmosphere interface).

We present a theoretical analysis of these interactions, which makes it possible to express the magnitude of the feedback for CO<sub>2</sub> and CH<sub>4</sub> alone, the additional gain due to interactions between these two feedbacks and the effects of these feedbacks on the difference in atmospheric CH<sub>4</sub> and CO<sub>2</sub> between 2100 and pre-industrial time (respectively  $\Delta\text{CH}_4$  and  $\Delta\text{CO}_2$ ). These gains are expressed as functions of different sensitivity terms, which we estimate based on prior studies and from experiments performed with the global terrestrial vegetation model ORCHIDEE.

Despite high uncertainties on the sensitivity of wetland CH<sub>4</sub> emissions to climate, we found that the absolute value of the gain of the climate-CH<sub>4</sub> feedback from wetlands is relatively low (<30 % of climate-CO<sub>2</sub> feedback gain), with either negative or positive sign within the range of estimates.

Whereas the interactions between the two feedbacks have low influence on  $\Delta\text{CO}_2$ , the  $\Delta\text{CH}_4$  could increase by 475 to 1400 ppb based on the sign of the C-CH<sub>4</sub> feedback gain.

Our study suggests that it is necessary to better constrain the evolution of wetland area under future climate change as well as the local coupling through methanogenesis substrate of the carbon and CH<sub>4</sub> cycles – in particular the magnitude of the CO<sub>2</sub> fertilization effect on the wetland CH<sub>4</sub> emissions – as these are the dominant sources of uncertainty in our model.

### 1 Introduction

Increased atmospheric CO<sub>2</sub> due to anthropogenic emissions is expected to lead to significant climate change in the 21st century (IPCC, 2007). Such climate change may indirectly affect the atmospheric CO<sub>2</sub> concentration by modifying the exchange of carbon between the atmosphere and the land and ocean. Several models have evaluated this climate-carbon cycle interaction, generally finding a positive feedback between climate change and the global carbon cycle (Friedlingstein et al., 2006). Methane (CH<sub>4</sub>) is a very efficient greenhouse gas, with a Global Warming Potential of 25 (for given time horizon to 100 years) (IPCC, 2007), and is currently the second anthropogenic greenhouse gas after CO<sub>2</sub>. Very few studies have investigated the potential feedback between CH<sub>4</sub> emissions by wetlands and climate.

CH<sub>4</sub> emissions from wetlands, the largest natural source in the present-day global CH<sub>4</sub> budget, are directly controlled by climatic conditions (e.g. Christensen et al., 2003). CH<sub>4</sub>



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emissions from wetlands depend on the global areal extent of wetlands (Ringeval et al., 2010; Bloom et al., 2010) and on the emission rate of these wetlands (e.g. Conrad, 1989; Fung et al., 1991). Both of these terms are controlled by, among other variables, soil temperature and hydrology. For instance, temperature controls the rate of methanogenesis, exerts a control on the quality and quantity of organic material substrate for CH<sub>4</sub> production and has an influence on the area of wetlands through control of surface evaporation and the soil water budget. There is a large uncertainty in current global wetland emissions (estimates range from 115; Fung et al., 1991 up to 237 TgCH<sub>4</sub> yr<sup>-1</sup>; Hein et al., 1997). Because the sensitivity of wetland CH<sub>4</sub> emissions to the environmental control factors is poorly understood, the behavior of wetland CH<sub>4</sub> emissions under future climate change (e.g. Updegraff et al., 2001) and the amplitude of the resulting climate-CH<sub>4</sub> emission feedback is far from being well understood.

Several studies have estimated changes in CH<sub>4</sub> emissions from wetlands under future climate change: e.g. Shindell et al. (2004) (hereinafter SWF04), Gedney et al. (2004) (hereinafter GCH04), Eliseev et al. (2008) (EMA08) and Volodin (2008) (V08). They all found an increase in CH<sub>4</sub> emissions despite differences in processes accounted for. GCH04 and EMA08 also estimated the resulting climate-CH<sub>4</sub> feedback and both found it to be relatively small. The additional warming induced by this feedback is small (e.g. only 3.7–4.9 % of the total projected warming by 2100 under the IS92a scenario found by GCH04). SWF04 accounts for changes in wetland area, using thresholds for variables they define as influencing wetland CH<sub>4</sub> emissions while GCH04 use a more realistic approach using a subgrid topographical model. EMA08 and V08 do not account for change in wetland extent. In these approaches, base CH<sub>4</sub> emissions are calculated using an empirical approach: parameterization for GCH04 and EMA08 and correlations between climate anomalies and wetland CH<sub>4</sub> emissions derived under current conditions for SWF04. With the exception of V08, none of these studies account for increasing CO<sub>2</sub> and its effect on plant productivity and hence on soil carbon available for methanogenesis. Similarly, they do not account for the climate change (driven by CO<sub>2</sub> or CH<sub>4</sub>) effect on soil carbon dynamics and hence on CH<sub>4</sub> emission rates. The strategy used by V08 is based on a more process-based approach which could allow accounting for these two effects but the contribution of each driver is not discussed.

In fact there is a tight coupling between the climate-CO<sub>2</sub> feedback and the climate-CH<sub>4</sub> feedback. As mentioned before, increasing atmospheric CO<sub>2</sub> has a direct concentration effect on wetland CH<sub>4</sub> emissions. Moreover, CO<sub>2</sub>-induced climate change will affect CH<sub>4</sub> emissions, and hence CH<sub>4</sub> concentration and climate. CH<sub>4</sub>-induced climate change will in turn affect the land and ocean CO<sub>2</sub> cycle and hence atmospheric CO<sub>2</sub> and climate. The combined effect of these two feedbacks (climate-CO<sub>2</sub> and climate-CH<sub>4</sub>) needs to be

explicitly accounted for in order to estimate the overall response of the coupled CO<sub>2</sub> cycle – CH<sub>4</sub> cycle – climate system.

Friedlingstein et al. (2003) expressed mathematically the magnitude of the climate-carbon cycle feedback using a gain formalism following Hansen et al. (1984). Here, we revisit this theoretical framework, first applying it to the climate-CH<sub>4</sub> gain in the absence of CO<sub>2</sub> perturbation; then generalizing it to the climate, CO<sub>2</sub> and CH<sub>4</sub> interactions. These gains and the interaction between the feedbacks are expressed as functions of sensitivity terms that we estimate from the values reported in the literature and from simulations performed with the ORCHIDEE global terrestrial carbon cycle model. Once these terms are estimated, we quantify the different gains and the increase of atmospheric CH<sub>4</sub> and CO<sub>2</sub> due to the feedbacks and their interactions.

## 2 Theoretical analysis

In the following, the climate-CH<sub>4</sub> emissions by wetlands feedback will be referred hereafter as “C-CH<sub>4</sub> feedback” as well as “C-CO<sub>2</sub> feedback” for climate-carbon cycle feedback (both terrestrial and oceanic) in the sense of Friedlingstein et al. (2006).

### 2.1 C-CH<sub>4</sub> feedback analysis

Similarly to the C-CO<sub>2</sub> feedback analysis by Friedlingstein et al. (2003), we assume that the coupling between CH<sub>4</sub> emissions by wetlands and the climate system can be linearized by the following set of equations:

$$\Delta\text{CH}_4 = F_{\text{MF}} + F_{\text{NAT}}^{\text{add}} - F_{\text{MA}}^{\text{add}} \quad (1a)$$

$$\Delta T = \alpha_{\text{M}} \Delta\text{CH}_4 \quad (2a)$$

where  $\Delta\text{CH}_4$  (in GtC) is the difference of CH<sub>4</sub> concentration in the atmosphere between a given time,  $t_1$ , and the initial state,  $t_0$ , defined here as the preindustrial state estimated at 1860.  $\Delta T$  (in K) is the change in global air temperature due to the change in CH<sub>4</sub> concentration. Equation (2a) can also be considered as a linearization of the more stringent, square root dependence between CH<sub>4</sub> radiative forcing and its concentration (IPCC, 2001).  $F_{\text{MF}}$  (GtC) represents the integral over the period since  $t_1$  of the anthropogenic emissions of CH<sub>4</sub>.  $F_{\text{NAT}}^{\text{add}}$  (GtC) represents the integral of the change in natural CH<sub>4</sub> emissions relative to the preindustrial emissions baseline. As the focus of this study is on wetlands, we assume here that  $F_{\text{NAT}}^{\text{add}}$  represents the change in CH<sub>4</sub> emissions by wetlands only. Even though other natural sources (such as biomass burning) are also climate dependent, and the general framework presented here applies to other CH<sub>4</sub> sources and sinks as well, we will focus only on the wetland component as assessment of climate-CH<sub>4</sub> feedbacks from all natural sources and sinks is beyond the scope of this paper.

The last term of Eq. (1a),  $F_{MA}^{add}$  (GtC), is the integral of the atmospheric sink of CH<sub>4</sub> through reaction with OH radicals (again relative to the preindustrial baseline) and closes the CH<sub>4</sub> budget. For the pre-industrial state, we assume here that CH<sub>4</sub> concentration was constant (apart from interannual to decadal variations), and hence natural sources were balanced by the atmospheric OH sink (and the minor soil sink neglected in Eq. 1a). Departure from that steady-state equilibrium can be represented by Eq. (1a), using a perturbation approach, accounting only for additional sources and sinks. The change in CH<sub>4</sub> emissions, integrated over time  $t_1-t_0$ , can be driven by a change in climate and by a change in CH<sub>4</sub> concentration. As in Friedlingstein et al. (2003), we use a single global  $\Delta T$  as a proxy for climate change. It is clear that a change in emissions could be also driven by changes in hydrology, and that regional variations in both the magnitude of  $\Delta T$  and hydrology will also occur, but we assume here that these other climate variables change would scale with global temperature.

The integral of additional natural sources of CH<sub>4</sub> is then expressed by:

$$F_{NAT}^{add} = \beta_M \Delta CH_4 + \gamma_M \Delta T \quad (3a)$$

where  $\beta_M$  (unitless) and  $\gamma_M$  (in GtC K<sup>-1</sup>) are the CH<sub>4</sub> flux sensitivities to the atmospheric CH<sub>4</sub> concentration and to climate, respectively. The  $\beta_M$  term results from the CH<sub>4</sub> atmospheric concentration affecting the CH<sub>4</sub> flux through its control on diffusion (via soil air or plants) from wetland soils to the atmosphere. The Eq. (3a) is constructed by analogy with that for CO<sub>2</sub> given by Friedlingstein et al. (2006, Eq. 7a). Even if the effect of increased atmospheric CH<sub>4</sub> concentration on concentration gradient between soil and atmosphere (and thus the value of  $\beta_M$ ) is presumed small (atmospheric concentration in CH<sub>4</sub>  $\sim$  1 % of wetland soil concentration), we keep it to be consistent with CO<sub>2</sub>. Although there is evidence that, at the site scale and on sub-annual timescales, an exponential dependence of CH<sub>4</sub> flux to temperature is observed (e.g. Christensen et al., 2003), Eq. (3a) here aims to represent the overall global response of wetlands to climate (not just temperature). To remain simple and comparable to the CO<sub>2</sub> framework, we thus assume that a linear relationship is appropriate. More investigations concerning (i) the relationship between global climate and global wetland CH<sub>4</sub> emissions and (ii) the range of temperature over which such a relationship may be valid are required. These investigations would be based, for instance, on long-term or interannual time scales.

Finally, the integral of the additional atmospheric sinks can be expressed by:

$$F_{MA}^{add} = \int_{t_0}^{t_1} \frac{\Delta CH_4(t)}{\tau} dt \quad (4a)$$

as the additional sink at each time step is assumed here to be equal to  $\frac{\Delta CH_4(t)}{\tau}$ , where  $\tau$  is the atmospheric lifetime of

CH<sub>4</sub>. We assume here that  $\tau$  is constant in time. There is a slight dependency of  $\tau$  on CH<sub>4</sub> concentration and on climate (IPCC, 1994) which is neglected here. In doing so, we de facto assume that there is neither year-to-year variability nor any trend in atmospheric OH concentration. Recent findings seem to indicate that global OH is quite stable (Montzka et al., 2011). In order to solve the set of Eqs. (1a) to (3a), one must linearize the sink term. Here by applying the mean value theorem, the integral of the changes of CH<sub>4</sub> sink over time (between the time  $t_1$  and preindustrial period  $t_0$ ) can be written as proportional to the change of CH<sub>4</sub> at time  $t_1$ .

$$F_{MA}^{add} = \mu \frac{\Delta CH_4}{\tau} (t_1 - t_0) \quad (4b)$$

with  $\mu$  considered here as a constant for a given scenario of CH<sub>4</sub> increase. For instance,  $\mu$  would be equal to 0.5 if CH<sub>4</sub> concentration increases linearly with time. For a given scenario of atmospheric CH<sub>4</sub> increase,  $\mu$  can be diagnosed as the ratio of the cumulative changes of CH<sub>4</sub> along the full length of the scenario to the change of CH<sub>4</sub> at the end of the scenario (equating the right members of Eqs. 4a and b).

Equation (1a) now reads:

$$\Delta CH_4 = F_{MF} + \beta_M \Delta CH_4 + \gamma_M \Delta T - \mu \frac{\Delta CH_4}{\tau} \Delta t \quad (1b)$$

We can now express the amplitude of the feedback using a “gain” as Friedlingstein et al. (2003) did for CO<sub>2</sub>. Combining Eqs. (2a) and (1b) we have:

$$\Delta CH_4^{COU} = \frac{1}{1 - g_M} \Delta CH_4^{UNC} \quad (5)$$

with

$$\Delta CH_4^{UNC} = \frac{F_{MF}}{(1 + \frac{\mu}{\tau} \Delta t - \beta_M)} \quad (6)$$

and

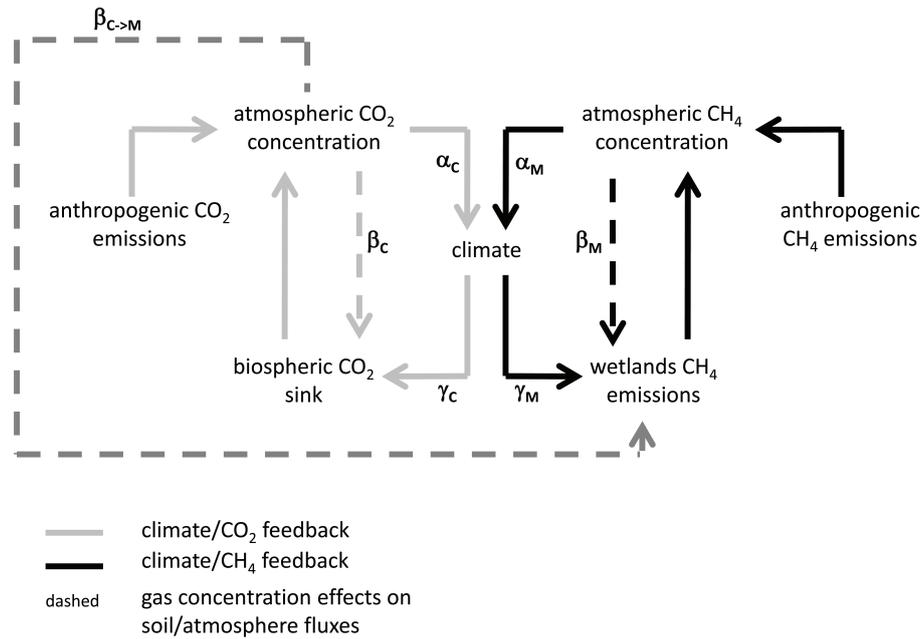
$$g_M = \alpha_M \gamma_M / \left(1 + \frac{\mu}{\tau} \Delta t - \beta_M\right) \quad (7a)$$

$\Delta CH_4^{COU}$  is the change of atmospheric CH<sub>4</sub> concentration in the case of C-CH<sub>4</sub> feedback while  $\Delta CH_4^{unc}$  is the change of atmospheric CH<sub>4</sub> concentration in the absence of C-CH<sub>4</sub> feedback (i.e.  $\gamma_M=0$ ).  $g_M$  is the gain of this feedback and it is larger if:  $\alpha_M$  and  $\gamma_M$  are positive and large and if  $\beta_M$  is positive and low. This is analogous to the C-CO<sub>2</sub> feedback gain defined in Friedlingstein et al. (2003) as:

$$g_c = -\alpha_c \gamma_c / (1 + \beta_c) \quad (7b)$$

## 2.2 Cross feedbacks

The previous feedback analysis was done for the case of a changing CH<sub>4</sub> concentration alone, together with climate. Here we extend the gain formalism in the more realistic case where both CO<sub>2</sub> and CH<sub>4</sub> vary at the same time.



**Fig. 1.** Schematic representation of the C-CO<sub>2</sub> feedback (light grey), the C-CH<sub>4</sub> feedback (black) and of their interaction. Gas concentration effects on the soil/atmosphere fluxes are represented by dashed lines. The different sensitivity terms ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) are listed on this schematic representation.

First, as mentioned before, both CO<sub>2</sub> and CH<sub>4</sub> will affect the climate through their radiative forcing.  $\Delta T$  should be now expressed as:

$$\Delta T = \alpha_C \Delta \text{CO}_2 + \alpha_M \Delta \text{CH}_4. \quad (2b)$$

As a consequence,  $F_{\text{NAT}}^{\text{add}}$  is affected by the change in climate (Eq. 3a) regardless of whether this climate change is induced by an increase in atmospheric CH<sub>4</sub> (as showed before) or by an increase in atmospheric CO<sub>2</sub>. The same applies to a climate-induced change in land CO<sub>2</sub> sinks. Interactions resulting from the Eq. (2b) will be referred to as the “*climate interaction*” below.

The second interaction comes from the dependence of CH<sub>4</sub> emissions to atmospheric CO<sub>2</sub>. Increasing atmospheric CO<sub>2</sub> is believed to enhance plant photosynthesis (fertilization effect) (e.g. Norby et al., 2005). As a result, rising CO<sub>2</sub> should increase the amount of available organic substrate for methanogenesis and hence CH<sub>4</sub> emissions from wetlands (see discussion). This effect is expressed by an additional term ( $\beta_C$ ) in the original Eq. (3a):

$$F_{\text{NAT}}^{\text{add}} = \beta_M \Delta \text{CH}_4 + \gamma_M \Delta T + \beta_{C \rightarrow M} \Delta \text{CO}_2. \quad (3b)$$

This interaction will be called the “*fertilization interaction*” hereafter.

The different sensitivity terms ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) are listed on a schematic representation of the feedbacks and of their interaction in Fig. 1.

Other minor interactions could be expressed between CO<sub>2</sub> and CH<sub>4</sub> (e.g. oxidation of CH<sub>4</sub> in atmosphere [EMA08] or

in the oxic part of wetland soils releases CO<sub>2</sub>) but these are not accounted for in our modelling approach below and are not quantified here.

One can introduce Eq. (2b) into Eq. (3b) then combine the resulting expression with Eq. (4b) into Eq. (1a) to obtain the following Eq. (8). Then, doing the same work for CO<sub>2</sub> (see Appendix A), we can obtain a two equations system with 2 unknowns ( $\Delta \text{CO}_2$  and  $\Delta \text{CH}_4$ ), i.e.

$$\begin{cases} -(\beta_{C \rightarrow M} + \gamma_M \alpha_C) \Delta \text{CO}_2 + (1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M - \gamma_M \alpha_M) \Delta \text{CH}_4 = F_{\text{MF}} & (8) \\ (1 + \beta_C + \gamma_C \alpha_C) \Delta \text{CO}_2 + \gamma_C \alpha_M \Delta \text{CH}_4 = F_{\text{CF}} & (9) \end{cases}$$

Using this system, we can express  $\Delta \text{CO}_2$  (and  $\Delta \text{CH}_4$ ) as a function of the integral of anthropogenic CO<sub>2</sub> and CH<sub>4</sub> emissions, i.e. respectively  $F_{\text{CF}}$  and  $F_{\text{MF}}$  (or  $\Delta \text{CO}_2^{\text{unc}}$  and  $\Delta \text{CH}_4^{\text{unc}}$ ; using Eq. (6) and its equivalent for CO<sub>2</sub>). We show in the following the CH<sub>4</sub> and CO<sub>2</sub> gains for the idealized (and simpler) case where  $\beta_{C \rightarrow M}$  is null (i.e. no fertilization interaction). This allows keeping symmetry between CO<sub>2</sub> and CH<sub>4</sub>. The more realistic case, accounting for this  $\beta_{C \rightarrow M}$  term and the introduced asymmetry is given in Appendix B. Although not shown until the Appendix, this term was taken into account in all the calculations of the next sections.

For the coupled climate-CO<sub>2</sub>-CH<sub>4</sub> system neglecting fertilization interaction, we obtain now:

$$\begin{aligned} \Delta \text{CH}_4^{\text{COU}} &= \frac{1}{1 - \left[ g_M + \frac{g_C g_M}{1 - g_C} \right]} \Delta \text{CH}_4^{\text{UNC}} & (10) \\ &+ \frac{1}{1 - \left[ g_M + \frac{g_C g_M}{1 - g_C} \right]} \frac{\alpha_C}{\alpha_M} \frac{g_M}{1 - g_C} \Delta \text{CO}_2^{\text{UNC}} \end{aligned}$$

and

$$\Delta\text{CO}_2^{\text{COU}} = \frac{1}{1 - \left[ g_C + \frac{g_C g_M}{1 - g_M} \right]} \Delta\text{CO}_2^{\text{UNC}} \quad (11)$$

$$+ \frac{1}{1 - \left[ g_C + \frac{g_C g_M}{1 - g_M} \right]} \frac{\alpha_M}{\alpha_C} \frac{g_C}{1 - g_M} \Delta\text{CH}_4^{\text{UNC}}$$

Equation (10) shows that the interaction between CO<sub>2</sub> and CH<sub>4</sub> results in an additional gain in the first term of the right hand side of the equation. For CH<sub>4</sub>, this additional gain is  $g_C g_M / (1 - g_C)$  and is in addition to the initial gain considering CH<sub>4</sub> alone,  $g_M$ . It represents the overall contribution on the CH<sub>4</sub> concentration of the positive climate-CO<sub>2</sub> feedback initiated by the original emission-induced change in CH<sub>4</sub> concentration (climate interactions loop) in the case of no CO<sub>2</sub> anthropogenic emissions, i.e. when  $\Delta\text{CO}_2^{\text{unc}} = 0$ .

If we then account for anthropogenic CO<sub>2</sub> emissions, an additional contribution to  $\Delta\text{CH}_4$  appears: the second term in the right hand side of the Eq. (10). This originates from the anthropogenic emissions of CO<sub>2</sub>, which induces an increase in the CO<sub>2</sub> concentration ( $\Delta\text{CO}_2^{\text{UNC}}$ ). This CO<sub>2</sub> increase induces a climate change that will affect CH<sub>4</sub> emissions and hence CH<sub>4</sub> concentrations. In Eq. (10),  $\Delta\text{CO}_2^{\text{UNC}}$  is multiplied by  $\frac{\alpha_C}{\alpha_M} \frac{g_M}{1 - g_C}$  to obtain its equivalent in  $\Delta\text{CH}_4$ . Finally, it is multiplied by the same net feedback factor as one in the front of  $\Delta\text{CH}_4^{\text{UNC}}$ . Anthropogenic emissions of CO<sub>2</sub> are independent of CH<sub>4</sub> and thus cannot be expressed as a function of  $\Delta\text{CH}_4$ . This prevents us from fully expressing the total additional gain of each feedback in the case of coupling between CO<sub>2</sub>, CH<sub>4</sub> and climate. Obviously, the same interpretation can be done to C-CO<sub>2</sub> feedback in presence of CH<sub>4</sub> with Eq. (11).

Changes in CO<sub>2</sub> and CH<sub>4</sub> can hence be computed from Eqs. (10) and (11), once the different sensitivity terms ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) are estimated. This is the aim of the next section.

### 3 Estimates of the gain components

In this section, we will first use simulations performed with ORCHIDEE, a dynamic global vegetation model (DGVM), to estimate the wetland emission sensitivity terms ( $\beta_M$ ,  $\beta_{C \rightarrow M}$  and  $\gamma_M$ ) as well as terms relative to C-CO<sub>2</sub> cycle. We will also make use of previous estimate of future changes in CH<sub>4</sub> emissions taken from the available literature. This will allow us to estimate the range of the climate-CH<sub>4</sub> gain and its effect on the projection of atmospheric CH<sub>4</sub>, CO<sub>2</sub> and global temperature (Sect. 4).

## 3.1 Based on an ORCHIDEE modelling approach

### 3.1.1 Wetland CH<sub>4</sub> emissions modelling into ORCHIDEE

ORCHIDEE simulates the land energy, hydrology and the carbon cycle (Krinner et al., 2005). The version used here was further developed to incorporate CH<sub>4</sub> emissions from wetlands. The computation of wetlands CH<sub>4</sub> emissions is based on the modelling of wetland area dynamics as well as one of the CH<sub>4</sub> flux by surface unit. The resulting model will be named ORCHIDEE-WET hereafter.

In ORCHIDEE-WET, wetland area dynamics were computed using the TOPMODEL (Beven and Kirkby, 1979) approach of Decharme et al. (2006). For each gridcell, using both topographic heterogeneities and soil moisture computed by ORCHIDEE-WET, the TOPMODEL subroutine computes a sub-grid saturated fraction. Saturated areas as simulated by ORCHIDEE-WET do not correspond necessarily to water-logged soil and emitting wetland areas. Thus, we used a climatology (1993–2000) constructed from the Prigent et al. (2007) dataset as a baseline for our present day estimate. Future simulated wetland extent was then calculated from the ORCHIDEE-WET simulations, corrected to subtract the systematic biases between the present day simulated saturated area and observed wetland distributions. More details will be found in Appendix C.

At each time step, CH<sub>4</sub> flux densities (per unit area of emitting surface) were computed using a process-based model (Walter et al., 2001) for each sub-grid water-table class calculated as above. The model simulates CH<sub>4</sub> flux from natural wetlands based on the calculation of: (a) the methanogenesis in the saturated deeper soil horizons; (b) the methanotrophic oxidation in the aerated upper soil; and (c) the upward transport by diffusion, ebullition and/or plant-mediated transport (Walter and Heimann, 2000). When including the Walter et al. (2001) CH<sub>4</sub> emission model in ORCHIDEE, we made the same following modification, described in Ringeval et al. (2010). The substrate for methanogenesis is computed from the active soil organic carbon pool computed by ORCHIDEE rather than using linear regression against soil temperature and Net Primary Productivity (NPP) as is done in Walter et al. (2001) based on 6 sites. More information can be found in Appendix D. As in the initial Walter et al. (2001) model, methanogenesis sensitivity to temperature for each grid-cell is expressed by a function  $g$  as followed:

$$g = f(T(t, z)) \cdot Q_{10}^{T(t, z) - T_{\text{mean}}} \quad (12)$$

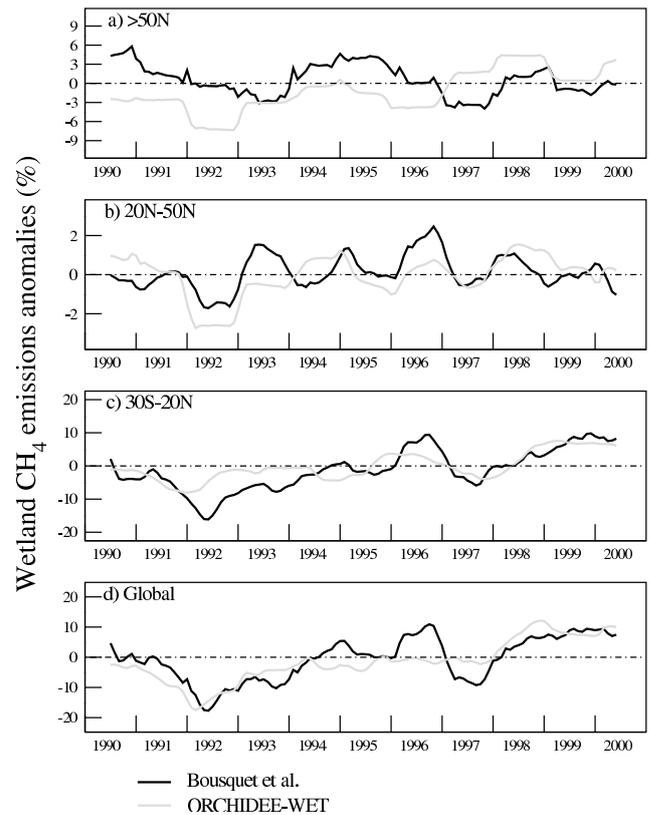
where  $T(t, z)$  is the soil temperature at time  $t$  and depth  $z$  and  $f(T)$  is a step-function equal to 0 if temperature is negative and 1 otherwise. A  $Q_{10}$  of 3, close to the mean value found in Ringeval et al. (2010), was used for all wetlands. As there is a high uncertainty about the value of  $Q_{10}$  (e.g. Valentine et al., 1994), a sensitivity test with a  $Q_{10}$  of 5.5 (in rough

agreement with higher value of range used by GCH04) is also performed. Relative to Walter and Heimann, “the temperature function describes the response to the seasonal variation of the soil temperature [...] relative to the annual mean temperature  $T_{\text{mean}}$  at the site”. As it is not clear if  $T_{\text{mean}}$  evolves in time or not, we have tested both configurations. Such a changing  $T_{\text{mean}}$  in time corresponds to the hypothesis that micro-organisms adapt relatively quickly to their environment (see Discussion).

The computation of a carbon stock whose active pool is used as a proxy for methanogenesis substrate is explained in a detailed way in Krinner et al. (2005). Briefly, in ORCHIDEE, the parameterizations of litter decomposition and soil carbon dynamics essentially follow Parton et al. (1988). Carbon dynamics are described through the exchanges of carbon between the atmosphere and the different carbon pools in plants and soils. Metabolic activity in the soil results in carbon fluxes within the three carbon pools (active, slow, and passive). Optimal residence times are prescribed for each pool, with temperature and moisture inhibition multipliers in order to parameterize the decrease of soil metabolic activity under cold or dry conditions. No modification is brought to ORCHIDEE-WET as regards soil wetlands conditions (see discussion below).

For each sub-grid water-table class given by TOPMODEL, ORCHIDEE-WET computes CH<sub>4</sub> fluxes with the corresponding mean water table depth value (respectively 0 and -5 cm). Other water table ranges could be calculated as well but would increase the time for calculation of the simulation. In the model, oxidation happens only in the second case, i.e. in the oxic soil layer between -5 cm and 0 for soils where the water table is 5 cm below the surface. The  $Q_{10}$  for methanotrophy is kept equal to the initial value (=2) of Walter et al. (2001). The model accounts also for oxidation when CH<sub>4</sub> entering the roots of plants has to pass through the small oxic zone around the root tips. A value of 50 % of the methane entering in the plant is considered as oxidized in the model (see Eq. 16 of Walter and Heimann, 2000). The CH<sub>4</sub> flux due to plant-mediated transport is a function of the Leaf Area Index (LAI) computed in ORCHIDEE-WET. As in the Walter et al. (2001) model, computation of a CH<sub>4</sub> flux which reaches the atmosphere by diffusive transport is based on the Crank-Nicolson scheme to resolve Fick’s first law. CH<sub>4</sub> atmospheric concentration serves as the upper boundary condition. Ebullition and transport by plant are not functions of the CH<sub>4</sub> atmospheric concentration in the model.

Under current climate forcing (the monthly NCEP climate forcing data corrected by CRU – N. Viovy, personal communication, 2009, <http://dods.extra.cea.fr/data/p529viov/cruncep/readme.htm>), ORCHIDEE-WET simulates a global mean wetland CH<sub>4</sub> emission flux of ~251 Tg yr<sup>-1</sup> over the 1990–2000 period. This is slightly above the upper end of IPCC range of estimates (100 to 231 TgC yr<sup>-1</sup>) (IPCC, 2007). Both (i) the spatial extrapolation of parameter relative to CH<sub>4</sub> flux densities optimized on 3 sites and (ii) the



**Fig. 2.** Year-to-year variability of simulated CH<sub>4</sub> wetlands emissions (grey curve) and comparison with a top-down approach (Bousquet et al., 2006) (black curve) over 1990–2002 period. The anomalies obtained by 12 months-shift mean are divided by the global annual average of each estimation (Bousquet et al., 2006 or ORCHIDEE-WET).

mismatch between mean real annual wetland extent and mean annual Prigent et al. (2007) data can lead to high simulated wetland emissions. The distribution over latitude bands is 68, 53 and 125 Tg yr<sup>-1</sup> for boreal (>50° N), temperate (20° N–50° N) and tropical wetlands (30° S–20° N), respectively. High uncertainty remains for both total wetland emissions and their distribution. Wetland CH<sub>4</sub> emissions diagnosed from one atmospheric inversion Bousquet et al. (2006) give an estimation of 155 Tg at the global scale over the same period with a distribution of: 32, 21 and 95 Tg for the same latitude bands as above. Comparison of the year-to-year variability of wetland CH<sub>4</sub> emissions given by ORCHIDEE-WET and Bousquet et al. (2006) is shown on Fig. 2.

This modelling approach will allow us to estimate the wetlands CH<sub>4</sub> emissions sensitivities to climate and to atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentrations for a transient run over the period 1860–2100. Some hydrological processes such as floodplain storage of water (Decharme et al., 2008) are not included in the model. Concerning the representation of permafrost, we account here for the freeze of the soil water content and decrease in soil carbon decomposition and

soil water holding capacity under these conditions but not for high carbon content in deep soil horizons which could be decomposed under warming, nor for the possible effects of thermokarst on lake and wetland expansion.

### 3.1.2 Experimental design

We forced the ORCHIDEE-WET model with climate fields taken from coupled ocean-atmosphere general circulation model (OAGCM) simulations and with the associated time-varying atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentrations scenarios. This allows us to estimate the different sensitivity terms of Eqs. (10) and (11) (or equations in Appendix B in the most general feedback calculation framework). Four ORCHIDEE-WET simulations have been performed over the period 1860–2100. Each ORCHIDEE-WET simulation needs as forcing: climate, atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentration values. For each forcing, we use either the pre-industrial state or a transient evolution from 1860 to 2100 following SRES-A2 scenario. The four ORCHIDEE-WET simulations are varied from one to the next by combining pre-industrial or transient forcing values as summarized in Table 1. This experimental design does not allow the testing of each term independently, nor their interaction effects, but is chosen to keep computational costs reasonable. Simulations 1 and 3 are also realized with a  $Q_{10}$  of 5.5 for methanogenesis to test the sensitivity of our results to this parameter. They will be called respectively Simulation 1- $Q_{10}$  and Simulation 3- $Q_{10}$  in the following. We performed all these simulations twice: first, considering a constant  $T_{\text{mean}}$  (see Eq. 12) and second, considering a  $T_{\text{mean}}$  varying in time.

The transient climate (1860–2100) is obtained from the IPSL-CM4 OAGCM simulations (Marti et al., 2010) with prescribed GHG-forcing for historical and future (SRES A2) scenarios. These climate fields were bias corrected by removing the difference between the climate model climatology (over the period 1961–1990) and the “observed” climatology (Sheffield et al., 2006 forcing data for air humidity and CRU – University of East Anglia’s Climate Research Unit, <http://www.cru.uea.ac.uk/> – for all other variables). For the pre-industrial climate forcing, we use a random succession of climate data taken from the first ten years (1860–1869) of the OAGCM simulation. The same climate data succession was used for all simulations with preindustrial climate forcing. Before the different simulations, ORCHIDEE-WET was first brought to equilibrium using preindustrial climate forcing. The simulation forced by pre-industrial climate, CO<sub>2</sub> and CH<sub>4</sub> concentration can be considered as the control simulation (CTRL hereafter).

By calculating the difference of the CH<sub>4</sub> emissions between the different simulations, we can isolate the CH<sub>4</sub> flux sensitivities to atmospheric CO<sub>2</sub>, CH<sub>4</sub> and climate. The same is done with the net terrestrial CO<sub>2</sub> flux in order to get the carbon sensitivity terms. The difference between simulation 1 (change in atmospheric CO<sub>2</sub> only) and CTRL gives

**Table 1.** Set of ORCHIDEE-WET simulations. Performed ORCHIDEE-WET simulations are defined by climate, atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentration values used as forcing. For each forcing, pre-industrial values (PI) or transient following SRES-A2 scenario (T) can be used.

|              | CO <sub>2</sub> | CH <sub>4</sub> | Climate |
|--------------|-----------------|-----------------|---------|
| CTRL         | PI              | PI              | PI      |
| Simulation 1 | T               | PI              | PI      |
| Simulation 2 | PI              | T               | PI      |
| Simulation 3 | T               | PI              | T       |

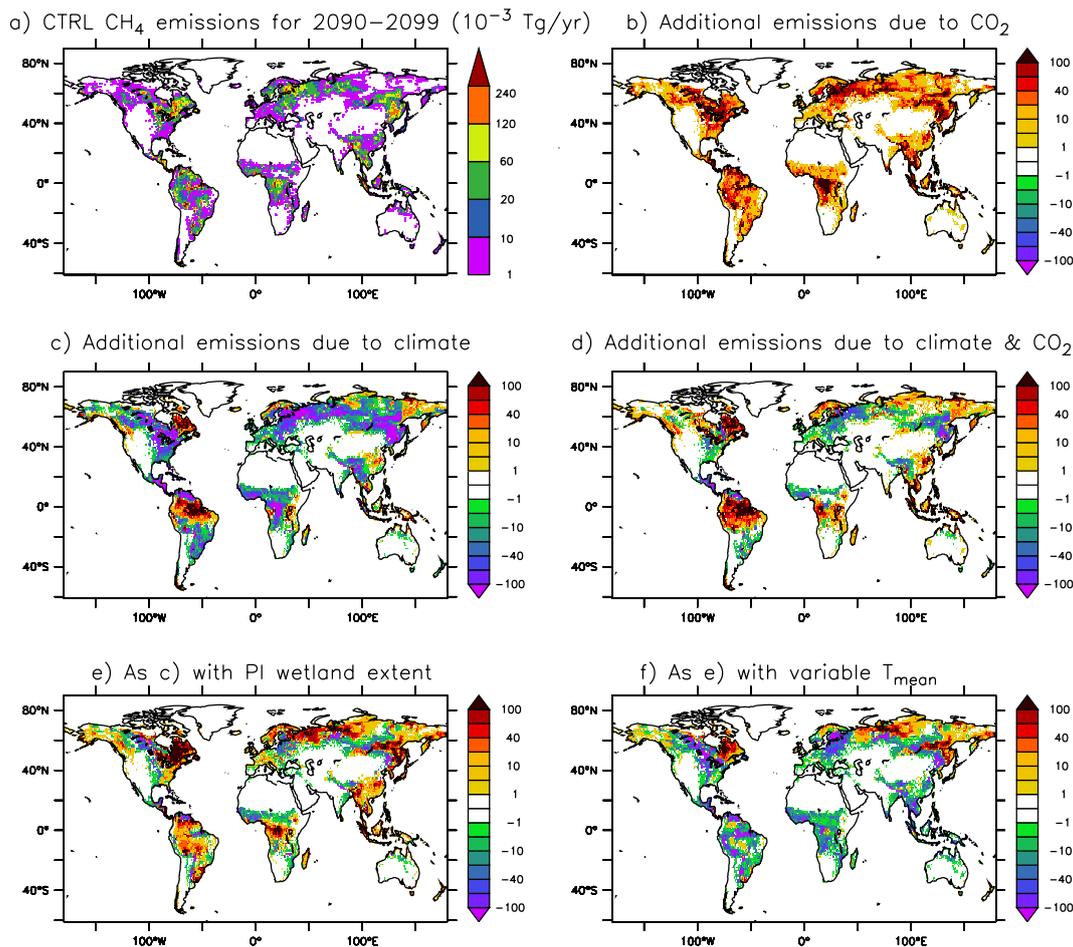
PI: Pre-industrial; T: Transient over 1860–2100

the sensitivity of CO<sub>2</sub> and wetland CH<sub>4</sub> emissions to atmospheric CO<sub>2</sub> (resp.  $\beta_C$  and  $\beta_{C \rightarrow M}$ ). The difference between simulation 2 (change in atmospheric CH<sub>4</sub> only) and CTRL gives the wetland CH<sub>4</sub> flux sensitivity to atmospheric CH<sub>4</sub> ( $\beta_M$ ); and the difference between simulation 3 (change in CO<sub>2</sub> and climate) and simulation 1 gives the sensitivities of CO<sub>2</sub> and wetland CH<sub>4</sub> flux to climate ( $\gamma_C$  and  $\gamma_M$ ).

Furthermore, we also estimated the contribution of changes in wetland extent vs. changes in CH<sub>4</sub> emission rate. To do so, we remove a posteriori, the evolution of the wetland extent from the previous estimates. For each simulation and each year, the CH<sub>4</sub> flux densities calculated per unit wetland area are combined with the climatological pre-industrial (but seasonally varying) wetland area to compute the wetland CH<sub>4</sub> emissions in the absence of changes to the wetland extent. Comparison as described above of such emissions gives an estimate of  $\beta_{C \rightarrow M}^f$  and  $\gamma_M^f$ , respectively the wetland CH<sub>4</sub> flux sensitivity to atmospheric CO<sub>2</sub> and to climate under constant wetland area. Regardless, using CH<sub>4</sub> flux densities and wetland area from two different simulations to compute wetland CH<sub>4</sub> emissions does not allow the possibility of removing the indirect effects of the variation of wetland extent on CH<sub>4</sub> fluxes: indeed, change in simulated wetland extent leads to change in the computed soil water content (through change in modelled runoff) that could have a small effect on the ORCHIDEE modelled carbon cycle.

Finally, the difference between Simulation 1- $Q_{10}$  and 3- $Q_{10}$ , after removing wetland area evolution, gives us the wetland CH<sub>4</sub> flux densities sensitivity to global climate with a higher  $Q_{10}$ , i.e. the sensitivity term  $\gamma_{M-Q_{10}}^f$ .

The different  $\gamma_M$  terms were computed for two cases: first, from simulations performed considering a constant  $T_{\text{mean}}$  and second, from simulations considering a  $T_{\text{mean}}$  that varies with climate. In the case where a constant  $T_{\text{mean}}$  is chosen, mean climatological pre-industrial surface temperature is used. If  $T_{\text{mean}}$  varies in time, it is computed in ORCHIDEE-WET by a slow relaxation method, as described by the Eq. (5) of Krinner et al. (2005) with a  $\tau = 365$  days.



**Fig. 3.** Mean annual CH<sub>4</sub> emissions by wetlands over 2090–2099 period for CTRL simulation (a) and changes in emissions due to increase in atmospheric CO<sub>2</sub> (b), climate change (c) and both (d). The shown changes in emissions are obtained by ORCHIDEE-WET simulations with  $Q_{10} = 3$ , constant in time  $T_{\text{mean}}$  and accounting for wetland extents variation, which is the basic configuration. Climate effect on CH<sub>4</sub> flux densities alone (i.e. without accounting for wetland extent evolution, see above) is given in (e). (f) displays the change in CH<sub>4</sub> flux densities due to climate but obtained with a  $T_{\text{mean}}$  variable in time.

### 3.1.3 Response of ORCHIDEE wetlands CH<sub>4</sub> emissions to CO<sub>2</sub>, CH<sub>4</sub> and climate

Figure 3a–d shows the mean annual CH<sub>4</sub> emissions by wetlands for the CTRL simulation over the period 2090–2099 (Fig. 3a) as well as the changes in emissions (2090–2099 average relative to the control) due to the change in atmospheric CO<sub>2</sub> (Fig. 3b), climate (Fig. 3c) and both atmospheric CO<sub>2</sub> and climate (Fig. 3d). Changes in CH<sub>4</sub> emissions due to an increase in atmospheric CH<sub>4</sub> are negligible (not shown). The changes in emissions shown in Fig. 3a–d are obtained by ORCHIDEE-WET simulations considering a methanogenesis  $Q_{10}$  of 3, a time-constant  $T_{\text{mean}}$  and accounting for variation in wetland extent, which is considered below as the basic configuration. The climate effect on CH<sub>4</sub> flux densities alone (i.e. without accounting for wetland extent evolution, as above) is given in Fig. 3e. Figure 3f displays the change in

CH<sub>4</sub> flux densities due to climate, as in Fig. 3e, but obtained with a time-varying  $T_{\text{mean}}$ .

The global averaged pre-industrial wetland CH<sub>4</sub> emission amounts to 253 TgC yr<sup>-1</sup> which is, as for present-day, slightly higher than previous estimates (e.g. Chappellaz et al., 1993). Changes in CH<sub>4</sub> emissions due to the various forcing show a large spatial variability. The overall effect of CO<sub>2</sub> and climate (Fig. 3d) is an increase in high latitudes, in the northern half of the Amazon basin, in South-east Asia and in some parts of central Africa. Elsewhere, the emissions decrease under future climate and CO<sub>2</sub>. This pattern is a combination of a widespread increase due to CO<sub>2</sub> alone (Fig. 3b) and of a general decrease due to climate change alone (Fig. 3c).

The atmospheric CO<sub>2</sub> concentration and the climate affect CH<sub>4</sub> wetland emissions via two main pathways: one due to changes in wetland areas (resulting from changes in the soil water balance); and one due to changes in CH<sub>4</sub> flux

per unit of wetland area (resulting from changes in methanogenesis rate, in the contribution of each sort of transport, etc.). Production of CH<sub>4</sub> can be affected by changes in the temperature-dependant methanogenesis rate but also by changes in substrate quantity.

Removing the wetland extent evolution leads to reducing the increase of CH<sub>4</sub> emissions under elevated CO<sub>2</sub> (not shown). The mechanism underlying this is that elevated CO<sub>2</sub> reduces the transpiration of plants, and therefore leads to an increase in soil water content given by ORCHIDEE-WET and thus an increase in the wetlands CH<sub>4</sub> emissions via an increase of the wetland areas. Wetland CH<sub>4</sub> flux densities also increase with atmospheric CO<sub>2</sub> increases. As mentioned before, this response can be explained by the fertilization effect. Increased atmospheric CO<sub>2</sub> stimulates plant productivity, which leads to a rise in the active soil carbon pool and hence to more substrate available for methanogenesis. The effect of CO<sub>2</sub> fertilization increasing productivity in ORCHIDEE-WET is similar to one of the four other DGVM models analyzed by Sitch et al. (2008).

Except for the north of South-America, the north and the north-east of Siberia, the west of China as well as the west of Canada the effect of climate change is to reduce CH<sub>4</sub> emissions (Fig. 3c). Removing the wetland area's sensitivity to climate decreases largely the reduction in CH<sub>4</sub> emissions (Fig. 3e). The region of the Amazon river is an exception as climate change leads to an extension in wetlands area. In high latitudes, the emission decrease is primarily driven by a decrease of wetland extension. In spite of extension of the active season and thus of the inundated period in this regions, the climate change would lead to a decrease in the maximum of inundated area that coincides with the period of maximum CH<sub>4</sub> flux density. In some places, the increase in methanogenesis rate, through its temperature dependence seems counterbalanced by a decrease in methanogenesis substrate.

Considering a  $T_{\text{mean}}$  that changes with climate over time restricts to high latitudes the places where we find an increase of CH<sub>4</sub> flux density due to climate (Fig. 3f). A varying  $T_{\text{mean}}$  reduces the CH<sub>4</sub> flux density sensitivity to temperature represented by  $Q_{10}$  formulation (Eq. 12; last term of right member). Thus, reduction in methanogenesis substrate drives the decrease displayed below 40° N. In high latitudes regions, the increase in active soil depth (switch of  $f(T)$  from 0 to 1 for some soil layers) counterbalance the evolution of carbon soil and explain the obtained increase in CH<sub>4</sub> flux densities (Eq. 12; first term of right member).

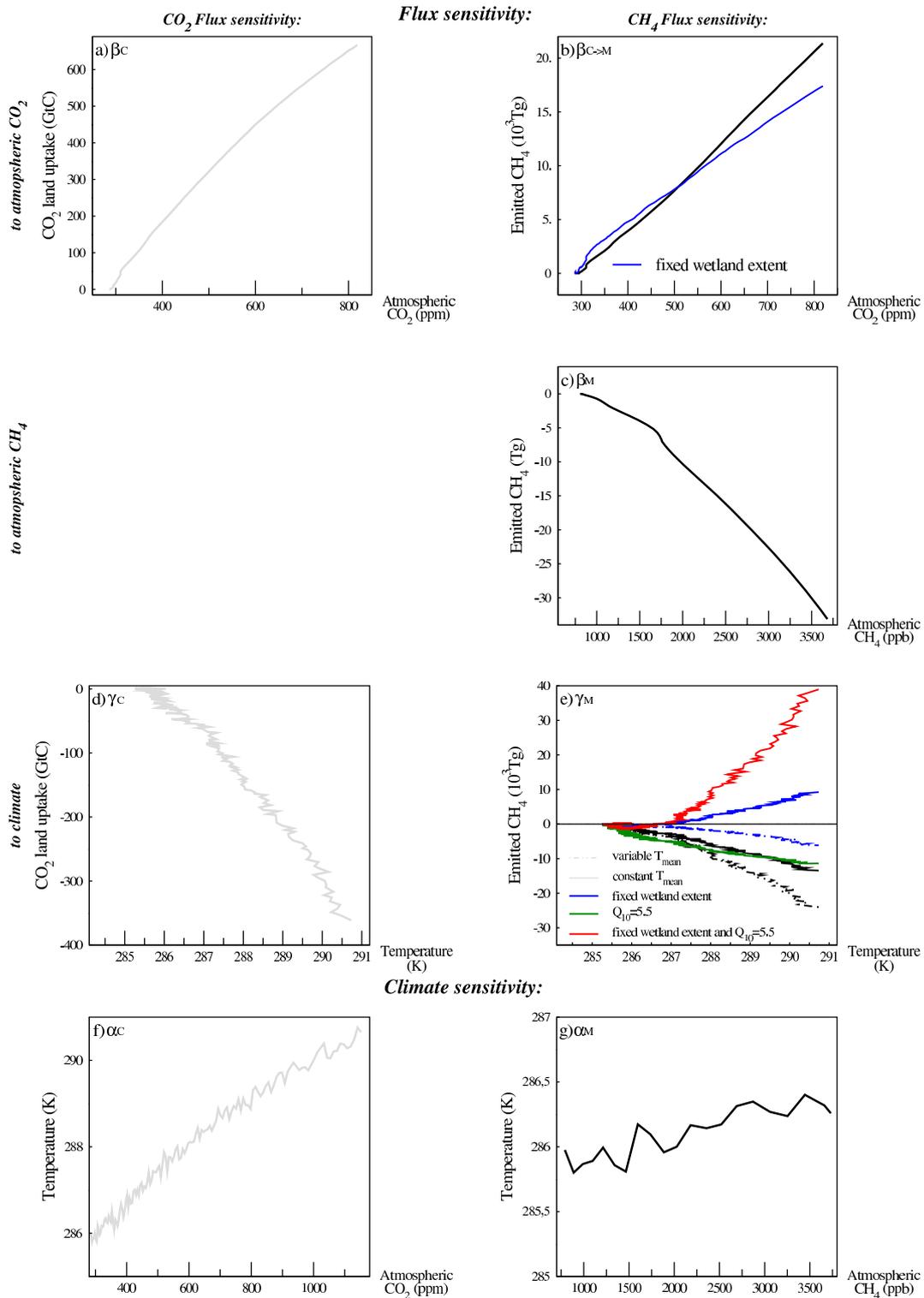
From these simulations, we can now calculate the CO<sub>2</sub> and CH<sub>4</sub> flux sensitivity terms of Eqs. (7a) and (7b) in order to estimate the climate-CH<sub>4</sub>-CO<sub>2</sub> gains (Fig. 4). The Fig. 4a–e displays the integral of changes over 1860–2100 for CO<sub>2</sub> uptake and wetland CH<sub>4</sub> emissions as function of atmospheric CO<sub>2</sub> (Fig. 4a–b), atmospheric CH<sub>4</sub> (Fig. 4c) and climate (Fig. 4d–e) and the slopes of these different curves give the sensitivity terms' values. The results shown in Fig. 4 shows

a linear relation between additional CH<sub>4</sub> and CO<sub>2</sub> flux and atmospheric CH<sub>4</sub>, atmospheric CO<sub>2</sub>, or climate over the period modeled here is supported by the model. This supports the assumption of a first-order linear relation in the theoretical analysis of Sect. 2. The ORCHIDEE-WET computed sensitivity values in 2100 are summarized in the Table 2 in the same units for CO<sub>2</sub> and CH<sub>4</sub>. We note that the global net terrestrial CO<sub>2</sub> flux sensitivity to rising atmospheric CO<sub>2</sub> ( $\beta_C$ ) and to climate change ( $\gamma_C$ ), depend also on the ocean carbon response. We used ocean sensitivity terms ( $\beta_O$  and  $\gamma_O$ ) from Friedlingstein et al. (2006) for the IPSL coupled-climate-carbon model to account for the ocean CO<sub>2</sub> uptake feedbacks. Thus,  $\beta_C$  (respectively  $\gamma_C$ ) in the Table 2 is the sum of the land flux sensitivity  $\beta_C$  (resp.  $\gamma_C$ ) computed using Fig. 4a (resp. Fig. 4d) and of the ocean flux sensitivity  $\beta_O$  (resp.  $\gamma_O$ ).

The individual sensitivity of the land CO<sub>2</sub> flux to atmospheric CO<sub>2</sub> (Fig. 4a) as well as its response to global warming (Fig. 4d) is not discussed here. A comprehensive analysis can be found in Friedlingstein et al. (2003).

Concerning CH<sub>4</sub> emissions from wetlands, as mentioned above, we obtain an increase of emissions when atmospheric CO<sub>2</sub> increases (Fig. 4b).  $\beta_{C \rightarrow M}$  amounts to 0.0142 by 2100. ORCHIDEE-WET simulates a negative effect of atmospheric CH<sub>4</sub> on wetland CH<sub>4</sub> emissions,  $\beta_M$  (Fig. 4c). The increase in atmospheric CH<sub>4</sub> leads to a decrease in the concentration gradient between wetland soil and the atmosphere, which drives a decline in the diffusive flux of CH<sub>4</sub> from soil, and thus a larger proportion of the CH<sub>4</sub> created is consumed by methanotrophy within the soils. However, the negative value of the sensitivity of emissions to atmospheric CH<sub>4</sub> is very low ( $\beta_M = -0.0040$ ) as assumed before and is explained by the fact that the CH<sub>4</sub> atmospheric concentrations always remains much lower than the CH<sub>4</sub> concentration in wetland soils.

As mentioned before (Fig. 3c), the simulated overall effect of climate changes is to reduce CH<sub>4</sub> emissions from wetlands (Fig. 4e). We find a sensitivity  $\gamma_M$  of  $-1.83 \text{ GtC K}^{-1}$ . Assuming constant wetland area would change the sign of the sensitivity term, with a  $\gamma_M^f$  of  $+1.27 \text{ GtC K}^{-1}$ . Hence, the overall climate-driven decline in CH<sub>4</sub> emission from wetlands is mainly driven by a decrease in wetland area. The negative value of  $\gamma_M$  obtained in the case where we consider a varying  $T_{\text{mean}}$  and do not include the dynamics of wetland area changes ( $\gamma_M^f = -0.84 \text{ GtC K}^{-1}$ ) shows that a reduction of the methanogenesis substrate reinforces the negative effect of climate on emissions driven by wetland extent. If a constant  $T_{\text{mean}}$  is used, taking a higher methanogenesis  $Q_{10}$  value ( $Q_{10} = 5.5$ ) leads to few changes when accounting for wetland extent (+17%; from  $-1.83$  to  $-1.51$ ) but a large change when not accounting for (more than 3 times; from  $+1.27$  to  $+5.37$ ).



**Fig. 4.** (a)–(e): Evolution of the integral of change in CO<sub>2</sub> land uptake and CH<sub>4</sub> wetlands emissions as function to atmospheric CO<sub>2</sub> concentration – (a) and (b), atmospheric CH<sub>4</sub> concentration (c) and global air temperature (e). Be careful for the different y-axis unit for (c). Blue curves of (b) and (e) correspond to the evolution of the integral of change in CH<sub>4</sub> wetlands emissions after removing the wetland extent evolution (i.e. using for all the time step the pre-industrial wetland extent). Red curve of (e) is the same as blue one but with a higher  $Q_{10}$  for the methanogenesis. (f)–(g): Temperature sensitivity to atmospheric CO<sub>2</sub> and CH<sub>4</sub>.

**Table 2.** Values of the CO<sub>2</sub> and CH<sub>4</sub> flux sensitivity in 2100 (top) as well as climate one (bottom). Given global net terrestrial CO<sub>2</sub> flux sensitivities are sum of ocean sensitivity terms from Friedlingstein et al. (2006) and the estimation of land flux sensitivity based on ORCHIDEE-WET simulations (cf. Fig. 4). Wetland CH<sub>4</sub> emissions sensitivity reported in this table are only based on ORCHIDEE-WET simulations and are also consistent to each other.

|   |                    | Flux sensitivity in 2100 |                         |                            |                                      |
|---|--------------------|--------------------------|-------------------------|----------------------------|--------------------------------------|
|   |                    | CO <sub>2</sub> flux     |                         | CH <sub>4</sub> flux       |                                      |
| to atmospheric CO <sub>2</sub><br>(unitless)                | $\beta_C = 1.11$   |                          |                         | With dynamic wetland       | $\beta_{C \rightarrow M} = 0.0142$   |
|   |                    |                          |                         | Without dynamic wetland    | $\beta_{C \rightarrow M}^f = 0.0155$ |
| to atmospheric CH <sub>4</sub><br>(unitless)                |                    | $\beta_M = -0.0040$      |                         |                            |                                      |
| to climate<br>(in GtC K <sup>-1</sup> )                     | $\gamma_C = -82.3$ |                          |                         | Constant                   | Variable                             |
|   |                    |                          |                         | $T_{\text{mean}}$          | $T_{\text{mean}}$                    |
|   |                    | $Q_{10} = 3$             | With dynamic wetland    | $\gamma_M = -1.83$         | $\gamma_M = -3.27$                   |
|   |                    | $Q_{10} = 3$             | Without dynamic wetland | $\gamma_M^f = +1.27$       | $\gamma_M^f = -0.84$                 |
|   |                    | $Q_{10} = 5.5$           | With dynamic wetland    | $\gamma_{M-Q10} = -1.51$   | $\gamma_{M-Q10} = -4.85$             |
|   |                    | $Q_{10} = 5.5$           | Without dynamic wetland | $\gamma_{M-Q10}^f = +5.37$ | $\gamma_{M-Q10}^f = -0.17$           |
|   |                    | Climate sensitivity      |                         |                            |                                      |
| to atmospheric CO <sub>2</sub><br>(in K GtC <sup>-1</sup> ) |                    | $\alpha_C = 0.0029$      |                         |                            |                                      |
| to atmospheric CH <sub>4</sub><br>(in K GtC <sup>-1</sup> ) |                    | $\alpha_M = 0.0840$      |                         |                            |                                      |

When  $T_{\text{mean}}$  varies in time, changing the  $Q_{10}$  tends to increase  $\gamma_M$  in high latitudes (not shown) due to the activation of some soil layers. At the global scale, this effect is hidden by small changes in contribution of the different latitudes bands to the total emissions from simulation with  $Q_{10} = 3$  to simulation with  $Q_{10} = 5.5$  (not shown).

### 3.2 Literature based estimates of $\beta_{C \rightarrow M}$ and $\gamma_M$

As mentioned before and despite some remaining uncertainty (e.g. because of interaction with nitrogen cycle), the CO<sub>2</sub> flux sensitivities to climate and atmospheric CO<sub>2</sub> have been already studied and estimated (notably the C<sup>4</sup>MIP intercomparison; Friedlingstein et al., 2006). In the present study, most uncertainty concerns terms relative to the sensitivity of wetlands CH<sub>4</sub> emissions.

A pair of previous studies investigated the future changes in CH<sub>4</sub> emissions from wetlands. Although these studies did not quantify the CH<sub>4</sub> emissions sensitivity to climate and atmospheric CO<sub>2</sub> (respectively  $\gamma_M$  and  $\beta_{CM}$ ) one can use their results to derive these quantities.

Neither of the previous studies (SWF04, GCH04, EMA08 and V08) explicitly accounted for changes in CH<sub>4</sub> concentration and its effect on CH<sub>4</sub>. To our knowledge there are also no site-level manipulative experiments with increased CH<sub>4</sub> concentration conditions. Therefore we cannot provide

a literature based estimate of  $\beta_M$ . However, we found this term to be negligible (see previous section).

A first-order estimate of  $\gamma_M$  is possible from SWF04, GCH04 and EMA08. Their approach does not account for the fertilizing effect of high CO<sub>2</sub> atmospheric level on wetland CH<sub>4</sub> emissions but only for the effect of the climate change induced by it. Thus, they allow for a direct estimate of  $\gamma_M$ . SWF04 estimate a rise of 78% of wetlands CH<sub>4</sub> emissions (from 156 to 277 Tg yr<sup>-1</sup>) under a transient 2 × CO<sub>2</sub> climate with a global warming of 3.4 °C. The calculation of  $\gamma_M$  needs the time evolution of the wetland CH<sub>4</sub> emission, as it is the ratio of the cumulated emissions divided by the related warming. Not having this time evolution, we assume here that the growth of CH<sub>4</sub> emission is linear, as the warming is close to linear in such transient 2 × CO<sub>2</sub> climate simulations (e.g. Cubasch et al., 2001). This gives a value of 0.93 GtC K<sup>-1</sup> for  $\gamma_M$ . The same estimate of  $\gamma_M$  can be done with GCH04 where they simulate a wetland CH<sub>4</sub> emission increase of 255 Tg yr<sup>-1</sup> over 110 years for a warming of 4.2 K (in their reference case, CTRL). This gives a value of 2.70 GtC K<sup>-1</sup> for  $\gamma_M$ .

EMA08 find an increase of 130–140 to 170–200 Tg yr<sup>-1</sup> under the SRES-A2 scenario (+3.4 °K) but the accounted effects of climate warming on wetland CH<sub>4</sub> emissions are only relative to temperature dependency of methanogenesis and to change in soil depth when permafrost thaws. Both wetland extent and water table depth are constant during their

simulation time and the methanogenesis substrate is constant. Such an increase gives a  $\gamma_M$  value of  $\sim 1.9 \text{ GtC K}^{-1}$ .

V08 obtained a wetland CH<sub>4</sub> emissions increase of +40% from 20th to the end of 21st century (from 240 Tg yr<sup>-1</sup> to 340 Tg yr<sup>-1</sup>) under a warming of 3.5 °C (scenario A1B). The results cannot be easily delineated into the theoretical framework we have developed in this paper: CO<sub>2</sub> fertilization effect on wetland CH<sub>4</sub> emissions seems to be accounted for (the paper uses NPP to approximate substrate) but is not discussed. Thus we cannot estimate the  $\gamma_M$  and  $\beta_{C \rightarrow M}$  effects based on this study.

We also note that the evolution of the global temperature in these previous studies is not the same as one simulated by the ISPL-CM4 OAGCM under SRES-A2. It has been shown for the C-CO<sub>2</sub> feedback that the rate of perturbation has an impact on the estimate of  $\gamma_C$  (Gregory et al., 2009). The same certainly applies for the C-CH<sub>4</sub> feedback and the value of  $\gamma_M$  considered here.

Finally, wetland CH<sub>4</sub> emissions sensitivity to temperature derived through warming manipulation on sites (e.g. Updegraff et al., 2001; White et al., 2008) could not be used to estimate  $\gamma_M$  because this term represents the overall global response of wetlands to climate and not just to temperature.

The published global modeling approaches do not give an estimate of the relationship between atmospheric CO<sub>2</sub> level and global wetlands CH<sub>4</sub> emissions. However, there are wetlands site level manipulative experiment where emissions are measured under ambient and elevated CO<sub>2</sub> (e.g. Dacey et al., 1994; Megonigal and Schlesinger, 1997; Kang et al., 2001; Vann and Megonigal, 2003; Pancotto et al., 2010). The measured response varies between 0% (Pancotto et al., 2010) and 136% under 2 × CO<sub>2</sub> (Megonigal and Schlesinger, 1997) according to the wetland type and the experimental conditions. ORCHIDEE-WET simulated wetland CH<sub>4</sub> emissions increase by +80% (respectively  $\sim +50\%$  with no evolution of wetland extent) when atmospheric CO<sub>2</sub> concentration given by SRES-A2 scenario grows from 355 to 716 ppm. The speed of the CO<sub>2</sub> perturbation of the manipulations experiment is totally different from that under the SRES-A2 scenario. Moreover, the relationship between atmospheric CO<sub>2</sub> concentration and wetland CH<sub>4</sub> emissions estimated at sites is extrapolated to global scale with difficulty. Thus we retain only the ORCHIDEE-WET based  $\beta_{C \rightarrow M}$  in the following. In Sect. 4, the effect of the different interactions on atmospheric CH<sub>4</sub> and CO<sub>2</sub> will be added successively. The effect without CO<sub>2</sub> fertilization on CH<sub>4</sub> emissions could be seen as lowest boundary of the uncertainty range for accounting for  $\beta_{C \rightarrow M}$ .

In summary, we find an estimate for  $\beta_M$ , based on ORCHIDEE-WET, of  $-0.0040$  and for  $\beta_{C \rightarrow M}$  of  $0.0142$ . For  $\gamma_M$ , we find, based on both ORCHIDEE-WET and literature based estimates, a range from  $-1.83$  to  $+2.70$ . The value of  $\gamma_M$  chosen as representative of ORCHIDEE-WET simulation corresponds to the best estimate (i.e. accounting for variation in wetland extent,  $Q_{10}=3$  and a constant  $T_{\text{mean}}$ ). ORCHIDEE-WET gives a negative value for  $\gamma_M$  while the

estimates based on GCH04 and SWF04 give a positive  $\gamma_M$ . An analysis on the reasons for the uncertainty on the sign of  $\gamma_M$  will be given in the discussion section.

### 3.3 Other terms

In order to estimate the gains, we finally have to calculate the climate sensitivity to CO<sub>2</sub> and to CH<sub>4</sub> ( $\alpha_C$  and  $\alpha_M$  respectively) as well as  $\mu$ , the atmospheric OH sink scaling term (Eq. 4b).

For  $\alpha_C$ , we used the transient global warming of the IPSL-CM4 model from an idealized simulation with changes in atmospheric CO<sub>2</sub> only (CMIP 1 % yr<sup>-1</sup>) (Fig. 4f). This gives a  $\alpha_C$  of  $0.0029 \text{ K ppm}^{-1}$ . For  $\alpha_M$  we have no parallel climate simulation with change in CH<sub>4</sub> concentration only. Thus, we used the standard CO<sub>2</sub> radiative forcing equations (IPCC, 2001, Table 6.2) to derive a climate sensitivity to changes in radiative forcing ( $\Delta\text{RF}$ ) from the previous simulation. The same standard radiative forcing equations, but for CH<sub>4</sub>, allow us to go from  $\Delta\text{RF}$  to an equivalent of atmospheric CH<sub>4</sub> concentration, if we assume the same climate sensitivity for  $\Delta\text{RF}$  whether it is due to CO<sub>2</sub> or CH<sub>4</sub>. We can also estimate the warming due to CH<sub>4</sub> only (Fig. 4f). This gives a  $\alpha_M$  of  $0.0840 \text{ K ppm}^{-1}$ .

We compute  $\mu$ , the atmospheric OH sink scaling term, as the ratio of the cumulative changes of atmospheric CH<sub>4</sub> along the SRES-A2 scenario to its change at the end of the scenario. We find a  $\mu$  of 0.322. Anthropogenic emissions of CH<sub>4</sub>,  $F_{\text{MF}}$ , come from the EDGAR database (<http://www.sec.gov/edgar.shtml>) for the historical period and from the SRES-A2 scenario for the 21st century. The CH<sub>4</sub> atmospheric lifetime,  $\tau$ , is assumed constant with a value of 9 years (IPCC, 2001). This lifetime is sensitive to the atmospheric composition (e.g. COV, see Valdes et al., 2005) and in particular to CH<sub>4</sub> concentration itself (e.g. V08), leading to a feedback. IPCC (2007) gives an adjustment time (Lelieveld et al., 1998) of 12 years to account for indirect effects of increase in CH<sub>4</sub> emissions. Not using of a coupled climate-chemistry model, we cannot account for dependency of  $\tau$  on CH<sub>4</sub> concentration and on climate.

## 4 Estimation of the feedbacks' gains and their interaction

### 4.1 C-CH<sub>4</sub> and C-CO<sub>2</sub> feedbacks' gains

Once the sensitivity terms are estimated, we computed the gains of the C-CO<sub>2</sub> and C-CH<sub>4</sub> feedbacks when each gas is considered alone (Eqs. 7a and b), as well as the interaction between these feedbacks as defined in Eqs. (10) and (11). Combining our range of  $\gamma_M$  (from  $-1.83$  to  $2.70 \text{ GtC K}^{-1}$ ; see above) we find the C-CH<sub>4</sub> feedback gain,  $g_M$ , when CH<sub>4</sub> is considered alone, ranging between  $-0.016$  and  $0.024$  by 2100, respectively obtained for the best ORCHIDEE-WET estimated  $\gamma_M$  and literature estimated  $\gamma_M$ . The sign

of the gain is controlled by the  $\gamma_M$ . Negative gains are due to the negative wetland emission sensitivity to climate found in ORCHIDEE-WET. For the C-CO<sub>2</sub> feedback gain, using our ORCHIDEE-WET simulations, we find a value of 0.113, slightly higher than the value found in Friedlingstein et al. (2006).

Going back to Eqs. (10) and (11), we can now calculate the cross-gains terms when not accounting for the fertilization interaction. For CH<sub>4</sub> concentration changes (Eq. 10), the  $g_M$  gain is augmented by  $g_C \cdot g_M / (1 - g_C)$ , the additional gain due to the interaction between CO<sub>2</sub> and CH<sub>4</sub>. Using a  $\gamma_M$  of  $-1.83 \text{ GtC K}^{-1}$ , this cross-gain is equal to  $-0.0017$  which represents a correction of  $\sim 10\%$  of the initial gain  $g_M$ . Similarly, for CO<sub>2</sub> (Eq. 11), the cross-gain term  $g_C \cdot g_M / (1 - g_M)$  amounts to  $-0.0015$  which represents only  $\sim 1.5\%$  of  $g_C$ . The CO<sub>2</sub> contribution to CH<sub>4</sub> is larger than the reciprocal because climate has a larger absolute effect on the net CO<sub>2</sub> flux than on the CH<sub>4</sub> emissions from wetlands. If we use the upper estimate of  $g_M$ , the cross-gains due to the interactions between C-CO<sub>2</sub> and C-CH<sub>4</sub> feedbacks have similar effects on  $g_M$  and  $g_C$  (cross-gain  $\sim 13\%$  of  $g_M$  and  $\sim 3\%$  of  $g_C$ ).

#### 4.2 Effect on atmospheric CO<sub>2</sub>, CH<sub>4</sub> and global temperature

We compute the changes of CH<sub>4</sub> in the atmosphere between future (2100) and pre-industrial time,  $\Delta\text{CH}_4$ , in the case of C-CH<sub>4</sub> feedback alone, and then with cross-feedbacks accounted, for using Eq. (10) (or equations from Appendix B for the most general case).  $\Delta\text{CH}_4$  and  $\Delta\text{CO}_2$  are expressed in the following in ppbv and ppmv, respectively. Figure 5a shows the incremental changes in the calculated  $\Delta\text{CH}_4$  when accounting for successive gains.  $\Delta\text{CH}_4^{\text{unc}}$  is the change in CH<sub>4</sub> in the absence of any retroaction, as given by Eq. (6). Then we account successively for the climate-CH<sub>4</sub> feedback (i.e. CH<sub>4</sub> emissions dependence on CH<sub>4</sub> induced temperature change), the *climate interaction* as explained in Sect. 2.2 (i.e. temperature dependence to atmospheric CO<sub>2</sub>;  $\alpha_C \neq 0$ ) and the *fertilization interaction* (i.e. CH<sub>4</sub> emissions dependence to atmospheric CO<sub>2</sub>;  $\beta_{C \rightarrow M} \neq 0$ ). Figure 5b shows the same calculation, but for  $\Delta\text{CO}_2$ . For each gas, we plotted both the case with (solid line) and without (dashed line) anthropogenic emissions of the other gas. All calculations were done with the ORCHIDEE-WET based estimated  $\beta_{C \rightarrow M}$ . However, given the high uncertainty on  $\gamma_M$ , we plotted also the case with the positive  $\gamma_M$  derived from literature (in grey) or with the negative  $\gamma_M$  based on the best ORCHIDEE-WET estimation (in green). We add also the case where  $T_{\text{mean}}$  is variable in time (in blue). As a first check on our framework, we compared the uncoupled estimates of  $\Delta\text{CH}_4^{\text{unc}}$  and  $\Delta\text{CO}_2^{\text{unc}}$  to the values given by the SRES-A2 scenario, where none of the feedbacks presented here were accounted for. We find a CH<sub>4</sub> concentration increase by 2100 of 3030 ppbv and a CO<sub>2</sub> concentration change of 496 ppm, not far from the SRES-A2 concentration changes (2925 ppbv for CH<sub>4</sub> and

5450 ppm for CO<sub>2</sub>; IPCC, 2001). This indicates that, for CH<sub>4</sub>, the assumption of a constant lifetime and the use of the scaling parameter  $\mu$  are appropriate. We note that the CO<sub>2</sub> concentrations given in IPCC (2001) already accounts for a C-CO<sub>2</sub> feedback.

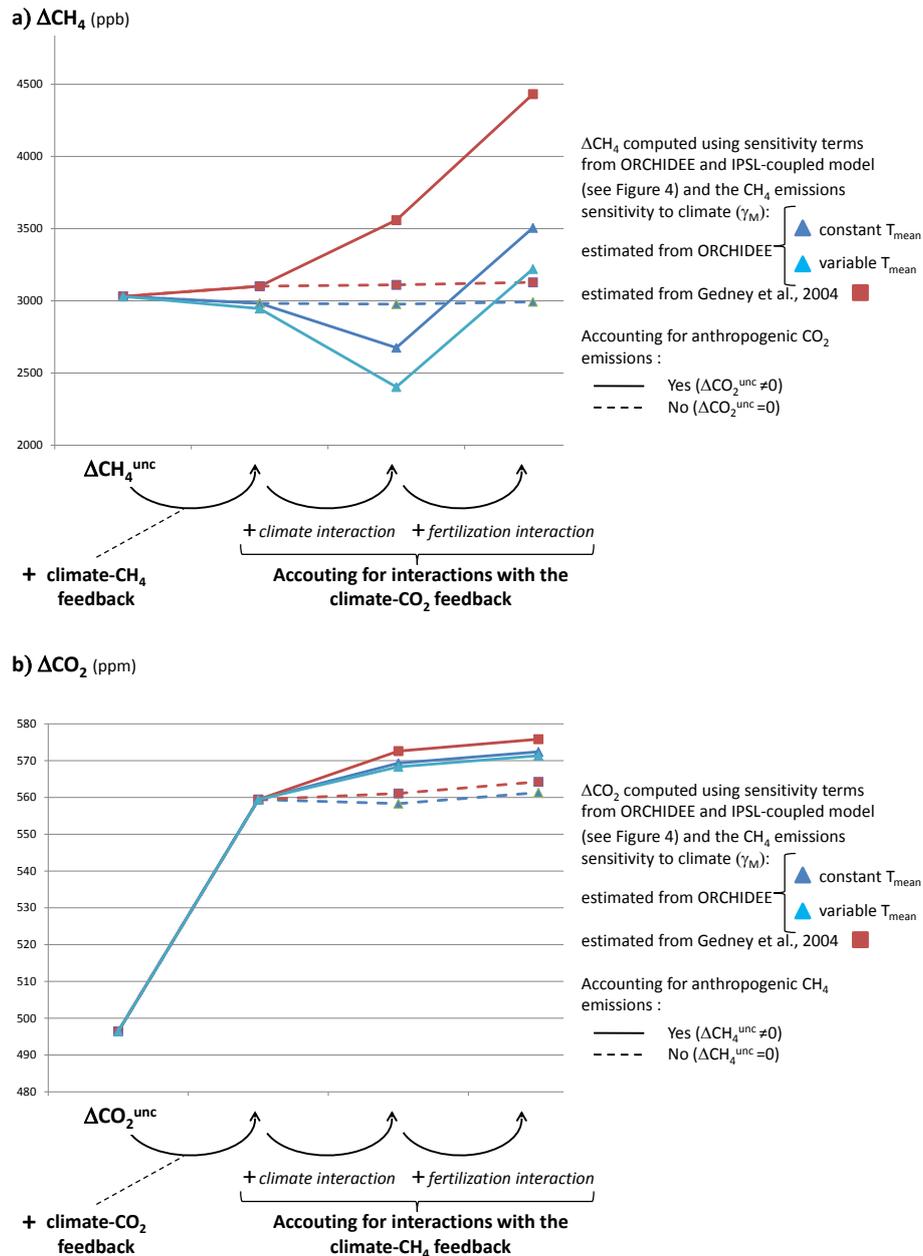
Concerning CH<sub>4</sub> (Fig. 5a), accounting for the different feedbacks does not have a large effect on the calculated CH<sub>4</sub> concentration as long as anthropogenic CO<sub>2</sub> emissions are neglected (dashed lines). This is because the climate effect of CH<sub>4</sub> anthropogenic emissions alone is too weak to generate a non-negligible C-CH<sub>4</sub> or C-CO<sub>2</sub> feedback. Only the CO<sub>2</sub> emissions induced climate change leads to a large effect on CH<sub>4</sub> emissions and CO<sub>2</sub> sinks and hence modify the calculated CH<sub>4</sub> concentration. This is clearly different for the CO<sub>2</sub> (Fig. 5b) for which its own feedback with the climate explains most of the  $\Delta\text{CO}_2$  (at least 80 % of the  $\Delta\text{CO}_2$  given with all interactions).

When anthropogenic CO<sub>2</sub> emissions are included, the large change in atmospheric CO<sub>2</sub> affects CH<sub>4</sub> emissions through (i) the climate effect on CH<sub>4</sub> emissions and (ii) the fertilization effect on substrate. Figure 5a shows that these two terms are important. Depending on the sign of  $\gamma_M$ , the CO<sub>2</sub> induced climate effect will enhance (grey line) by 457 ppbv or reduce (green line) by 310 ppbv the calculated CH<sub>4</sub> concentration. This *climate interaction* includes temperature change due modification of  $\Delta\text{CO}_2$  caused by both anthropogenic emissions and C-CO<sub>2</sub> feedback. The CO<sub>2</sub> fertilization effect is always positive and, depending on the previous value of  $\gamma_M$ , further increase (red line) or compensate (blue line) the CO<sub>2</sub> induced climate effect.

When accounting for all interactions between CO<sub>2</sub> and CH<sub>4</sub>,  $\Delta\text{CH}_4$  is 1400 ppbv larger than the uncoupled  $\Delta\text{CH}_4^{\text{unc}}$  in the case of positive  $\gamma_M$  and 475 ppbv larger in the negative case (with constant  $T_{\text{mean}}$ ). Variable  $T_{\text{mean}}$  leads to an increase of only 190 ppbv.

For CO<sub>2</sub> (Fig. 5b), as mentioned above, most of the change in the calculated concentration comes from the C-CO<sub>2</sub> gain, where  $\Delta\text{CO}_2$  rise from 495 to 560 ppm. Accounting for the interactions with CH<sub>4</sub> slightly changes this value and can lead to an increase of 15 ppm. The climate change induced by anthropogenic CH<sub>4</sub> emissions is preponderant to the C-CO<sub>2</sub>-CH<sub>4</sub> effect on the  $\Delta\text{CO}_2$  (comparison between dash and plain lines) while the C-CH<sub>4</sub> feedback induced climate change has only a small effect. In all the cases, the increase in wetland CH<sub>4</sub> emissions induced by the *fertilization interaction* has a little effect on  $\Delta\text{CO}_2$  ( $\sim 3$  ppm).

The change in global temperature,  $\Delta T$  that would follow these different changes in atmospheric CO<sub>2</sub> and CH<sub>4</sub> can be estimated using Eq. (2b). Several combinations of  $\Delta\text{CH}_4$  and  $\Delta\text{CO}_2$  are possible, according to the interactions that are accounted for. Here, we limit the  $\Delta T$  computation to specific cases. In the absence of anthropogenic CH<sub>4</sub> emissions, accounting for C-CO<sub>2</sub> feedbacks leads  $\Delta T$  to rise from 3.05 to 3.44 K. Accounting for anthropogenic CH<sub>4</sub> emissions in addition leads  $\Delta T$  to rise to 3.98 K. In the case where  $\gamma_M$



**Fig. 5.** Evolution of the difference in CH<sub>4</sub> (a) and CO<sub>2</sub> (b) atmospheric concentration between future and pre-industrial time accounting or not for feedback with climate and interactions with the other feedback. “Climate interaction” and “Fertilization interaction” report to definitions into Sect. 2.2 of the manuscript. To reminder, concerning CH<sub>4</sub> (respectively CO<sub>2</sub>), “climate interaction” means that climate is also a function of CO<sub>2</sub> (respectively CH<sub>4</sub>). Accounting for “fertilization interaction” consists in accounting for wetland CH<sub>4</sub> emissions dependence to atmospheric CO<sub>2</sub>.

is negative, adding the C-CH<sub>4</sub> feedback and its interactions with C-CO<sub>2</sub> leads to a  $\Delta T$  of 4.14 K. The same addition with positive  $\gamma_M$  leads to a  $\Delta T$  of 4.33 K. The estimate of  $\Delta T$  when accounting for the C-CH<sub>4</sub> feedback and its interaction with CO<sub>2</sub> is non-negligible (in comparison with the warming directly due to anthropogenic CH<sub>4</sub> emissions) but strongly depends on the sensitivity of wetland CH<sub>4</sub> emissions to climate.

## 5 Discussion

In the above calculations, the highest uncertainty comes from the sensitivity of wetland CH<sub>4</sub> emissions to climate ( $\gamma_M$ ). Contrary to SWF04, GCH04 and EMA08, we find a negative value for  $\gamma_M$ . In our ORCHIDEE-WET based estimation, the climate-driven change in wetland extent plays a large role in the overall emission reduction. As explained

above, EMA08 did not account for change in wetland extent. GCH04 obtained also a weak wetland reduction, while SWF04 simulates a small increase in wetland extent. However, as both GCH04 and our study use a mechanistic approach (TOPMODEL) as opposed to the empirical approach used by SWF04, we have a higher confidence in a reduction of wetland surfaces. Regardless, large uncertainty remains on the representation of wetland extent (e.g. Bohn and Lettenmaier, 2011; Ringeval et al., 2011). Despite a decrease in wetland extension, GCH04 shows an increase in overall emissions. That is to say their emission rate increases and compensates for the reduction of emitting surface, a feature we do not find with ORCHIDEE-WET.

GCH04 tested a large range of methanogenesis  $Q_{10}$  values with an upper range higher than the standard value we used in this study. Even if there is a clear evidence that methanogenesis rates increase with temperature (e.g. Conrad, 1989), much uncertainty about the  $Q_{10}$  value remains (Valentine et al., 1994). To investigate the role played by this parameter and to test the case in which a higher  $Q_{10}$  can counterbalance the decrease in wetland extent, we performed an additional simulation with a  $Q_{10}$  of 5.5 in accordance with greatest value of GCH04 (see Sect. 3.2). In the case where  $T_{\text{mean}}$  is variable, we obtain a more negative value for  $\gamma_M$ . An indirect effect of a  $Q_{10}$  increase is a little change in the preindustrial latitudinal distribution of wetland emissions (not shown). When  $T_{\text{mean}}$  is considered as a variable, changing the  $Q_{10}$  has a very little impact on the methanogenesis rate which cannot counterbalance the effect of change in latitudinal emissions. Thus, the  $\gamma_M$  is more negative ( $-4.85$ ) in this case. In the case where  $T_{\text{mean}}$  is constant (a configuration more directly comparable to GCH04), we find a smaller but still negative value for  $\gamma_M$  at the global scale, contrary to GCH04.

In ORCHIDEE-WET, the evolution of CH<sub>4</sub> flux density is explained by a balance between an increase of methanogenesis rate due to its temperature dependence and a decrease of substrate. In our results, with the exception of some locations where the increase due to temperature dependence seems to be the predominant factor, the decrease of substrate contributes to limit this increase. Neither GCH04 nor SWF04 and EMA08 account for a climate-induced change in substrate, they only account for a methanogenesis dependence on temperature. For the sake of comparison, we calculate the change in wetland CH<sub>4</sub> emissions which ORCHIDEE would simulate by 2100 if soil carbon pools were unchanged (i.e. held at the initial pre-industrial value). We estimate roughly this for each simulation by multiplying the CH<sub>4</sub> flux densities at each year and at each grid-cell by the ratio of pre-industrial active soil carbon to the stock of the simulation considered. The different effects are summarized in Table 3. In the  $Q_{10} = 5.5$  case, removing the variability in soil carbon switches the climate effect on the difference between wetland CH<sub>4</sub> emissions in 2100 and pre-industrial time from a decrease of 10 % to an increase of 84 %. Hence, we find that

**Table 3.** CO<sub>2</sub> alone, climate alone and combined effect on difference in global wetland CH<sub>4</sub> emissions between 2099–2090 and 1860–1869. Results are done for simulations with a constant  $T_{\text{mean}}$ . CH<sub>4</sub> emissions with pre-industrial soil carbon (last line of the table) correspond to a sensitivity test done a posteriori (cf. discussion). Results are done in percent of global pre-industrial emissions. In our study, CO<sub>2</sub> effect and climate alone are considered independent and are derived from only 3 simulations (cf. Table 1) thus last row of the Table 3 is the sum of the two previous rows.

| CH <sub>4</sub> Flux densities |             | Wetland extent | CO <sub>2</sub> effect | Climate effect | CO <sub>2</sub> + Climate effect |
|--------------------------------|-------------|----------------|------------------------|----------------|----------------------------------|
| $Q_{10}$                       | Soil carbon |                |                        |                |                                  |
| 3                              | T           | T              | +134 %                 | −64            | +69                              |
| 3                              | T           | PI             | +83                    | +64            | +148                             |
| 3                              | PI          | T              | +34                    | +25            | +59                              |
| 3                              | PI          | PI             | +3                     | +134           | +137                             |
| 5.5                            | T           | T              | +138                   | −10            | +128                             |
| 5.5                            | T           | PI             | +85                    | +209           | +294                             |
| 5.5                            | PI          | T              | +33                    | +84            | +117                             |
| 5.5                            | PI          | PI             | +1                     | +274           | +275                             |

PI: Pre-industrial; T: Transient over 1860–2100

if we assume no change in substrate, we also find a positive  $\gamma_M$  as in GCH04.

Thus, a crucial question for understanding changes to the CH<sub>4</sub> flux density is whether methanogenesis substrate will change in the future as a response to global warming. In ORCHIDEE-WET, we account for this change, which we model as the active soil carbon pool, whereas GCH04 and SWF04 do not account for any change.

The ORCHIDEE modeled reduction of active soil carbon pools by future warming is driven by a change in inputs (NPP) and outputs (CO<sub>2</sub> heterotrophic respiration). The active soil carbon used as a CH<sub>4</sub> production substrate is the total active carbon stock of all natural plant functional types in each grid-cell. The current parameterization may not capture realistically productivity and decomposition processes in northern wetlands soil (Ise et al., 2008; Bridgman et al., 2006). In particular, in some regions, NPP decreases under future climate change because of a decrease of plant water availability. This might not be realistic for the water-saturated fraction of such grid-cell.

Regarding heterotrophic respiration, in a wetland, the rate of soil organic carbon decomposition is lower due to anoxic conditions. In fact, data from permanently inundated sites shows a slow-down of decomposition processes (Freeman et al., 2002) yielding to carbon accumulation in the soil, i.e. peat growth (Clymo et al., 1998). In those wetlands which are saturated throughout the year, the direct respiration of soil carbon into CO<sub>2</sub> is thus strongly inhibited. Despite this inhibition, the decomposed carbon in a wetland is mainly turned into CO<sub>2</sub> and not to CH<sub>4</sub>. The observed range of CH<sub>4</sub>/CO<sub>2</sub> ratios in anaerobic conditions is large (from 0.0001 to 1.7, see e.g. Wania et al., 2010; Updegraff et al., 2001;

Rinne et al., 2007). Neither the inhibition of decomposition into CO<sub>2</sub> nor the effect of CH<sub>4</sub> decomposition on soil carbon pool is accounted for in ORCHIDEE-WET.

Lastly, CO<sub>2</sub> heterotrophic respiration in our model does increase with temperature in the model ( $Q_{10}=2$ ). Again, we might overestimate this effect over wetlands, as one would expect the wetland soils decomposers to be less responsive to temperature because of the anoxic conditions. Flooding contributes to decrease the apparent temperature sensitivity of decomposition (Davidson and Janssens, 2006). Nevertheless, it seems unlikely that the methanogenesis substrate in wetland soils would not respond at all to climate as in GCH04, SWF04 and EMA08.

Our results point to the necessity of being able to accurately simulate the changes in methanogenesis as well as its available substrate as it was suggested by Kaplan (2002) over other time periods. Having wetland-specific plant functional types with their own productivity and soil decomposition parameters as done by Wania et al. (2009) seems necessary. It enables the model to also account for changes in wetland vegetation composition under future climate change (Ström et al., 2003). Regardless, large uncertainties remain on how to represent the methanogenesis substrate in global models, mainly because of the challenge of upscaling local information on, for example, substrate available for methanogenesis (Limpens et al., 2008; Zona et al., 2009) to large scale quantities such as productivity or soil carbon active pool production (Christensen et al., 2003).

The difference of results obtained for simulations performed with constant or variable  $T_{\text{mean}}$  underlines the effect of the uncertainty in the micro-organisms response to change in environment on global wetland CH<sub>4</sub> emissions. As underlined by lots of studies (e.g. Rainey and Travisano, 1998), microorganisms are likely to adapt to changing conditions. This adaptation could be done either by mutation or by change in communities, and implies that the microbial community is already highly optimized for a given site and can thus benefit (or suffer) less from changing climate than if adaptation is not accounted for. But we found that accounting or not for this adaptation will not change the sign of the climate effect on wetland CH<sub>4</sub> emissions as much as the variation in wetland extent accounts for.

Another uncertainty relates to the wetland CH<sub>4</sub> emissions' sensitivity to atmospheric CO<sub>2</sub> ( $\beta_{C \rightarrow M}$ ). Large increases in CH<sub>4</sub> emissions in response to elevated CO<sub>2</sub> can occur in a wide variety of wetland ecosystems (Vann and Megonigal, 2003). One hypothesis to explain this increase in CH<sub>4</sub> emissions is the rise of photosynthates that become available for fermentation through root exudation or rapid root turnover via enhanced photosynthesis (Dacey et al., 1994; Vann and Megonigal, 2003). In herbaceous dominated wetland, another possibility is the increase of the plant-mediated transport via an increase in plant biomass and thus in tiller number/stem weight at maturity (Vann and Megonigal, 2003). In our modelling approach, we represent increase in substrate

for methanogenesis only through variation in active carbon pool. We do not represent roots exudates in ORCHIDEE. The increase in plant transport is indirectly accounted for via the CO<sub>2</sub>-induced increase in LAI modelling by ORCHIDEE. Further investigation is needed to quantify the contribution of each of these processes to the response to CO<sub>2</sub> we simulate and how they agree with observations. Moreover, experimentation had underlined many uncertainties linked to interactions with nutrient cycle, which are not accounted currently for in the model. Indeed, direct fertilization effects of CO<sub>2</sub> could be balanced by their effects on the substrate quality and thus on the decomposition rate (Pancotto et al., 2010). Other uncertainties are linked to the change in wetland plant physiology (e.g. modification of the turnover rate under high CO<sub>2</sub> level; Megonigal and Schelsinger, 1997) or to modification of oxidation rate in the case of change in transport by plant (higher supply of oxygen transport into the rhizosphere; Kang et al., 2001).

Another limitation of our approach is that we did not account for permafrost carbon decomposition and associated CO<sub>2</sub> and CH<sub>4</sub> emissions. The release of CH<sub>4</sub> by decomposition of thawed deep soil carbon under increase of active layer (Khvorostyanov et al., 2008) could dramatically increase to the CH<sub>4</sub> emissions sensitivity to climate.

## 6 Conclusions

In this study, we have generalized the theoretical analysis of Friedlingstein et al. (2003) for the interplay between the climate-carbon cycle and the climate-CH<sub>4</sub> feedback. These two feedbacks are not independent, instead they interact through two processes. The first is that a warming due to a CO<sub>2</sub> release would have an effect on wetland CH<sub>4</sub> emissions through changes in available substrate, methanogenesis rate, and the extent of wetland areas. Reciprocally, a CH<sub>4</sub>-induced warming would affect carbon storage and hence atmospheric CO<sub>2</sub>. The second is that increased atmospheric CO<sub>2</sub> would increase the amount of available organic substrate for methanogenesis (via enhancement of plant photosynthesis), in the absence of other limitations or dynamic vegetation responses, and modify the plant-mediated transport intensity and hence increase CH<sub>4</sub> emissions from wetlands. Our theoretical approach makes it possible to express the additional gains arising from these interactions and to quantify the effect on atmospheric CH<sub>4</sub> and CO<sub>2</sub> concentrations. High uncertainty remains, even for the sign and amplitude of the C-CH<sub>4</sub> feedback gain essentially due to the lack of knowledge about wetland extent evolution as well as the representation of wetland soil carbon dynamics in global models. Nevertheless, we find that, when each gas is considered alone, the gain of the C-CH<sub>4</sub> feedback (−0.016 to 0.024) is much lower than the C-CO<sub>2</sub> feedback gain (~0.113). Concerning the interaction between the two feedbacks, because of the much larger radiative forcing associated with CO<sub>2</sub> than

CH<sub>4</sub> (in the scenario used here), the cross feedback effects are only significant on atmospheric CH<sub>4</sub> concentration when anthropogenic CO<sub>2</sub> emissions are included. The different interactions between the two feedbacks can offset or add up, based on the sign of the C-CH<sub>4</sub> feedback gain. Thus, ΔCH<sub>4</sub> could be increased between 475 and 1400 ppb due to feedbacks, with various effects on ΔT.

Still, large uncertainties remain in the C-CH<sub>4</sub> feedback gain. These mainly arise from (i) the sensitivity of both the wetland extent and methanogenesis substrate to climate as well as (ii) the CO<sub>2</sub> fertilizing effect on the wetland CH<sub>4</sub> emissions. Our results suggest that, in particular, the representation of methanogenesis substrate and its specific local-scale response to the larger scale global change is an area that deserves further development.

### Appendix A

#### Getting of Eq. (9) using equations relative to C-CO<sub>2</sub> feedback

The only one modification of the following equations as compared as Friedlingstein et al. (2003) is the CH<sub>4</sub>-dependance of ΔT. In the following equations, F<sub>CF</sub> is the integral of anthropogenic CO<sub>2</sub> emissions and F<sub>C<sup>add</sup></sub>(GtC) is the integral of the change in natural net fluxes between surface and atmosphere. We had brought together ocean and continental surface.

$$\begin{cases} \Delta\text{CO}_2 = F_{CF} - F_C^{\text{add}} \\ F_C^{\text{add}} = \beta_C \Delta\text{CO}_2 + \gamma_C \Delta T \\ \Delta T = \alpha_C \Delta\text{CO}_2 + \alpha_M \Delta\text{CH}_4 \end{cases} \quad (\text{A1})$$

$$\Rightarrow (1 + \beta_C + \gamma_C \alpha_C) \Delta\text{CO}_2 + \gamma_C \alpha_M \Delta\text{CH}_4 = F_{CF}$$

### Appendix B

#### Equations in the most general feedback calculation framework (i.e. with fertilization interaction)

$$\begin{aligned} \Delta\text{CH}_4^{\text{COU}} & \quad (\text{B1}) \\ &= \frac{1}{1 - \left[ g_M - \frac{\beta_{C \rightarrow M} \alpha_M \gamma_C}{(1 + \beta_C + \gamma_C \alpha_C) \left(1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M\right)} + \frac{g_C g_M}{1 - g_C} \right]} \Delta\text{CH}_4^{\text{UNC}} \\ &+ \left( \frac{\beta_{C \rightarrow M}}{\left(1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M\right)} + \frac{\alpha_C}{\alpha_M} g_M \right) \cdot \frac{1}{(1 - g_C)} \\ &\cdot \frac{1}{1 - \left[ g_M - \frac{\beta_{C \rightarrow M} \alpha_M \gamma_C}{(1 + \beta_C + \gamma_C \alpha_C) \left(1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M\right)} + \frac{g_C g_M}{1 - g_C} \right]} \Delta\text{CO}_2^{\text{UNC}} \end{aligned}$$

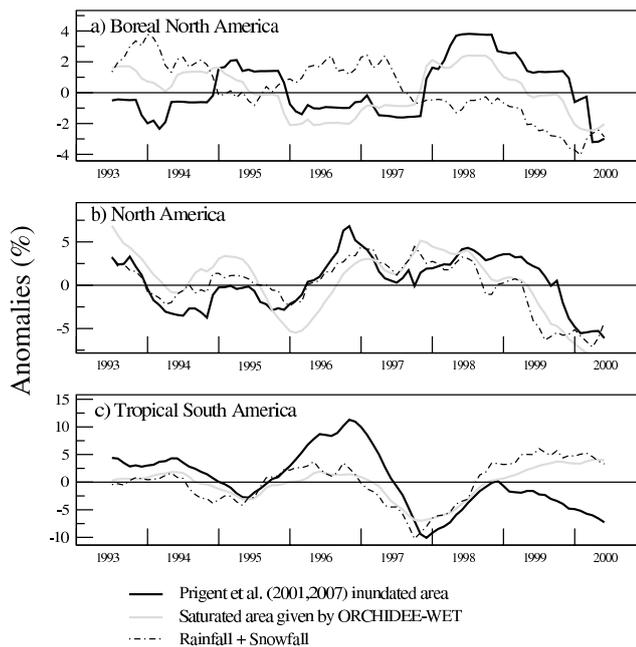
$$\begin{aligned} \Delta\text{CO}_2^{\text{COU}} & \quad (\text{B2}) \\ &= \frac{1}{1 - \left[ g_C + \frac{\beta_{C \rightarrow M} \alpha_M}{\alpha_C \left(1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M - \gamma_M \alpha_M\right)} g_C + \frac{g_C g_M}{1 - g_M} \right]} \Delta\text{CO}_2^{\text{UNC}} \\ &+ \frac{\alpha_M}{\alpha_C} \cdot \frac{g_C}{1 - g_M} \\ &\cdot \frac{1}{1 - \left[ g_C + \frac{\beta_{C \rightarrow M} \alpha_M}{\alpha_C \left(1 + \frac{\alpha_C}{\tau} \Delta t - \beta_M - \gamma_M \alpha_M\right)} g_C + \frac{g_C g_M}{1 - g_M} \right]} \Delta\text{CH}_4^{\text{UNC}} \end{aligned}$$

### Appendix C

#### Details about the way to compute wetland extent dynamic

In ORCHIDEE-WET, wetland area dynamics were computed using the TOPMODEL (Beven and Kirkby, 1979) approach of Decharme and Douville (2006). For each grid-cell, using both topographic heterogeneities and soil moisture computed by ORCHIDEE-WET, the TOPMODEL subroutine computes a sub-grid saturated fraction. The simulated space-time distribution of saturated soils was evaluated globally against data from a suite of satellite observations from multiple sensors (Prigent et al., 2001, 2007) interpolated at 1° resolution. Multi-satellite data gives information about inundated fraction (i.e. water-logged soil) whereas our ORCHIDEE-WET model gives the saturated fraction. Thus, the two variables are not comparable in absolute value; saturated area being not necessary free-water surface/stagnant water-logged (over 1993–2000, mean Prigent et al. (2007) areas = 2.8 % of global surface, mean ORCHIDEE-WET areas = 11.2 %). Moreover, absolute values of Prigent et al. (2007) data is prone to some uncertainties: multi-satellite approach has difficulty to catch small, isolated water patches in areas with large dry fraction; as well as small dry patch in areas with large wet fraction. The product could be also affected by ocean contamination on the coast. That is why we focus our evaluation step only comparing normalized variability of Prigent et al. (2007) data and one of ORCHIDEE-WET areas. We show in Fig. C1 comparison between year-to-year variability for these two distributions for the period 1993–2000 for three large regions. More details about this evaluation will be found in Ringeval et al. (2010, 2011).

Saturated areas as simulated by ORCHIDEE-WET do not correspond necessarily to water-logged soil and emitting wetland areas. Gedney and Cox (2003) used also a TOPMODEL approach to diagnose wetland area and raised the same issue. They introduced a global scaling factor in order to simulate a global wetland extent in agreement with observations taken from Aselmann and Crutzen (1989). Here, we opted for a different method and used a climatology (1993–2000) constructed from the Prigent et al. (2007) dataset as a



**Fig. C1.** Comparison between year-to-year variability for inundated area of Prigent et al. (2007) (black curve) and saturated area simulated by ORCHIDEE-WET (grey curve) over 1993–2000 for three regions for instance (Boreal North America, North America and Tropical South America). Regions definitions come from the TRANSCOM atmospheric inversions intercomparison project (Gurney et al., 2003). Anomalies of precipitations from Sheffield et al. (2006) climate forcing data are also added (dashed curve).

baseline for our present day estimate. Future simulated wetland extent was then calculated from the ORCHIDEE-WET simulations, corrected to subtract the systematic biases between the present day simulated saturated area and observed wetland distributions. Only the mean climatology (average of 1993–2000) of the modelled wetland extent is normalized to the same climatology from Prigent et al. (2007) data. As underlined by sensitivity tests (not shown), the way in which the bias is removed (absolute or relative anomalies; Francois et al., 1998) has no influence on the role played by wetland extent in the following (see Sect. 3.1.3).

## Appendix D

### Incorporation of Walter et al. (2001) model into ORCHIDEE

As mentioned in Sect. 3.1.1, when including the Walter et al. (2001) CH<sub>4</sub> emission model in ORCHIDEE, we made the same following modification as in Ringeval et al. (2010): substrate for methanogenesis is computed from active soil organic carbon computed by ORCHIDEE rather using linear regression versus soil temperature and Net Primary

Productivity (NPP) based on 6 sites as it was done by Walter et al. (2001). Contrary to Ringeval et al. (2010), ORCHIDEE-WET was run here not assuming absence of water stress for vegetation. Thus ORCHIDEE carbon stocks are different in the two studies and new optimization for the base rate of methanogenesis parameter is necessary ( $\alpha_0$  in Eq. 2 of Ringeval et al., 2010). To do so, same approach as in Ringeval et al. (2010) is used: simulated CH<sub>4</sub> fluxes with ORCHIDEE-WET were performed on 3 sites (Abisko, Jackowicz-Korczynski et al., 2010; Michigan, Shannon and White, 1994 and Panama, Keller, 1990) using the monthly NCEP climate forcing data corrected by CRU (n. Viovy et al., personal communication, 2009, <http://dods.extra.cea.fr/data/p529viov/cruncep/readme.htm>) and compared to the site level observations. Optimized values are respectively:  $3.51$ ,  $2.63$  and  $15.77 \times 10^{-6} \text{ m}^{-1} \text{ month}^{-1}$ . Only three sites are chosen because we did not optimize the metanotrophy-related parameters and hence we restrict our calibration only to the flooded sites (i.e. sites where the water table depth reaches soil surface) and flooded period. Contrary to Ringeval et al. (2010), identification of each grid-cell to a wetland type (i.e. sharing the same optimized parameter as Abisko, Michigan or Panama) is not based on latitudinal criteria yet but on a criteria of vegetation type.

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