Clim. Past Discuss., 8, 3093–3142, 2012 www.clim-past-discuss.net/8/3093/2012/ doi:10.5194/cpd-8-3093-2012 © Author(s) 2012. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Climate of the Past (CP). Please refer to the corresponding final paper in CP if available.

Response of methane emissions from wetlands to the Last Glacial Maximum and an idealized Dansgaard-Oeschger climate event: insights from two models of different complexity

B. Ringeval^{1,2,3,*}, P. O. Hopcroft¹, P. J. Valdes¹, P. Ciais³, G. Ramstein³, A. J. Dolman², and M. Kageyama³

¹Bristol Research Initiative for the Dynamic Global Environment (BRIDGE), School of Geographical Sciences, University of Bristol, Bristol, BS8 1SS, UK ²VU University Amsterdam, Department of Earth Sciences, Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

³Laboratoire des sciences du climat et de l'environnement (LSCE),

UMR8212 CEA/CNRS/UVSQ, CEA Saclay – Orme des Merisiers, Gif-sur-Yvette, 91191, France

^{*}now at: Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht, The Netherlands



Received: 17 July 2012 – Accepted: 28 July 2012 – Published: 1 August 2012

Correspondence to: B. Ringeval (b.ringeval@sron.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.



Abstract

The role of different sources and sinks of CH_4 in changes in atmospheric methane ([CH_4]) concentration during the last 100 000 yr is still not fully understood. In particular, the magnitude of the change in wetland CH_4 emissions at the last glacial maximum

- ⁵ (LGM) relative to the pre-industrial period (PI) as well as during abrupt climatic warmings or Dansgaard-Oeschger events of the last glacial period, is largely unconstrained. In the present study, we aim to understand the uncertainties related to the parameterization of the wetland CH₄ emissions models relevant to these time periods by using two wetland models of different complexity (SDGVM and ORCHIDEE). These models
- ¹⁰ have been forced by identical climate fields from low resolution coupled atmosphereocean general circulation model (FAMOUS) simulations of these time periods. Both emissions models simulate a large decrease in emissions during LGM in comparison to PI consistent with ice core observations and previous modeling studies. The global reduction is much larger in ORCHIDEE than in SDGVM (respectively -67 and -46 %),
- ¹⁵ and whilst the differences can be partially explained by different model sensitivities to temperature (i.e. Q_{10} values), the major reason for spatial differences between the models, is the inclusion of freezing of soil water in ORCHIDEE and the resultant impact on methanogenesis substrate availability in boreal regions. Besides, a sensitivity test performed with ORCHIDEE in which the methanogenesis substrate sensitivity to the
- precipitations is modified to be more realistic gives a LGM reduction of -36%. The range of the global LGM decrease is still prone to uncertainty and here, we underline its sensitivity to different process parameterizations. Over the course of an idealized D-O warming, the magnitude of the change in wetland CH₄ emissions simulated by the two models at global scale is very similar at around 15 Tg yr^{-1} , but this is only around
- 25 % of the ice-core measured changes in [CH₄]. The two models do show regional differences in emissions sensitivity to climate with much larger magnitudes of Northern and Southern tropical anomalies in ORCHIDEE. However, the simulated Northern and Southern tropical anomalies partially compensate each other in both models limiting



the net flux change. Future work may need to consider the inclusion of more detailed wetland processes (e.g. linked to permafrost or tropical floodplains), other non-wetland CH_4 sources or different patterns of D-O climate change in order to be able to reconcile emissions estimates with the ice-core data for rapid CH_4 events.

5 1 Introduction

Reconstructions from polar ice cores show that the atmospheric CH_4 concentration ([CH_4]) has varied greatly as a function of past climate changes. Spectral analyses performed by (Loulergue et al., 2008) indicate that the variability in [CH_4] over the last 800 kyr is dominated by the 100 kyr glacial–interglacial cycles and by the preces-

- sional component of Milankovitch cycles. Suggested underlying mechanisms involve a link between wetland extent and northern ice sheet dynamics as well as between the strengths of tropical sources/sinks and tropical climate patterns, for example through monsoon systems and via the position of the intertropical convergence zone (Loulergue et al., 2008; Singarayer et al., 2011).
- Large uncertainty remains surrounding to what extent the main natural source (wet-lands) contributed to the interglacial-glacial change in [CH₄], and whilst earlier bottom-up modeling studies could not explain the interglacial-glacial change in [CH₄] with a reduction in wetland CH₄ emissions alone in response to cooling and change in hydro-logical cycle (Kaplan et al., 2006; Valdes et al., 2005), more recent studies suggest that
 a modification in sink strength is neither required (Weber et al., 2010) nor reproduced
- by atmospheric chemistry model simulations (Levine et al., 2011).

Overlaid on the glacial/inter-glacial changes, the climate of the Pleistocene was also prone to a strong climatic variability on a millennial time-scale; the most extreme feature of which is a series of abrupt jumps in Greenland temperature of between 8°C and 16°C over the course of 10–40 yr (e.g. Wolff et al., 2010). These abrupt warm-

²⁵ and 16 °C over the course of 10–40 yr (e.g. Wolff et al., 2010). These abrupt warming called Dansgaard-Oeschger (D-O) events also have counterparts in the ice-core records of CH₄, with CH₄ jumps of up to two-thirds the glacial-interglacial concentration



change. This suggests a coupling between climate changes associated with D-O warming events and the global response of the CH_4 biogeochemical cycles.

Until recently bottom-up modelling approaches over D-O events were limited not only by the lack of process-based wetland CH₄ emissions models, but also by the absence of climate forcing data representative of these events, necessary to drive wetland emission models. Recently, progresses have been made in both directions. Firstly, a number of coupled ocean-atmosphere general circulation models (OAGCMs) have been used to simulate important paleoclimate events (e.g. Paleoclimate Model Intercomparison Project – PMIP1 then PMIP2; Braconnot et al., 2007) and in particular concerning climate transition and millennial-scale variation (e.g. Singarayer and Valdes, 2010; Kageyama et al., 2009). While many uncertainties remain, the most commonly invoked mechanism to explain the glacial millennial climate variability is related to different states of the Atlantic Meridional Overturning Circulation (AMOC). OAGCMs can reproduce part of the D-O events (e.g. Kageyama et al., 2009) by starting at LGM equilibrium then modifying AMOC by imposing freshwater perturbations in the North

Atlantic (the so-called "water-hosing experiments").

Further, global models have been recently developed to incorporate explicitly wetlands CH_4 emissions in dynamic global vegetation models (DGVMs) (e.g. Wania et al., 2010; Riley et al., 2011; Ringeval et al., 2011; Petrescu et al., 2010). The strategy used to simulate wetlands CH_4 emissions variant from and DCV(M to another. The differences

to simulate wetlands CH₄ emissions varies from one DGVM to another. The differences between the models arise from both the inclusion or not of certain processes (e.g. the wetland extent dynamics) and in the representation of the sensitivity of a given process to the climate (e.g. the methanogenesis sensitivity to the temperature). Currently, an intercomparison between many global wetland CH₄ emissions models focusing on the current time period is in progress (WETCHIMP, Melton et al., 2012).

To our knowledge, only one bottom-up modeling study (Hopcroft et al., 2011) investigated changes in wetland CH_4 emissions during D-O events. The results of this study suggest that atmospheric changes driven by modifications of the AMOC induced CH_4 variations from natural wetlands that are too small to explain the variation in $[CH_4]$



observed in ice-cores during D-O events. But the CH_4 emissions model in the global vegetation model (the Sheffield DGVM, called SDGVM hereafter) used in Hopcroft et al. (2011) is relatively simple, and the low sensitivity of SDGVM to climate change is one of the reasons advanced by the authors to explain the mismatch with the ice-core

data. The scope of the present paper is to perform simulations using the same climate fields from an idealized D-O event as in Hopcroft et al. (2011) but with a processoriented and recently developed wetland emission model, the ORCHIDEE-WET model (Ringeval et al., 2011, 2010).

An intercomparison of the wetland CH₄ emissions simulated during an idealized D-O event between the two models (SDGVM and ORCHIDEE-WET) is performed. Through this intercomparison, our purpose is to evaluate and understand a potential difference of modelled wetland CH₄ emissions sensitivity to climate change between the models. Because (i) ORCHIDEE-WET has never been used to simulate the change in wet-

land CH₄ emissions between the Last Glacial Maximum (LGM) and Pre-Industrial period (PI) and (ii) given the uncertainty remaining of the contribution of wetland emissions to LGM climate conditions, we will perform the intercomparison at first on the LGM-PI transition. Then we will focus on one idealized D-O event.

In the Sect. 2, we describe the climate simulations and the two used wetland CH_4 emissions models. The intercomparison between the two models on both the LGM-PI transition and idealized D Q event is performed in the Sect. 2. Finally the results are

transition and idealized D-O-event is performed in the Sect. 3. Finally the results are discussed in the Sect. 4.

2 Methods

2.1 Climate simulations

The climate simulated by the Fast Met Office UK Universities Simulator (FAMOUS:

²⁵ Smith et al., 2008) has been used to force two Global Vegetation Models (GVMs), namely the Sheffield DGVM (SDGVM) and aversion of the ORCHIDEE model able to



simulate the wetland CH₄ emissions, ORCHIDEE-WET (see Sect. 2.2). FAMOUS is a low-resolution version ($5^{\circ} \times 7.5^{\circ}$) of the UK Met Office's HadCM3 coupled general circulation model. Forced with boundary conditions relevant to the last glacial maximum (i.e. the orbital configuration, the atmospheric concentrations of major greenhouse gases,

- the glaciation extent and the sea level) following the PMIP protocol (Braconnot et al., 2007, http://pmip2.lsce.ipsl.fr/), FAMOUS has been used to simulate two equilibrium climates representative of the PI and the LGM. In addition, starting from LGM conditions, freshwater forcing has been applied in the Atlantic Ocean in order to perturb the AMOC (Atlantic Meridional Overturning Circulation) and to simulate the space-time patterns of
- climate during the simulated course of an idealized transient D-O event. During this idealized event, the Greenland temperature is characterized by a cold period (analogous to a Herinrich stadial, HS) then by a warm period (analogous to a Greenland Interstadial, GI). The reader is referred to Sect. 2.3 of Hopcroft et al. (2011) for a full description of the FAMOUS simulations and resulting climate. The imposed freshwater forcing, the
- FAMOUS simulated AMOC and Greenland temperature are given in Fig. A1. Hopcroft et al. (2011) also performed different simulations modifying the background climate from which the freshwater forcing is applied. Given the larger computational cost of the ORCHIDEE-WET model in comparison to SGDVM, we will use the outputs of only one FAMOUS climate simulation to force the GVMs: the D-O simulation with LGM back ground, i.e. the reference D-O simulation in Hopcroft et al. (2011).
- ²⁰ ground, i.e. the reference D-O simulation in Ho

2.2 Wetland CH₄ emissions models

SDGVM and ORCHIDEE-WET have been forced with FAMOUS climate output to simulate the wetland CH₄ emissions during PI, LGM and over an idealized D-O event. SDGVM and ORCHIDEE-WET are two models of different complexity and, regard-²⁵ ing wetland CH₄ emissions, have been used for different time scales: paleo studies for SDGVM (Singarayer et al., 2011; Valdes et al., 2005) and studies over current (Bousquet et al., 2011; Ringeval et al., 2010) or future time period (Koven et al., 2011; Ringeval et al., 2011) for ORCHIDEE-WET.



ORCHIDEE-WET is more process-based than SDGVM in the computation of both the wetland extent dynamic and the CH₄ flux densities. The wetland extent computation is based on a subgrid topographic approach in ORCHIDEE-WET while it corresponds to a simple orographic correction in SDGVM. In ORCHIDEE-WET, the CH₄ flux densities are computed from the process-based Walter et al. (2001) model which accounts for a soil vertical discretization and for an explicit representation of CH₄ transport from

- the soil to the atmosphere, whilst in SDGVM transport and vertical discretisation are ignored. The wetland extents computed in ORCHIDE have been evaluated against remote sensing products of inundated area (Ringeval et al., 2012) and the CH₄ flux densities have been optimized with site-level observations (Ringeval et al., 2010). The year-to-year variability of the wetland CH₄ emissions reflects the wetland CH₄ emissions sensitivity to the climate variability. The ORCHIDEE-WET simulated year-to-year variability in wetland emissions have been evaluated against top-down estimates over
- the 1990–2000 (succinctly displayed in the Fig. 2 of; Ringeval et al., 2011) and is being
 further analyzed over the 1990–2009 period (I. Pison, personal communication, 2012),
 whilst the interannual variability of SDGVM has not been explored in detail. All of these elements increase our confidence in the modelled wetland emissions sensitivity to the climate of ORCHIDEE-WET relative to SDGVM, at least over the current time period.

The SDGVM model has already been described in Hopcroft et al. (2011). Thus, the following paragraphs mainly focus on ORCHIDEE-WET (Sect. 2.2.1) as well as on the differences of methodology used to compute the wetland CH_4 emissions in the two models (Sect. 2.2.2). Similarly, only the ORCHIDEE-WET simulations will be presented (Sect. 2.2.3) and the reader should refer to Hopcroft et al. (2011) for more details of the SDGVM simulations.



2.2.1 The ORCHIDEE-WET model

In the ORCHIDEE-WET model, the wetland CH_4 emissions (E_{CH_4}) are computed for each grid-cell *g* and for each time-step *t* through the following equation:

$$E_{CH_4}(g,t) = \sum_{WTD_i} S_{WTD_i}(g,t) \cdot D_{WTD_i}(g,t) \text{ with } WTD_i = 0 \text{ and } -3 \text{ cm}$$
(1)

- ⁵ where S_{WTDi} and D_{WTDi} are respectively the extent (given as a grid-cell fractional area) and the CH₄ flux density of a wetland with a water table depth equal to WTD_i. A negative value for WTD_i means that the WTD is below the soil surface. In the present study, not only the emissions of the *innundated* wetland (i.e. with WTD = 0) are computed as in (Ringeval et al., 2011) but the emissions of wetlands with a mean water table equal to -3 cm are also considered. This methodology is close to the one used in (Bohn et al., 2007). S_{WTDi} and D_{WTDi} are computed by the coupling of ORCHIDEE-WET with respectively (i) a TOPMODEL approach and (ii) a slight modification of the (Walter et al., 2001) model.
- For each grid-cell and at each time-step, ORCHIDEE-WET simulates a soil water content resulting from a hydrologic budget accounting for some inputs (snowmelt and rainfall not intercepted by the canopy) and losses (soil evaporation, transpiration, sublimation, deep drainage, and surface runoff). This soil water content could be used to express a mean soil water deficit over the grid-cell. This deficit is defined as a gap between the simulated soil water content and the maximum soil water content in the
- ²⁰ model, i.e. the soil field capacity. The coupling between ORCHIDEE-WET and TOP-MODEL allows us to distribute the mean soil water deficit over each grid-cell as function of the sub-grid topographic index distribution. This leads to diagnosis of the fraction of the grid-cell with a deficit equal to 0. Then, the inundated wetland extents are computed from these "field capacity extents". In Ringeval et al. (2011), remote sensing data
- of inundated extent were used to do this computation. The mean climatology (average of 1993–2000) of the modelled field capacity extents were normalized to the same climatology of Prigent et al. (2007) data and only the simulated temporal variability was



kept. Here to prevent the use of current remote sensing data over paleo time scale, a parameterization has been introduced. Briefly, the parameterization consists in a shift of the topographic index distribution in each grid-cell. The shift value is the same for all grid-cells and has been optimized to obtain a current global wetland fraction close

to 4% (Prigent et al., 2007). The reader is referred to Ringeval et al. (2012) for more details. The coarse resolution effect on the wetland extent simulation through the coupling between ORCHIDEE-WET and TOPMODEL is illustrated in Fig. A2. As in (Bohn et al., 2007), the coupling with TOPMODEL has been extended to compute wetland extents with a negative water table depth value. In Eq. (1), S_{-3 cm} are taken as extents
 given by TOPMODEL with a deficit between 0 and -6 cm.

The CH₄ flux densities are computed using a slight modification of the Walter et al. (2001) model as in Ringeval et al. (2010). As in Ringeval et al. (2010), the main modification of the original Walter et al. (2001) model concerns the use of the labile carbon pool simulated by ORCHIDEE-WET (C_L) to approach the methanogenesis substrate in such a way the production rate for a soil layer *z* and a time *t* (Prod (*t*,*z*)) is defined as follows:

$$\operatorname{Prod}(t, z) = \alpha_0 \cdot f_{\operatorname{org}}(z) \cdot C_{\mathsf{L}}(t) \cdot H(T(t, z)) \cdot Q_{10}^{(T(z, t) - T_{\operatorname{ref}})/10}$$

where f_{org} is a function that vertically distributes the carbon in the soil, H(T(t,z)) is the Heaviside step function for the temperature, and T_{ref} varies in space as in the (Walter et al., 2001) model. In the present study, T_{ref} is defined as the mean surface temperature computed by ORCHIDEE-WET when forced by the 1960–1991 CRU (http://www.cru. uea.ac.uk/) climatology. The parameter α_0 which contains both the fraction of the labile carbon pool which could be used as methanogenesis substrate and the base rate at T_{ref} has been optimized against three sites and then extrapolated at latitude band scale as in (Ringeval et al., 2010). Here, this optimization has been performed using CRU

climatology at FAMOUS resolution at monthly time step. A Q_{10} of 3 has been chosen at global scale for the methanogenesis sensitivity to temperature as in (Ringeval et al.,



(2)

3103

Regarding the CH₄ flux densities, the main differences between SDGVM and 25 ORCHIDEE-WET relate to the soil physics vertical discretization, the accounting for CH_{4} transport from the soil to the atmosphere, the proxy of the methanogenesis

differences in the case of a given grid-cell q at time step t. The methodology in SDGVM leads to a binary estimation of S, but allows the simulated WTD in a wetland to continuously vary from +10 cm to -10 cm. By contrast, the 10 more process-oriented approach in ORCHIDEE-WET, through is coupling with TOP-MODEL, allows S to vary continuously between 0 and 1. Nevertheless, only two WTD classes (0 and -3 cm; cf. Eq. 1) are considered in a given grid-cell in ORCHIDEE-WET. In SDGVM, the wetland extent, S, is equal either to 0 or to f_{max} depending on a

2011). This value allows us to match the observed seasonal cycle of CH_4 flux densities on both boreal and temperate sites.

The Fig. 1 summarizes the differences between the CH_4 emissions parameterizations

5 of the two models. As succinctly mentioned above, the major differences between the

Differences between SDGVM and ORCHIDEE-WET 2.2.2

the CH₄ flux densities parameterization.

15

20

two models are related to the computation of both the fractional area covered by a complexity CH_4 emitting wetland (S) dynamic and the CH_4 flux densities (D). We describe the **Discussion** Paper B. Ringeval et al. **Title Page** Introduction Abstract Conclusions References Discussion Paper criterion varying with the latitude. This criterion is the value of the 2 m temperature in Tables Figures boreal regions: the wetland presence in a given year starts for temperature above 5°C. In the non-seasonally frozen environments, a positive difference between precipitation and evapotranspiration is required to reach f_{max} . f_{max} is equal to the product of the entire area of g and an orographic correction. In the wetland covered fraction $S \in \{0, f_{max}\}$ of a grid-cell, a WTD value is computed following the (Cao et al., 1996) relationship applied to the SGDVM soil water content. As in the (Cao et al., 1996) model, the wetlands Back Close with the highest water table position allowed by the model (+10 cm) are considered as **Discussion** Paper Full Screen / Esc inundated and the others are called non-inundated wetlands; a distinction determining Printer-friendly Version

Discussion Paper

Interactive Discussion

8, 3093-3142, 2012

Insights from two

models of different



substrate supply and the parameterization of the methanogenesis sensitivity to the temperature.

In SDGVM, the CH_4 flux density for a given grid-cell is estimated from by the difference between a production and an oxidation rates. The methanogenesis rate is a function of the Ω m sin temperature (T) the calculated WTD and the betweetworkie rate

⁵ function of the 2 m air temperature (T), the calculated WTD and the heterotrophic respiration through:

$$Prod(t) = P_0 \cdot R_{H}(t) \cdot f(WTD(t)) \cdot Q_{10}(T_{ref}) \cdot Q_{10}^{(T(t) - T_{ref})/10}$$

where P_0 is a constant factor used to compute the base methanogenesis rate from the heterotrophic respiration ($R_{\rm H}$). Thus, $R_{\rm H}$ could be considered as the proxy for the ¹⁰ methanogenesis substrate as applied in the Cao et al. (1996) approach. *f* (WTD) is equal to 1 in the case of the inundated wetland and decreases exponentially when the WTD decreases. The methanogenesis sensitivity to the temperature is parameterized using a Q_{10} formulation with a $Q_{10} = 1.5$ and a global constant reference temperature $T_{\rm ref} = 30$ °C.

- ¹⁵ The oxidation rate is a given percent of the production (0.9) for non-inundated wetland and a function of GPP in the other wetlands. In ORCHIDEE-WET, following (Ringeval et al., 2010), the flux density at the atmosphere/surface interface is the result of 3 processes: production in the soils layers below the WTD, oxidation above the WTD and transport by diffusion, ebullition and through the plants aerenchyma. A soil
- ²⁰ vertical discretization is used as in the Walter et al. (2001) model. As for SDGVM, a Q_{10} formulation defines the methanogenesis sensitivity to the temperature but the Q_{10} is here equal to 3 and the reference temperature (T_{ref} of the Eq. 2) varies in space. In ORCHIDEE-WET, oxidation only occurs in the soil layers above the WTD and is also function of temperature.

The comparison of the results of the two models driven by glacial-interglacial and D-O climate changes, will first focus on the change in emissions between different time periods. Then, to better understand the reason of eventual differences between the two models, we will compare the change in the different components of the wetland CH₄



(3)

emissions (i.e. the wetland extents and the CH_4 flux densities per unit of wetland) as in the Eq. (1). To compare more easily each component between the two models, we will compute them in the case of a saturated wetland. Thus, we will compare between the two models both the *saturated wetland extent* (S_0) and the CH_4 flux density for a saturated wetland (CH_{40}). These two variables are direct outputs of ORCHIDEE-WET (WTD_{*j*} = 0 in Eq. 1). For SDGVM, the *saturated wetland extents* are defined a posteriori as the wetland extents with a water table depth above the soil surface (and below +10 cm which is the prescribed maximum value). They encompass the so-called

inundated wetlands by Cao et al. (1996) and the non-inundated wetland with a WTD between +10 cm and 0. The 0 value is used as threshold because it is the maximum value allowed by the TOPMODEL approach (following Saulnier and Datin, 2004) used in ORCHIDEE-WET. For SDGVM, the CH_4 flux densities for a saturated wetland are approached by dividing the simulated CH_4 flux densities by *f* (WTD), i.e. by the function used to decrease the potential methanogenesis rate depending on the WTD value.

15 2.2.3 The ORCHIDEE-WET simulations

The boundary conditions for the ORCHIDEE-WET simulations concern the soil texture (fractions of sand, silt and clay), the vegetation distribution and the orography/topography.

The soil texture maps come from the ISLSCP data (http://badc.nerc.ac.uk/data/ ²⁰ islscp/hydro.html) and are the same as the one used as input of SDGVM in Hopcroft et al. (2011). In ORCHIDEE-WET, a given grid-cell represents the heterogeneous vegetation using a "mosaic" of 10 natural Plant Functional Types (PFT) and bare soil. The fraction of the grid-cell occupied by each PFT is either calculated (and thus variable in time) or prescribed (Krinner et al., 2005). In the present study, dynamic vegetation ²⁵ is not activated; thus, vegetation maps are used as fixed boundary conditions. How-

Is not activated; thus, vegetation maps are used as fixed boundary conditions. However, this does not prevent accounting for wetland extent dynamics (see above) which is decoupled from the vegetation dynamics in the ORCHIDEE-WET model. For the PI period, the vegetation map from the HYDE 3.0 database (Klein Goldewijk et al., 2007)



is used. The prescribed LGM vegetation comes from (Woillez et al., 2011). Contrary to SDGVM, the LGM vegetation is static during the entire transient D-O simulations in ORCHIDEE-WET.

- The mean altitude of each grid-cell is taken from the orography boundary condition ⁵ used in FAMOUS and is derived from the ICE-5G data (Peltier, 2004). The mean altitude is used to derive the surface atmospheric pressure. The altitude is considered constant during the D-O run. Concerning the sub-grid topography necessary as input of ORCHIDEE-WET through its coupling with TOPMODEL, we use the current subgrid topography given by HYDRO1k (http://webgis.wr.usgs.gov/globalgis/metadata_qr/ 10 metadata/hydro1k.htm) for all the simulated time-periods. Thus, it is implicitly assumed
- that the large scale (i.e. the mean altitude of each grid-cell) and the small scale topography are independent. As described in Decharme and Douville (2007) and Ringeval et al. (2012), the spatial distribution of the topographic indices in each grid cell is derived from the mean, standard deviation, and skewness of the actual distribution using
- a three parameter gamma distribution. For the grid-cells for which the continental fraction increases from PI to LGM, the same statistical variables as for the PI are used to extend the sub-grid distribution to the new land part of the grid-cell. For entirely new grid-cells under LGM conditions, we use the sub-grid topography distribution of the closest grid-cell existing under PI conditions. An optimal alternative would have been
- to use the bathymetry data (e.g. http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html) for these new grid-cells (J. O. Kaplan, personal communication, 2011). No changes in the topography/orography are accounted for during the transient D-O run for the two models and they are fixed to LGM conditions. Note also that the sea level is considered constant during the D-O transient run as in Hopcroft et al. (2011).
- A spin-up run of several thousand of years was performed to bring all ORCHIDEE-WET carbon pools to their long-term equilibrium values for both the PI and LGM conditions. A 30-yr interannual simulation was then carried out for both the PI and the LGM with year-to-year variability deriving from FAMOUS and is used to perform the intercomparison with SDGVM.



In the present study, three ORCHIDEE-WET configurations named hereafter V0, V1 and V2, have been used (see Table 1). V0 is the standard ORCHIDEE-WET set-up. The aim of the two other configurations is either to estimate the contribution of different parameterizations to potential differences between ORCHIDEE-V0 and SDGVM, or to better understand the wetland CH₄ emissions sensitivity to climate in ORCHIDEE-WET.

V1 differs from V0 by a change in the parameterization of the methanogenesis sensitivity to temperature. The same sensitivity as in SDGVM is used in V1. It corresponds to a spatially invariant T_{ref} equal to 30 °C and $Q_{10} = 1.5$. As explained in the Sect. 2.2.1, the parameter α_0 which represents the fraction of the labile carbon pool which could be used as methanogenesis substrate accounts also for a methanogenesis base rate at T_{ref} . A change in T_{ref} and Q_{10} requires a new optimization of α_0 that we performed on the same three sites as for ORCHIDEE-V0 (see Table 1). Through the V1 simulation, we aim to estimate the role played by the Q_{10} formulation on the difference between SDGVM and ORCHIDEE-V0. V1 is closer to SDGVM than V0. Note, however that using such a low Q_{10} value in ORCHIDEE-WET leads to poor agreement between the simulated and observed seasonal cycles of CH₄ flux densities for present day site-level observations (not shown).

Finally, ORCHIDEE-V2 differs from V1 through the prescription of the maximum soil water content in each grid-cell and at each time-step to compute the CH_4 flux densities. That means we fixed the soil moisture at its field capacity everywhere regardless of the soil water budget, in the computation of the different carbon pools. The computation of the wetland extent is not affected by this operation: the ORCHIDEE-V1 modeled wetland fractions are combined with such CH_4 flux densities to compute the CH_4 emis-

sions. This is done to remove what we consider as a bias of the methodology used in ORCHIDEE-WET (see also Sect. 4). In ORCHIDEE-WET, a sub-grid approach (TOP-MODEL) is used to diagnose the wetland fraction of each grid-cell. But this sub-grid treatment has no effect on the carbon cycle computation. Indeed, there is no wetland PFT and thus no sub-grid wetland/non-wetland distinction to compute the carbon cycle



variables. Instead of this, the mean value of the labile soil carbon content over the gridcell is used as the wetland substrate. Thus the methanogenesis substrate is sensitive to change in precipitation in the model while it would be less sensitive in the reality for a continually *saturated* wetland. The strategy used in V2 allows us to treat each grid-cell

- ⁵ as a saturated wetland and to remove the effects of the temporal variability in the soil water content on the CH_4 flux densities computation. α_0 is not again optimized on sites but a correction is applied to the V1 value (cf. Table 1). Note finally that using constant soil field capacity conditions have an effect not only on the substrate but also on the surface temperature and on the NPP which could both additionally modify CH_4 emis-10 sions, through the methanogenesis and transport respectively. However, these effects
- are estimated to be of second order in comparison to the effect on the substrate (not shown).

3 Results

3.1 LGM-PI

15 3.1.1 Magnitude and latitudinal distribution of the LGM-PI change in emissions

The basic parameterization of the two models leads to larger simulated PI emissions in ORCHIDEE-WET than in SDGVM (275 vs. 197 Tg yr⁻¹; Table 2) but with a similar latitudinal distribution at FAMOUS resolution (Figs. 2 and 3-left side). The ORCHIDEE-WET PI emissions are slightly higher than previous estimates (e.g. Chappellaz et al., 1993).

This apparent over-estimation against commonly accepted values was also obtained over the period 1990–2000 (Ringeval et al., 2011). Contrary to some other studies (e.g. Spahni et al., 2011), the global ORCHIDEE-WET emissions had not been calibrated to match other estimates. Instead of this, the model has been independently tuned to reproduce the wetland extent against remote sensing data and the CH₄ flux densities



against sites measurements. This underlines the uncertainty linked to the contribution of the wetlands to the global CH_4 budget (Kirschke et al., 2012).

Both (i) the global magnitude and (ii) the latitudinal distribution of the LGM-PI change are different between SDGVM and ORCHIDEE-V0. The global decrease of emissions

- ⁵ during LGM is higher in ORCHIDEE-V0 than in SDGVM (respectively -67 vs. -46 %) (cf. Table 2 for values in both Tg yr⁻¹ and percent). Both models leads to higher decrease during LGM than the range given by Weber et al. (2010) (35–42 %) which focused on the effect of the uncertainty in the LGM climate modelling on the wetland CH₄ emissions using a very simple wetland CH₄ emissions parameterization (see Sect. 4). Here the lower LCM wetland CH₄ emissions parameterization (see Sect. 4).
- ¹⁰ Here the lower LGM wetland CH_4 emissions simulated by ORCHIDEE-WET could completely explain the observed change in $[CH_4]$ as suggested by previous top-down studies as e.g. Chappellaz et al. (1997) and Dallenbach et al. (2000).

In ORCHIDEE-V0, the decrease of CH_4 emissions in northern latitudes (> 30° N) is higher than the decrease in tropics (30° S–30° N) while they are of the same magnitude

- in both latitude bands in SDGVM (Table 2; Fig. 2-right). Boreal wetlands emissions are almost shut down in ORCHIDEE-WET (decrease of 88–97% in emissions northwards of 60°N), which seems to be in agreement with the large drop of boreal wetland emissions in LGM inferred by Fischer et al. (2008) using CH₄ isotopic information from ice cores.
- The different LGM-PI change at global scale between the two models could be reconciled by prescribing the same Q_{10} formulation to quantify the methanogenesis sensitivity to temperature in each model (Table 2, SDGVM and ORCHIDEE-V1). This underlines the large consequence of the uncertainty relating to particular key parameters. Contrary to the global magnitude of the LGM-PI difference, the latitudinal distribution
- of this difference cannot be easily reconciled between the two models: the decrease in the > 30° N region is higher than the one in 30° S– 30° N whatever the ORCHIDEE-WET version and in contrasts with SDGVM (Table 2).



3.1.2 Factors explaining the difference in the LGM-PI change in emissions between the two models

To explain the differences between the two models, we examine the two components of the emissions as explained in the Sect. 2.2.3: the *saturated wetland extent* (S_0) vs.

the *CH*₄ *flux density for a saturated wetland* (*D*₀). We focus also on the drivers of the sensitivity of each component to the climate. At first, Fig. 4 shows the components of the PI emissions for both models (top panels for SGDVM and bottom ones for OR-CHIDEE). The contribution of each component to the PI emissions is very different between SDGVM and ORCHIDEE-WET (Fig. 4). Indeed, the mean yearly PI *D*₀ over
the globe for SGDVM is about half the ORCHIDEE-V0 value (respectively 47.4 and 87.5 gCH₄ m⁻² yr⁻¹). Given the relatively similar global PI emissions between the two models (Fig. 2), the opposite relationship is obtained for the mean saturated wetland component (*S*₀). In the next figures, the LGM-PI change of each component will be expressed in percent of its PI value because of the difference of PI value between the two models.

The role played by the changes in wetland extent in explaining the LGM-PI difference in emissions is weak in the two models (Figs. 3 and 5). Thus, the impact of the additional complexity of the hydrological scheme employed in ORCHIDEE-WET compared to in SDGVM has only a limited effect on the LGM-PI difference in CH₄ emissions. The change in wetland extent between LGM and PI is partially due to the change in both continental ice sheets (decrease of land area available for wetlands) and continental shelves (increase in land area available for wetlands); which are named "geographic effects" in Weber et al. (2010). The contribution of the "geographic effects" to the change

in emission is close in the two models. Indeed, the gain of emissions during PI over areas covered by continental ice-sheets during LGM is 16 and 19 Tg yr⁻¹ for SDGVM and ORCHIDEE, respectively. In the same way, the loss of emissions during PI due to shrinking continental shelves area (higher sea level) is of 13 and 11 Tg yr⁻¹ for SDGVM



and ORCHIDEE, respectively. These effects nearly oppose each other, and together do not contribute to the global difference between the two models.

The lower LGM emissions in boreal regions in ORCHIDEE-WET as compared to PI values, are mainly explained by the drop of the $\rm CH_4$ flux densities from PI to LGM

- ⁵ (Fig. 5). The LGM-PI difference in the CH₄ flux densities between the two models explains the larger extra-tropical decrease of emissions in ORCHIDEE-WET compared with SDGVM (Fig. 5). In ORCHIDEE, the decrease in substrate supply is responsible for the LGM-PI CH₄ flux densities change (Fig. 6). In particular, in boreal regions, modifying the methanogenesis sensitivity to the temperature (compare ORCHIDEE-V0 and
- ¹⁰ ORCHIDEE-V1 in Fig. 5) has a very little effect on the change in CH_4 flux densities. The difference in CH_4 emissions between the two models for the LGM-PI is thus mainly due to different methanogenesis substrate availability. The substrate sensitivity to the change in climate between LGM and PI explains the different of behaviour between the two models. This cannot be explained by a difference of variable chosen to represent
- the substrate availability (heterotrophic respiration (HR) in SDGVM vs. labile carbon pool in ORCHIDEE): in ORCHIDEE, the LGM-PI change in HR is similar to the change in active carbon pool (not shown). Between the two equilibrium states (LGM and PI), the change in substrate supply is caused by a change of input, reflecting change Net Primary Productivity (NPP). In ORCHIDEE, the large decrease in NPP seems to be
- ²⁰ mainly driven by a change in NPP flux density per vegetation type rather than by a change in vegetation coverage (see Fig. A3). In particular, the increase in summer vegetation moisture stress in ORCHIDEE-WET from PI to LGM is a major contributor to the decrease in NPP (see Fig. A3). Soil freezing processes which limit the availability of liquid water to plants is accounted for in ORCHIDEE and not in SDGVM, which could make the level of the level NPP seed on batter availability is a processe.
- ²⁵ explain the lower NPP and substrate availability in ORCHIDEE compared to SDGVM.



3.2 D-O events

3.2.1 Change in emissions at global scale and contribution of the tropics vs. extra-tropics

We now analyze the changes in the wetland CH₄ emissions over one idealized D-O
events and in particular during two key-periods relative to the LGM: (i) the cold period corresponding to the AMOC off phase and here denoted as analogous to a Heinrich Stadial (HS) and (ii) the warm period corresponding to the strong overturning behaviour and denoted as analogous to a Greenland Interstadial (GI). The LGM, the HS and the GI periods are respectively delimited by the following transient simulation years: 1–30, 10 151–180 and 301–330.

The magnitude of the wetland CH_4 emissions evolution during D-O events is very similar between the two models (SDGVM and ORCHIDEE-V0, Fig. 7 top panel). During the cold period of the D-O (HS), the wetland CH_4 emissions are 5.7% (respectively 3.3%) lower in comparison to LGM values for SDGVM (respectively for ORCHIDEE).

- ¹⁵ The change during the warm period of the D-O (GI) relative to the LGM value is slightly larger in ORCHIDEE-V0 than in SGDVM (respectively +11.5 and +8.5%) leading to very similar GI-HS differences for the two models (+14.2 for SDGVM and +14.8% for ORCHIDEE). Despite this consistent global picture, the contribution of each latitude band to the global D-O change (Fig. 7-bottom) is very different between the two models.
- The Northern regions (> 30° N) play a minor role in the global signal in ORCHIDEE-V0 contrary to the situation in SDGVM. For instance, this latitude band explains 53% of the global GI-LGM difference in emissions in SDGVM and only 28% in ORCHIDEE-V0. The difference between the two models regarding the latitudinal distribution of the D-O change in emissions can be totally explained by the much lower LGM emissions of
- the > 30° N band in ORCHIDEE-V0 than in SDGVM. Indeed, the variation of the extratropical latitude band normalized by the LGM boreal emissions is higher in ORCHIDEE-V0 than in SDGVM (not shown). In the later case, the higher boreal emission sensitivity



to D-O climate changes obtained with ORCHIDEE-V0 is explained by its higher Q_{10} value (3 against 1.5 in SDGVM).

Concerning the Tropics, ORCHIDEE-V0 shows a HS-LGM change of the same amplitude as SDGVM but a larger increase in the emissions during GI relative to LGM

- (+4.2 for SGDVM and +8.2% for ORCHIDEE-V0). Moreover, it seems the tropical HS-LGM change in ORCHIDEE-WET is very sensitive to the different parameterizations (Fig. 7; differences between V0, V1 and V2) with, surprisingly, a positive HS-LGM difference simulated by ORCHIDEE-V1. Thus, while we obtain the same picture at global scale for the two models, the underlying drivers of the sensitivity of each model are
 not the same, in particular in the tropics. To investigate this, we now examine the contribution of each particular in the tropics.
- tribution of each component (CH_4 flux densities vs. wetland extent) to the modeled emissions change between LGM, HS and GI.

3.2.2 Drivers of the change in emissions

We have carried out sensitivity analysis to assess the contribution of wetland extent vs. ¹⁵ CH₄ flux density to the difference in CH₄ emissions between LGM, HS and GI. In each latitude band, we computed the CH₄ emissions yearly anomalies relative to the mean global LGM value for the HS and GI periods using the simulations described above. These anomalies are called VAR in the following. We have also computed the yearly CH₄ emissions anomalies in the case where the wetland extent is prescribed and equal

- for each grid-cell to its mean LGM value in each model. The latter emissions anomalies are called hereafter FIXED. Figure 8 displays FIXED against VAR. In Fig. 8, the triangles delimited by the X-axis and the 1 : 1 line defines the area in which anomalies of CH₄ flux densities andwetland extent have the same sign. In these plot areas, the closer a point comes to the X-axis, the higher the contribution of wetland extent in the emission anomaly. The points outside of these triangles are defined by opposite sign
 - anomalies for the two components of the emissions.

At the global scale (\Box), the role played by the change in wetland extent in the emission anomaly in SDGVM is smaller than in ORCHIDEE-V0 for both the warm and cold



D-O periods (the symbols are closer to the 1 : 1 line in SDGVM than in ORCHIDEE). The contribution of the changes in wetland extent is small in the two models over the boreal region (\diamond) and cannot explain the difference of behavior between SDGVM and ORCHIDEE-V0 at global scale: indeed, for each model and in the extra-tropical regions,

⁵ VAR and FIXED are close. Thus, much of the difference between the two models at global scale is driven by differences in the tropical regions.

In the tropics (Δ), during HS (blue symbols), accounting for the wetland extent variability leads to reduce the CH₄ emissions anomaly from -7.1 ± 3.3 (FIXED) to -0.9 ± 4.4 Tg yr⁻¹ (VAR) in ORCHIDEE-V0 and to change the emissions from -2.2 ± 3.4 (FIXED) to -2.08 ± 3.4 Tg yr⁻¹ (VAR) in SDGVM. In ORCHIDEE-V0, the HS climate

- ¹⁰ (FIXED) to $-2.08 \pm 3.4 \text{ Tg yr}^{-1}$ (VAR) in SDGVM. In ORCHIDEE-V0, the HS climate change (in comparison to LGM) leads to both increased emitting areas and decreased flux densities at the same time, with opposite effect on the total CH₄ flux entering the atmosphere. The tropical band can be divided into two sub-regions: the 0–30°N and the 30°S–0 latitudes bands. In each model, these two sub-regions have a very
- different behaviour regarding the CH₄ emissions anomalies during HS: the southern (respectively northern) tropical band is characterized by an increase (respectively a decrease) of the CH₄ emissions. This is related to a southward shift in the ITCZ simulated by FAMOUS in response to the AMOC perturbation (see Hopcroft et al., 2011, for more details). SDGVM and ORCHIDEE mainly differ in terms of (i) the intensity
- of the emissions anomaly in each sub-region and (ii) the contribution of the wetland extent in the emissions anomaly of the southern tropical band. Indeed, in ORCHIDEE-V0, the HS emission anomalies reach -11.6 ± 1.8 and $+10.3 \pm 3.8$ Tg yr⁻¹ for respectively the northern (∇) and southern tropics (\triangleleft) while they are only about of -6.3 ± 2.4 and $+3.1 \pm 3.0$ Tg yr⁻¹ in SDGVM. In the southern tropics, the wetland extent explains
- around 90 % of the increase in emissions in ORCHIDEE-V0 and only 35 % for SDGVM. These two characteristics show that, while the same HS anomaly is obtained in the two models for the entire tropical band due to a compensating effect, the underlying processes are different.



Besides, Fig. 8 also demonstrate that the emissions anomaly in the northern tropics (∇) in ORCHIDEE-V0 is mainly due to the substrate sensitivity to change in precipitation once the wetland extent variability is removed (see the difference of the FIXED values between ORCHIDEE-V0 and ORCHIDEE-V2). Regarding the CH₄ flux densi-

- ties, the decrease in precipitation occurring in the northern tropics during HS leads to a decrease in the ORCHIDEE-simulated NPP leading to a drop of the methanogenesis substrate supply. An opposite effect on the substrate supply takes place through the HR sensitivity to the precipitation in the ORCHIDEE-WET model but is not the prevailing effect here.
- ¹⁰ Regarding the CH₄ emissions during the GI period, the difference between the two models described in the Sect. 3.2.1 is driven by the changes in the band 0–30° N (∇). The emission anomaly in this region is about 5.3 ± 2.9 Tg yr⁻¹ where 88 % can be explained by the expansion of wetland in ORCHIDEE-V0 against 2.5 ± 2.6 Tg yr⁻¹ and 63 % in SDGVM.
- ¹⁵ Finally, Fig. 8 allows us to understand why the tropical anomaly obtained in ORCHIDEE-V1 during HS is positive contrary to the one obtained in V0. The change in the temperature sensitivity formulation from V0 to V1 leads to a small decrease of the positive anomaly in the northern tropics (from -8.7 ± 1.8 to -6.9 ± 1.3 Tg yr⁻¹ for FIXED, i.e. a decrease of ~ 20%) but with no modification in the southern tropics. A weak
- ²⁰ change in the magnitude of the anomaly of a given tropical sub-region could strongly modify the magnitude of the entire tropical band anomaly given the compensating effect described above. This underlines an increased sensitivity in ORCHIDEE-WET compared to SGDVM and thus a potential larger sensitivity to smaller local changes; while this is without any substantial change at global scale in the case described above.

25 4 Discussion and conclusions

Weber et al. (2010) quantified the effect of the uncertainties linked to the LGM climate on the different factors controlling glacial changes in CH_4 production by wetlands. To



do so, they used different OAGCMs outputs to force a unique and simple formulation of CH₄ production. They found that global methane emissions from wetland were reduced by 35–42 % during the LGM in comparison to the PI. Such a reduction is larger than calculated in earlier bottom-up approaches (between –16 % and –27 % for Kaplan et al., 2006; Kaplan, 2002; Valdes et al., 2005) and is attributed to differences in the LGM climate simulations (PMIP 2 vs. PMIP1: Braconnot et al., 2007). The LGM reduction found by Weber et al. (2010) is closer to the range of reduction found in studies based on top-down modelling (e.g., Crutzen and Brühl, 1993; Martinerie et al., 1995, Chappel-

- laz et al., 1997) or as suggested based on atmospheric chemistry simulations (Levine et al., 2011). These studies constrained multi-dimensional chemical transport models with ice core observations and inferred the source terms, finding a LGM wetland reduction by 40–60%. The present study deals with a complementary approach to Weber et al. (2010) by using the same climate forcing as input for two different wetland CH₄ emissions models. We found a decrease of 46 and 67% at global scale for respec-
- ¹⁵ tively SDGVM and the base ORCHIDEE-WET model (version V0). In order to better compare our simulation results with wetland CH₄ emissions estimates from ice-core data, we performed a last ORCHIDEE simulation, hereafter called ORCHIDEE-opt. In this simulation, as in ORCHIDEE-V2, the substrate sensitivity to precipitation is removed. However, a space-constant *T*_{ref} is used as well as a *Q*₁₀ equal to 3. The aim of
- the previous configurations (V1 and V2) was either to estimate the contribution of different parameterizations to potential differences between ORCHIDEE-V0 and SDGVM, or to better understand the wetland CH₄ emissions sensitivity to climate in ORCHIDEE-WET. The aim of ORCHIDEE-opt is to provide our best ORCHIDEE estimates of the change in wetland emissions. This version leads to a LGM decrease of 36 %. Thus, the
- ²⁵ LGM decrease in emissions simulated by both SDGVM and the optimal ORCHIDEE version is close to the lower limit of the range given by top-down studies as discussed above.

The differences between CH_4 concentrations in Greenland and Antarctica as well as the CH_4 isotopic information from ice cores are additional constraints used in top-down



modeling to derive the latitudinal change of (wetland) emissions between LGM and PI. Chappellaz et al. (1997) (based on the inter-hemispheric gradient) and Fischer et al. (2008) (based on isotopic information) lead to the same conclusion of a large decrease of boreal wetland emissions during LGM but do not agree on the magnitude of

⁵ this decrease. The latitudinal distribution of the LGM-PI difference given by SDGVM is consistent with Chappellaz et al. (1997) (-57% for latitudes > $r30\degree$ N) while the simulated shut-down of boreal wetland emissions in ORCHIDEE-WET is more in agreement with Fischer et al. (2008).

New high-resolution CH_4 records from Greenland and Antarctica suggest the boreal wetland were not completely shut down (Baumgartner et al., 2012). Using the SDGVM and ORCHIDEE simulations, we computed the relative interpolar concentration difference of CH_4 , noted rIPD hereafter and defined by Eq. (9) of Baumgartner et al. (2012) as:

$$rIPD(s_n, s_s, \tau, t_{ex}) = 2 \cdot \frac{s_n - s_s}{s_n + s_s} \cdot \frac{1}{1 + 2\frac{\tau}{t_{ex}}}$$

- ¹⁵ where s_n and s_s are the CH₄ source for respectively the North (0° N–90° N) and the South (0° S–90° S) Hemisphere, τ is the atmospheric lifetime of CH₄ and t_{ex} is the interhemispheric mixing time. Figure 9a displays LGM rIPD using SDGVM and ORCHIDEE for different value of τ and t_{ex} . By assuming a present-day value of τ (10.1 yr), as suggested by Levine et al. (2011), and t_{ex} (2 yr), Baumgartner et al. (2012) derived from ice cores a rIPD = 3.7 ± 0.7 % for LGM. Using the same values for τ and t_{ex} , we find a rIPD of 5.4 % for SDGVM and between –1.0 and 1.7 % for ORCHIDEE-V0,V1 and V2. ORCHIDEE-opt gives a rIPD = 3.5 %, very close to the value found by Baumgartner et al. (2012). However, the value of rIPD is very sensitive to a small difference in s_n and s_s .
- This is underlined on Fig. 9a by the error-bars that give the range of rIPD for SDGVM and ORCHIDEE if 25% of the closest grid-cells of South Hemisphere to the Equator are accounted for in s_n instead of into s_s (or vice-versa). Given the uncertainties linked to the latitudinal change of emissions, it is not possible to unambiguously discriminate

Jiscussion Pape

viscussion Pape

Iscussion Pape

(4)

between SDGVM and ORCHIDEE-opt. However, the comparison between the "observed" rIPD and the rIPD computed using the different ORCHIDEE versions suggests that the modification of the methanogenesis substrate sensitivity to the precipitation in the ORCHIDEE model improves the performance of the model in comparison with the 5 ice-core data (see below).

The intercomparison between two independent models which account for different process could help us to improve our understanding of the potential drivers of the wetland CH_4 emissions change during glacial-interglacial transition. While temperature seems to play a small role in the LGM decrease of wetland CH_4 emissions in Weber et al. (2010) we have shown that modifying the Q_{10} parameterization of the methanogenesis sensitivity is sufficient to reconcile the global LGM-PI change between the two models studied here. The CH_4 production sensitivity to temperature is highly uncertain at different spatial scales with large effects on the global distribution of wetland emissions (see e.g. Riley et al., 2011, for the effect on both sites and global scale under a surrent dimate). It is however likely that a $Q_{10} = 1.5$ as used in SDGVM is too low

- ¹⁵ current climate). It is however likely that a $Q_{10} = 1.5$ as used in SDGVM is too low. Bringing together the different constraints (i.e. measurements at sites, the distribution of wetland emissions at global scale against top-down estimates, ice-core measurements of LGM-PI change in [CH₄]) could help us to reduce the range of plausible Q_{10} values. A further issue is the baseline temperature used in the Q_{10} formulation (T_{ref})
- and its potential variability in space and time as a way to represent microbial spacescale processes of adaptation (Riley et al., 2011; Z. M. Subin, personal communication, 2011). An interesting feature of this work is that modification of the Q₁₀ formulation (from ORCHIDEE-V0 to ORCHIDEE-V1) does not reconcile the latitudinal distribution of the LGM-PI change between the ORHIDEE-WET and SDGVM.

In the present study and contrary to Weber et al. (2010), the wetland extent seems to play a small role in explaining the LGM-PI change in emissions. This is particularly true in ORCHIDEE-WET in the boreal regions where the CH_4 flux densities collapse and drive the major part of the reduction in emission. This pattern is explained by a large decrease in the ORCHIDEE-simulated methanogenesis substrate. The difference of



modelled substrate supply between SDGVM and ORCHIDEE-WET underlies why a modification of the *Q*₁₀ value cannot reconcile the latitudinal distribution of the LGM-PI of the two models. This emphasizes the key role of the substrate supply as suggested by Kaplan (2002). However, the driver of the NPP decrease is still not clear: while
Kaplan (2002) explains the low LGM NPP is driven by the reduction in atmospheric CO₂ concentration, we highlight the impact of soil freezing on vegetation productivity as a potentially important influence. It is also likely the surface hydrology of models during LGM needs to be improved. For example, consideration of permafrost covered areas, glacial runoff from the Andes and Asian mountains and different hydrological
drainage systems may all be important

This intercomparison discloses some limitations of each model and allows us to suggest different ways of improvements. Regarding ORCHIDEE, we require an improvement to the sub- grid computation of the methanogenesis substrate. A limitation is linked to the fact a sub-grid computation is performed for the hydrology (through TOPMODEL) but not far the earben and a link this way the mean earben and the grid.

- ¹⁵ TOPMODEL) but not for the carbon cycle. In this way, the mean carbon over the gridcell is used as proxy of the wetland substrate and this makes the modelled substrate more sensitive to change in precipitation since pre-existing wetland fractions might in reality see less relative change in the soil moisture. This inconsistency between the treatments of hydrology/carbon cycle could be resolved by introducing new wet-
- ²⁰ land Plant Functional Types which would be restricted to fractional gridcells diagnosed as wetlands using TOPMODEL. In SDGVM, we suggest modifying the contribution of the wetland extent versus CH₄ flux densities under PI conditions (see Fig. 4) to more closely satisfy available observations. This could be done by scaling the CH₄ flux densities to measurement from sites, and the wetland extent against e.g. the Papa
- et al. (2010) dataset. While the present study does not underline a large effect of the imbalance between the two emissions components on the simulated change in emissions in comparison to ORCHIDEE, it may not be the case under other climates. Also, we suggest increasing the value of the Q_{10} for the methanogenesis parameterization.



Finally, introducing a simple parameterization of freeze/thaw of soil water could help to more accurately model changes in the methanogenesis substrate availability.

Over the idealized D-O events, the magnitude of the change in wetland CH_4 emissions simulated by two models at global scale is very similar (GI-HS: 14.2 and 14.8 %

- relative to LGM emissions respectively for SDGVM and ORCHIDEE-V0). Our best estimate using ORCHIDEE leads to a slightly higher change of 18 % (cf. dash orange curve in Fig. 7-top). As described by Hopcroft et al. (2011), the SDGVM-simulated changes in wetland CH₄ emissions during the idealized D-O event are too low to explain the measured change in [CH₄]. In the present study, the same conclusion is also reached
 with ORCHIDEE-WET: the likely impact of the simulated emissions on the [CH₄] will
- not differ between the two models. And without any change in the CH_4 lifetime, the amplitude of the change in global emissions simulated by the two models (~ 15 Tg yr⁻¹) is much lower than that required (~ 60 Tg yr⁻¹) to match a change of 200 ppb in the [CH₄], the upper range of observed D-O events (see Fig. 9 of Hopcroft et al., 2011).
- Our simulations point to two features that could lead to increased D-O forced change in emissions simulated by ORCHIDEE-WET in both the tropics and extra tropics. Firstly, in ORCHIDEE-WET, the LGM boreal emissions are nearly zero thus the global D-O changes are almost exclusively explained by the tropics. However, because the *Q*₁₀ of the methanogenesis is larger in ORCHIDEE-WET than in SDGVM, larger boreal emissions at the beginning of the D-O simulations will likely lead to increase the global change during the different phases of the D-O events. Additionally, we have shown that the local (half tropical band scale) anomalies are much larger in ORCHIDEE-WET
- than in SDGVM (between twice and three times larger). A weak change in the magnitude of the anomaly of a given tropical sub-region could strongly modify the magnitude of the overall total tropical anomaly given the compensating effect described in the Sect. 3.2.2. This underlines an increased sensitivity in ORCHIDEE-WET compared with SGDVM and thus a potential larger sensitivity to local changes. Sensitivity
 - FAMOUS simulations with different background conditions (i.e. modifying orbital insolation, global ice volume, greenhouse gases level) have been performed in Hopcroft



et al. (2011) and could be used to test these two assumptions relative to the boreal and tropical regions. Relatively little information about the latitudinal change in wetland CH_4 emissions during D-O events has been derived from the ice core measurements up to now. Bock et al. (2010) used combined information from the inter-hemispheric gradient and CH_4 isotopes to derive source contributions and latitudinal change in emissions of each source between different time periods of the D-O 8 (~ 37 kyr BP). According to their modelling approach, the high-latitude wetland emissions strengthened from ~ 5 to ~ 32 Tg yr⁻¹ from stadial to early-interstadial conditions, whereas tropical wetland emissions strengthened only moderately (from ~ 84 to ~ 118 Tg yr⁻¹). While the change in boreal emissions between HS and GI is larger in SDGVM than in ORCHIDEE (respectively 9.7 and 5.4 Tg yr⁻¹), both models simulate a lower variation of heread emissions the print hy Pack of et al. (2010)

- tion of boreal emissions than inferred by Bock et al. (2010). Baumgartner et al. (2012) computed also rIPD for different D-O events and found values of 7.1 ± 0.5 , 2.9 ± 2.3 and 6.2 ± 2.4 % for respectively the D-O 2, 3 and 4 using present-day values for τ and
- t_{ex} . Levine et al. (2012) suggested that the lifetime stayed relatively constant during D-O events because the effects of both warming and changes in VOC emission were found to produce effects of approximately equal but opposite sign in their atmospheric chemistry simulations. We compute also rIPD during our idealized GI for SGDVM and the different ORCHIDEE versions (Fig. 9b). Both SGDVM and our best ORCHIDEE
- estimation are close to the value found by Baumgartner et al. (2012) for D-O 2 and 4. This could suggest that, while the wetland CH₄ emissions sensitivity to the D-O climate seems to be under-estimated in the models, this under-estimation is homogeneously shared between the Northern and Southern Hemispheres. However, it should also be noted that a 2-box model of the global CH₄ sources and atmospheric mixing may not discriminate adequately between the tropical and boreal source regions. This limitation
- will need to be addressed in future work.

While potential increases in ORCHIDEE-WET simulated wetland CH_4 emissions seems to be possible, the results are very similar for the two models over the idealized D-O event. Moreover, contrary to what has been found for the LGM, the



ORCHIDEE-simulated change in emissions during D-O shows a relatively low sensitivity to the different parameterizations. This hints at either missing processes related to wetlands, a change in other sources/ in the OH sink or alternative D-O mechanism of D-O climate change. The two latter have been discussed in Hopcroft et al. (2011)

- ⁵ and we focus here on the first point. The present study as Singarayer et al. (2011) and Hopcroft et al. (2011) underlines the key-role of the tropics in controlling the variability in wetland CH₄ emissions over paleo time-scales. However, many processes important for tropical wetlands are not accounted for in the current wetland CH₄ emissions models which have been developed primarily for the conditions encountered in the most
- extensively investigated mid-to-northern latitudes. In particular, explicit representation of floodplain hydrology processes in connection with river routing will be required in addition to wetlands saturated from below as represented by ORCHIDEE-WET and SDGVM. As suggested by Bock et al. (2010) and discussed above, a change in boreal wetland CH₄ emissions appears to be required during some D-O events. In these re-
- gions, slow processes such as the exposure of land surface as the ice sheet retreated are clearly not capable of producing such fast variations (Wolff and Spahni, 2007). CH₄ emissions associated with permafrost destabilization need to be incorporated into paleo modeling studies such as the one performed here.

Acknowledgements. We would like to thank Angela V. Gallego-Sala and Pierre Friedlingstein for informative and helpful discussions during the elaboration of this work. We would like also to thank Marie-Noelle Woillez for providing the LGM vegetation map for ORCHIDEE.



The publication of this article is financed by CNRS-INSU.



References

- Bock, M., Schmitt, J., Möller, L., Spahni, R., Blunier, T., and Fischer, H.: Hydrogen isotopes preclude marine hydrate CH₄ emissions at the onset of Dansgaard-Oeschger events, Science, 328, 1686–1689, doi:10.1126/science.1187651, 2010.
- ⁵ Bohn, T. J., Lettenmaier, D. P., Sathulur, K., Bowling, L. C., Podest, E., McDonald, K. C., and Friborg, T.: Methane emissions from western Siberian wetlands: heterogeneity and sensitivity to climate change, Environ. Res. Lett., 2, 045015, doi:10.1088/1748-9326/2/4/045015, 2007.
 Bousquet, P., Ringeval, B., Pison, I., Dlugokencky, E. J., Brunke, E.-G., Carouge, C., Chevallier, F., Fortems-Cheiney, A., Frankenberg, C., Hauglustaine, D. A., Krummel, P. B., Langenfelds,
- R. L., Ramonet, M., Schmidt, M., Steele, L. P., Szopa, S., Yver, C., Viovy, N., and Ciais, P.: Source attribution of the changes in atmospheric methane for 2006–2008, Atmos. Chem. Phys., 11, 3689–3700, doi:10.5194/acp-11-3689-2011, 2011.
 - Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A.,
- Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, Clim. Past, 3, 261–277, doi:10.5194/cp-3-261-2007, 2007.

Cao, M., Marshall, S., and Gregson, K.: Global carbon exchange and methane emission from

- natural wetlands: Application of a process-based model, J. Geophys. Res., 101, 14399– 14414, 1996.
 - Chappellaz, J., Bluniert, T., Raynaud, D., Barnola, J. M., Schwander, J., and Stauffer, B.: Synchronous changes in atmospheric CH₄ and Greenland climate between 40 and 8 kyr BP, Nature, 366, 443–445, 1993.
- ²⁵ Chappellaz, J., Blunier, T., Kints, S., Dällenbach, A., Barnola, M., Schwander, J., Raynaud, D., Stauffer, B., Dallenbach, A., and Barnola, J.: Changes in the atmospheric CH₄ gradient between Greenland and Antarctica during the Holocene, J. Geophys. Res., 102, 15987–15997, doi:10.1029/97JD01017, 1997.

Crutzen, P. J. and Brühl, C.: A model study of atmospheric temperatures and the concentrations

³⁰ of ozone, hydroxyl, and some other photochemically active gases during the glacial, the preindustrial Holocene and the present, Geophys. Res. Lett., 20, 1047–1050, 1993.



- Dallenbach, A., Blunier, T., Fluckiger, J., Stauffer, B., Chappellaz, J., and Raynaud, D.: Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Last Glacial and the transition to the Holocene, Geophys. Res. Lett., 27, 1005–1008, doi:10.1029/1999GL010873, 2000.
- ⁵ Decharme, B. and Douville, H.: Global validation of the ISBA sub-grid hydrology, Clim. Dynam., 29, 21–37, doi:10.1007/s00382-006-0216-7, 2007.
 - Fischer, H., Behrens, M., Bock, M., Richter, U., Schmitt, J., Loulergue, L., Chappellaz, J., Spahni, R., Blunier, T., Leuenberger, M., and Stocker, T. F.: Changing boreal methane sources and constant biomass burning during the last termination, Nature, 452, 864–867, doi:10.1038/nature06825, 2008.
- Hopcroft, P. O., Valdes, P. J., and Beerling, D. J.: Simulating idealized Dansgaard-Oeschger events and their potential impacts on the global methane cycle, Quaternary Sci. Rev., 30, 3258–3268, doi:10.1016/j.guascirev.2011.08.012, 2011.

10

Kageyama, M., Mignot, J., Swingedouw, D., Marzin, C., Alkama, R., and Marti, O.: Glacial climate sensitivity to different states of the Atlantic Meridional Overturning Circulation: results from the IPSL model, Clim. Past, 5, 551–570, doi:10.5194/cp-5-551-2009, 2009.

Kaplan, J. O.: Wetlands at the Last Glacial Maximum: Distribution and methane emissions, Geophys. Res. Lett., 29, 3–6, 2002.

Kaplan, J. O., Folberth, G., and Hauglustaine, D. A.: Role of methane and biogenic volatile

- organic compound sources in late glacial and Holocene fluctuations of atmospheric methane concentrations, Global Biogeochem. Cy., 20, GB2016, doi:10.1029/2005GB002590, 2006.
 Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Bergamaschi, P., Bergmann, D., Bruhwiler, L., Cameron-Smith, P., Canadell, J. G., Castaldi, S., Chevallier, F., Dlugokencky, E. J., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Lamargue, J.-F., Le
- Quéré, C., Naik, V., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Spahni, R., Strode, S. A., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Williams, J. E., and Zeng, G.: Three decades of methane sources and sinks: budgets and variations, Nat. Geosci., submitted, 2012.
- Klein Goldewijk, K., Bouwman, A. F., and van Drecht, G.: Mapping contemporary global cropland and grassland distributions on a 5 by 5 minute resolution, Journal of Land use Science, 2, 167–190, 2007.



Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, P. Natl. Acad. Sci. USA, 108, 14769–14774, doi:10.1073/pnas.1103910108, 2011.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P.,
 ⁵ Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, GB1015, doi:10.1029/2003GB002199, 2005.

Levine, J. G., Wolf, E. W, Jones, A. E., Sime, L. C., Valdes, P. J., Archibald, A. T., Carver, G. D., Warwick, N. J., and Pyle, J. A.: Reconciling the changes in atmospheric methane sources

- and sinks between the Last Glacial Maximum and the pre-industrial era, Geophys. Res. Lett., 38, L23804, doi:10.1029/2011GL049545, 2011.
 - Levine, J. G., Wolff, E. W., Hopcroft, P. O., and Valdes, P. J.: Controls on the tropospheric oxidizing capacity during an idealized Dansgaard-Oeschger event, and their implications for the rapid rises in atmospheric methane during the last glacial period, Geophys. Res. Lett., 39. L12805 doi:10.1029/2012GL051866. 2012.
- 39, L12805 doi:10.1029/2012GL051866, 2012.
 Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B.,
 - Barnola, J.-M., Raynaud, D., Stocker, T. F., and Chappellaz, J.: Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years, Nature, 453, 383–386, doi:10.1038/nature06950, 2008.
- Martinerie, P., Brasseur, G. P., and Granier, C.: The chemical composition of ancient atmospheres: A model study constrained by ice core data, J. Geophys. Res., 100, 14291–14304, 1995.
 - Melton, J. R., Wania, R., Hodson, E., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C. A., Beerling, D. J., Chen, G., Eliseev, A. V., Denisov, S. N., Hopcroft, P. O., Lettenmaier,
- D. P., Riley, W. J., Singarayer, J. S., Subin, Z. M., Tian, H., Zürcher, S., Brovkin, V., van Bodegom, P. M., Kleinen, T., Yu, Z. C., and Kaplan, J. O.: Present state of global wetland extent and wetland methane modelling: Conclusions from a model intercomparison project (WETCHIMP), Biogeosciences Discuss., accepted, 2012.
- Papa, F., Prigent, C., Aires, F., Jimenez, C., Rossow, W. B., and Matthews, E.: Interannual variability of surface water extent at the global scale, 1993–2004, J. Geophys. Res., 115, 1–17, doi:10.1029/2009JD012674, 2010.
 - Petrescu, A. M. R., van Beek, L. P. H., van Huissteden, J., Prigent, C., Sachs, T., Corradi, C. A. R., Parmentier, F. J. W., and Dolman, A. J.: Modeling regional to global CH₄ emissions of bo-



real and arctic wetlands, Global Biogeochem. Cy., 24, GB4009, doi:10.1029/2009GB003610, 2010.

- Prigent, C., Papa, F., Aires, F., Rossow, W. B., and Matthews, E.: Global inundation dynamics inferred from multiple satellite observations, 1993–2000, J. Geophys. Res., 112, 1–13, doi:10.1020/2006.JD002847.2007
- ⁵ doi:10.1029/2006JD007847, 2007.

30

- Riley, W. J., Subin, Z. M., Lawrence, D. M., Swenson, S. C., Torn, M. S., Meng, L., Mahowald, N. M., and Hess, P.: Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM, Biogeosciences, 8, 1925–1953, doi:10.5194/bg-8-1925-2011, 2011.
- ¹⁰ Ringeval, B., de Noblet-Ducoudré, N., Ciais, P., Bousquet, P., Prigent, C., Papa, F., and Rossow, W. B.: An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales, Global Biogeochem. Cy., 24, 1–12, doi:10.1029/2008GB003354, 2010.

Ringeval, B., Friedlingstein, P., Koven, C., Ciais, P., de Noblet-Ducoudré, N., Decharme, B., and

- ¹⁵ Cadule, P.: Climate-CH₄ feedback from wetlands and its interaction with the climate-CO₂ feedback, Biogeosciences, 8, 2137–2157, doi:10.5194/bg-8-2137-2011, 2011.
 - Ringeval, B., Decharme, B., Piao, S. L., Ciais, P., Papa, F., de Noblet-Ducoudré, N., Prigent, C., Friedlingstein, P., Gouttevin, I., Koven, C., and Ducharne, A.: Modelling sub-grid wetland in the ORCHIDEE global land surface model: evaluation against river discharges and remotely
- sensed data, Geosci. Model Dev., 5, 941–962, doi:10.5194/gmd-5-941-2012, 2012. Saulnier, G.-M. and Datin, R.: Analytical solution to a bias in the TOPMODEL framework balance, Hydrol. Process., 18, 1195–1218, doi:10.1002/hyp.1346, 2004.
 - Singarayer, J. S. and Valdes, P. J.: High-latitude climate sensitivity to ice-sheet forcing over the last 120 kyr, Quaternary Sci. Rev., 29, 43–55, doi:10.1016/j.quascirev.2009.10.011, 2010.
- Singarayer, J. S., Valdes, P. J., Friedlingstein, P., Nelson, S., and Beerling, D. J.: Late Holocene methane rise caused by orbitally controlled increase in tropical sources, Nature, 470, 82–85, doi:10.1038/nature09739, 2011.

Smith, R. S., Gregory, J. M., and Osprey, A.: A description of the FAMOUS (version XDBUA) climate model and control run, Geosci. Model Dev., 1, 53–68, doi:10.5194/gmd-1-53-2008, 2008.

Spahni, R., Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P. N., Joos, F., Prentice, I. C., and van Velthoven, P.: Constraining global methane emissions



and uptake by ecosystems, Biogeosciences, 8, 1643-1665, doi:10.5194/bg-8-1643-2011, 2011.

- Valdes, P. J., Beerling, D. J., and Johnson, C. E.: The ice age methane budget, Geophys. Res. Lett., 32, 2–5, doi:10.1029/2004GL021004, 2005.
- ⁵ Walter, P., Heimann, M., and Matthews, E.: Modeling modern methane emissions from natural wetlands 1. Model description and results, J. Geophys. Res., 106, 34189–34206, doi:10.1029/2001JD900164, 2001.
 - Wania, R., Ross, I., and Prentice, I. C.: Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1.3.1, Geosci. Model Dev., 3, 565– 584, doi:10.5194/gmd-3-565-2010, 2010.

10

15

- Weber, S. L., Drury, A. J., Toonen, W. H. J., and van Weele, M.: Wetland methane emissions during the Last Glacial Maximum estimated from PMIP2 simulations: Climate, vegetation, and geographic controls, J. Geophys. Res., 115, 1–13, doi:10.1029/2009JD012110, 2010.
- Wolff, E. and Spahni, R.: Methane and nitrous oxide in the ice core record, Philos. T. R. Soc. A, 365, 1775–1792, doi:10.1098/rsta.2007.2044, 2007.
- Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., and Svensson, A.: Millennial-scale variability during the last glacial: the ice core record, Quaternary Sci. Rev., 29, 2828–2838, 2010.

Woillez, M.-N., Kageyama, M., Krinner, G., de Noblet-Ducoudré, N., Viovy, N., and Mancip,

²⁰ M.: Impact of CO₂ and climate on the Last Glacial Maximum vegetation: results from the ORCHIDEE/IPSL models, Clim. Past, 7, 557–577, doi:10.5194/cp-7-557-2011, 2011.



Table 1. Description of the different ORCHIDEE-WET simulations (ORCHIDEE-V0, V1 and V2).

	ORCHIDEE-WET- V0	ORCHIDEE-WET-V1	ORCHIDEE-WET-V2	ORCHIDEE-WET-opt	
General description	Standard ORCHIDEE-WET set-up	As ORCHIDEE-V0 with the same methanogenesis sensitivity to the temperature as SDGVM	As ORCHIDEE-V1 with prescribed soil water content to compute the CH ₄ flux densities	"Optimal" version	
Q ₁₀ /T _{ref}	$Q_{10} = 3$ Space-varying T_{ref} . For each grid-cell, T_{ref} is equal to the mean yearly surface temperature computed by ORCHIDEE-WET when forced by the 1960–1991 CRU climatology	$Q_{10} = 1.5$ $T_{ref} = 30^{\circ}C$ everywhere	$Q_{10} = 1.5$ $T_{ref} = 30^{\circ}C$ everywhere	$Q_{10} = 3.0$ $T_{ref} = 30^{\circ}C$ everywhere	
Way to compute α_0 and value for the different latitude bands (boreal, temperate, tropical) (in 10 ⁻⁶ m ⁻² month ⁻¹)	Optimized against three sites then extrapolated at latitude band scale as in Ringeval et al. (2010) (1.1, 2.2, 17.5)	Optimized against three sites then extrapolated at latitude band scale as in Ringeval et al. (2010) (5.5, 8.5, 20.1)	For each sites, equal to α_0 (ORCHIDEE-V1) C_{sol} (ORCHIDEE-V2)/ C_{sol} (ORCHIDEE-V1) then extrapolated at latitude band scale (6.9, 5.4, 24.5)	Optimized against three sites then extrapolated at latitude band scale as in Ringeval et al. (2010) (34.8, 21.1, 37.6)	
Soil water conditions used to compute the CH_4 flux densities	Computed by the model	Computed by the model	Prescribed: constant in time and space and equal to the maximum soil water content in the model	Prescribed: constant in time and space and equal to the maximum soil water content in the model	

8, 3093-3142, 2012 Insights from two models of different complexity B. Ringeval et al. Title Page Abstract Introduction Conclusions References

Figures

►

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

 $(\mathbf{\hat{H}})$

DΥ

(cc)

Tables

<

Back

Table 2. (Top) global PI and LGM emissions for SDGVM and ORCHIDEE-WET and (bottom)
the LGM-PI change (in percent) for different latitudinal bands. In the top table, first (respec-
tively. second) number between brackets corresponds to ORCHIDEE-WET saturated (resp.
non-saturated) emissions.

	SDGVM	ORCHIDEE-WET-V0	ORCHIDEE-WET-V1	ORCHIDEE-WET-V2	ORCHIDEE-WET-opt
Tg yr ⁻¹					
Global PI	197	275 (203 + 72)	259 (191 + 68)	236 (174 + 62)	229 (168 + 61)
Global LGM	106	90 (65 + 25)	128 (92 + 36)	161 (117 + 44)	146 (106 + 40)
LGM-PI (%)					
Global	-46%	-67%	-51%	-32 %	-36 %
> 30° N	-41 %	-87 %	-75%	-52 %	-45%
30° S–30° N	-48 %	-57 %	-39%	–25 %	-32 %



CH, emission models: differences between

٠

٠

SDGVM

Used for paleo studies



1) Wetland fraction (S)

• S = 0 or f_{max} • With $f_{max} = 1$ x orographic correction

2) CH, flux density (D) computed following

- (Cao et al., 1993)
- D = prod oxy
- With $prod = f(WTD).f(T).R_{_{H}}$
- And oxy = fixed % of prod
- Varying Water Table Depth (WTD)
- No transport
- Substrate's proxi = the heterotophic respiation, ${\rm R}_{_{\rm H}}$
- In f(T), $Q_{10} = 1.5$ and T_{ref} is constant for all grid-cells
- 3) Vegetation dynamic: Yes



ORCHIDEE

i.e. for two given WTD values

1) Wetland fraction (S)

More process-based

- Use a subgrid-scale topographic approach (TOPMODEL)
- Compute a wetland fraction with a given WTD value
- · Evaluated against remote sensing data of inundated area

2) CH, flux density (D) computed following the

process-based model of (Walter et al., 2001)

- Vertical discretization
- Production/oxidation/3 types of transport
- Substrate's proxi: mean labile carbon pool (C_L)
- For a given WTD value
- Evaluated against few data on sites

• in production, Q_{10} = 3.0 and T_{ret} varies from one grid-cell to other. T_{ref} is equal to the yearly temperature given by the CRU climatology

3) Vegetation dynamic: No (but PI or LGM static vegetation)



Fig. 1. Summary of the methodology used to simulate the wetland CH_4 emissions in SDGVM (left) and ORCHIDEE-WET (right).



Fig. 2. Latitudinal distribution of the PI (top) and LGM (bottom) CH_4 emissions for SDGVM (red) and the different ORCHIDEE-WET simulations. Each PI ORCHIDEE-WET latitudinal distribution has been normalized to match the SDGVM PI global emissions. The same correcting factor has been applied for each LGM ORCHIDEE-WET distribution.





Fig. 3. Left: PI emissions $(Tg yr^{-1})$ for SDGVM (a) and for the different ORCHIDEE-WET versions (c, e, g). Right: LGM-PI change $(Tg yr^{-1})$ for each model. The same normalization as for Fig. 2 is applied to the ORCHIDEE-WET plots. Grey areas correspond to grid-cells without any vegetation.





Fig. 4. Components of the PI emissions for each model (SDGVM and ORCHIDEE-V0). Left: saturated wetland extent (in grid-cell fraction); right: CH_4 flux densities for a saturated wetland (g CH_4 m⁻² yr⁻¹). As for Fig. 3, grey areas correspond to grid-cells without any vegetation.





Fig. 5. LGM-PI change of each component of the CH_4 emissions (in percent of its PI-value) for SDGVM (**a**–**b**) and the different ORCHIDEE-WET versions (**c**–**f**). Left: saturated wetland area; right: CH_4 flux densities for a saturated wetland.





Fig. 6. LGM-PI change in the proxy of methanogenesis substrate in each model (in percent of its LGM values). **(a)**: heterotrophic Respiration for SDGVM. **(b,c)**: soil labile carbon pool for ORCHIDEE.













Fig. 8. Caption on next page.

Fig. 8. Role played by the change in wetland extent in the change in emissions over the idealized D-O event for SDGVM (top) and the different ORCHIDEE-WET versions (bottom). For each latitude band, the CH_4 emissions annual anomalies relative to the mean global LGM emissions have been computed in two configurations (VAR and FIXED) for HS (blue) and GI (orange). The VAR anomalies (x-axis) are computed accounting for the variability in the wetland extents. The FIXED anomalies (y-axis) are computed after removing the wetland extent variability (i.e. the mean LGM wetland extents are prescribed during the entire D-O transient run). The errors-bars give the variability between the years of the each (HS or GI) period.





Fig. 9. relative interpolar concentration difference of CH₄ (rIPD, in %) computed for LGM (a) and over the idealized D-O (b) event using SDGVM (red curve) and the different ORCHIDEE versions. Both sensitivity to the CH₄ atmospheric lifetime (τ , top) and the interhemispheric mixing time (t_{ex} , bottom) are given. While one parameter is varied, the other is set to its present day-value ($\tau = 10.1$ yr and $t_{ex} = 2$ yr). Values of rIPD derived from ice cores by Baumgartner et al. (2012) assuming present day-value for τ and t_{ex} are plotted with errors-bars relative to uncertainty in measurements. The error-bars for models give the range of rIPD if 25% of the closest grid-cells of South Hemisphere to the Equator are accounted for in North Hemispheric sources (s_n) instead of into the South Hemispheric ones (s_s) (or vice-versa).





Fig. A1. Applied freshwater forcing to FAMOUS from LGM conditions to perturb the AMOC and mimic D-O events (top). Corresponding evolution of the AMOC (middle) and Greenland temperature (bottom) simulated by FAMOUS





Fig. A2. Effect of the change in resolution on the Prigent et al. (2007) dataset (inundated areas) (left) and on the saturated wetland extents simulated by ORCHIDEE-TOPMODEL (right) (expressed in mean annual fraction). The number given in the left bottom corner of each panel corresponds to the global coverage of the wetland extent in %.





Fig. A3. For ORCHIDEE: **(a–b)** distribution of the main supra-PFT classes (please, refer to Woillez et al., 2011, for the class definitions) for PI **(a)** and LGM **(b)** used as input of ORCHIDEE. **(c–d)**: LGM. PI change in NPP for boreal trees **(c)** and for C3-grass **(d)** (in percent of its PI value). **(e–f)**: LGM. PI change in JJA humidity stress for C3 grass vegetation for ORCHIDEE-V0 **(e)** and ORCHIDEE-V2 **(f)** (in percent of its PI-value).

