Indirect relationship between surface water budget and wetland extent

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[1] We used a suite of two models: a global climate model, and a hydrological routing scheme, to estimate the changes in the surface water budget and extent of natural wetlands, at the last interglacial (126000 years ago) and at the last glacial maximum (21000 years ago). At both time periods, in northern tropical Africa as well as in northern South America, our simulations exhibit, in many places, an indirect relationship between the surface water budget and the extent of natural wetlands. In relatively moist regions, decreasing (increasing) rainfall and runoff at the last glacial maximum (last interglacial) result in increased (decreased) wetland area due to the reduction (increase) in lake depth. This counter-intuitive result has never been hypothesized before and may shed a new light on the interpretation of past changes in atmospheric methane, as derived from ice core analyses. It also points to the importance of using a bottom-up modelling approach in this field of study. *INDEX TERMS:* 1890 Hydrology: Wetlands; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1615 Global Change: Biogeochemical processes (4805); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions

1. Introduction

[2] Understanding the link between methane (CH_4) emissions and atmospheric concentration is crucial for future projections of the behaviour of this very important greenhouse gas. Because natural wetlands largely contribute to these emissions [*Fung et al.*, 1991] and there is evidence of large fluctuations in wetland area over the last glacial-interglacial cycle [*Brook et al.*, 1996; *Chappellaz et al.*, 1997; *Petit et al.*, 1999], it is necessary to better understand the mechanisms responsible for their variations. Very few studies though have addressed this complicated problem due to the lack of sufficient data on past distributions of natural wetlands throughout the globe. Only two studies have used a bottom-up approach with geographically explicit computation of wetlands distribution.

[3] *Chappellaz et al.* [1993] have combined information on topography and paleo-vegetation (subjectively derived from a limited set of data sites, sparsely distributed [*Adams et al.*, 1990]), to determine the distribution of natural wetlands at the last glacial maximum. A mean annual flux of CH_4 (empirically derived from present-day estimates [*Fung et al.*, 1991]) was then applied to all wetlands associated with the same vegetation group.

[4] *Kaplan* [2001] built a more sophisticated process-based model which, given a prescribed climate change, simulates the distributions of vegetation and seasonal wetlands responding to this forcing, together with the associated CH_4 emissions based on ecosystem carbon turnover in seasonally or perennially wet soils. This approach is certainly the most complete to date, with respect to methane emissions, but it includes a very important simplification: wetlands result only from locally saturated soils while lateral import of surface water, through runoff, is neglected. Yet *Coe and Bonan* [1997], and *Coe and Harrison* [2000], have demonstrated the importance of routing water on the extent of wetlands in tropical Africa at the mid-Holocene (6000 years ago).

[5] All other approaches have only focused on changes in methane emissions, with no estimations based on the extent of natural wetlands. Different sets of global or regional source estimates of CH_4 from natural wetlands (no explicit geographical patterns) have been tested as inputs to 1) atmospheric photochemical models to simulate the observed CH_4 atmospheric concentration [e.g. *Pinto and Khalil*, 1991, *Thompson et al.*, 1993; *Crutzen and Brühl*, 1993;, *Martinerie et al.*, 1995], or 2) box models to derive, from the measured changes in the past interpolar difference of atmospheric CH_4 mixing ratio, the bulk contributions from the tropics (30°N–30°S) and the mid-to-high latitudes of the northern hemisphere [*Chappellaz et al.*, 1997; *Dällenbach et al.*, 2000; *Brook et al.*, 2000].

[6] In this study we develop a new bottom-up approach that is based on the hydrological routing scheme (HYDRA) developed by *Coe* [2000]. Because of the large computational cost of this model, we have restricted its application to two tropical regions (northern South America, 85°W–30°W/20°S–15°N, and northern tropical Africa, 20°W–50°E/10°S–25°N), which are the largest sources of methane in the tropics, and two contrasted past climates, the last interglacial (126000 years ago, hereafter LIG) and the last glacial maximum (21000 years ago, hereafter LGM), the former being much wetter than today while the latter was drier in the tropics. The change in atmospheric methane concentration between these time periods is the largest one experienced during the last glacial-interglacial cycle (over Antarctica, 710ppbv during LIG compared to 350ppbv at the LGM *Chappellaz et al.*, 1990.), if we neglect anthropogenic changes.

2. Tools and Methods

[7] *HYDRA* (the HYDrological Routing Algorithm) simulates the time-varying flow and storage of water in terrestrial hydrological systems [*Coe*, 1998; *Coe*, 2000]. The model couples a digital elevation model representation of the land surface with a linear reservoir model to simulate rivers, lakes, and wetlands as a continuous hydrological network. The model is forced by precipitation, runoff, and evaporation. HYDRA successfully produces the modern observed global distribution of inland bodies of water [*Coe*, 1998] and has been extensively tested in northern Africa [*Coe and Foley*, 2001, *Coe and Harrison*, in press]. Contrary to the approach developed by *Kaplan* [2001], wetlands developed from saturated soils are not considered. This is certainly a limitation of our approach, especially in the Amazon basin where HYDRA is known to significantly underestimate the extent of wetlands [*Coe*, 1998, Coe et al. in review.]. In the Amazon basin, seasonally flooded plains occupy

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Table 1. Mean annual values for selected climate variables at all time periods, in northern tropical Africa and northern South America. Ambient air temperature is in °C, while runoff, rainfall rates and water budget (precipitation - potential evaporation; P-EP) are in mm/day.

Geographical Regions	Time periods	Runoff	Rainfall	P-EP	Temperature
Northern	Present-day	1.2411	2.7417	0.7437	12.9251
South America	LGM (21 ky)	0.8531	2.3180	0.3339	12.1241
(85°W-30°W; 20°S-15°N)	LIG (126 ky)	1.4254	2.9604	0.9559	13.0391
Africa	Present-day	0.5089	2.0622	−1.7234	23.0948
(20°W-15°E; 5°N-20°N)	LGM (21 ky)	0.2476	1.0499	−2.6786	20.7760
Africa	Present-day	0.1026	0.7994	−3.4851	23.9249
(20°W-50°E; 10°N-25°N)	LIG (126 ky)	1.0776	2.7159	−1.1231	22.8397

a large area compared to permanent open waters. But in this paper the mechanism we have found applies only to permanent waters. Our conclusions would therefore remain valid, even if we had considered all possible types of wetland formations. The model currently operates at 5-minute spatial resolution (~9km at the equator) and 1-hour temporal resolution. The simulated inland water bodies are therefore updated every hour.

[8] The discrimination between lakes and wetlands is based, in HYDRA, only on the water depth. In our study it is assumed that, above a certain depth, methane is consumed by methanotrophic bacteria, before being released to the atmosphere [*Boone*, 2000]. This critical threshold is fixed to one meter in all our simulations, but we have carried out a number of studies (not presented here) to test the sensitivity of our results to the choice of this threshold. Varying this depth from fifty centimeters to one meter and a half did not affect the trends shown here (changes are within ±20% of the values displayed in Tables 1–3).

[9] *The climate fields* used to force HYDRA come, for the LIG and the LGM, from simulations carried out using the LMD5.3 atmospheric general circulation model [*Harzallah and Sadourny*, 1995; *de Noblet et al.*, 1996]. For present-day climate we have used the runoff provided by the Global Runoff Data Center [GRDC, *Fekete et al.*, 1999], the continental precipitation rates and ambient surface air temperature provided by *Leemans and Cramer* [1991, herafter LC91], and the potential evaporation computed by the BIOME1 model [*Prentice et al.*, 1992] forced with LC91.

[10] Present-day simulations of lakes and wetlands extent started from non-flooded (i.e. completely dry) soils, and were integrated until equilibrium was reached, that is until there were no more significant variations of the seasonal extent of lakes and wetlands from one year to another (~200 years). All paleo-simulations started from the equilibrium present-day extent of lakes and wetlands. Although this may not seem to follow the chronological order, the final state of a HYDRA simulation is independent of the initial surface conditions assigned to the model. Our choice was driven by the necessity to limit the computational cost of these experiments.

3. Simulated Changes in Wetland Extent and CH_4 Emission

[11] At the last glacial maximum, in northern South America, simulated precipitation and runoff rates were lower than those of today (Table 1). The amount of surface water available to fill the potential lake/wetland areas was also less and as a result the simulated extent of lakes was lower at the LGM. However, the extent of simulated wetlands was larger (Table 2). The reason for this counter-intuitive behavior is that many of the lakes in the modern simulation were large shallow wetlands at the LGM, with a water depth sufficiently small (lower than one meter) to allow in principle methane to be released to the atmosphere.

[12] During the last interglacial (126000 years ago) in northern South America, the simulated hydrological cycle was enhanced with more rainfall and more surface runoff. Our simulations give results symmetric to the ones obtained for the LGM: the area occupied by lakes was larger than present while the wetland area was smaller (Table 2). More lakes were formed at the expense of wetlands, since during this relatively wet time-period precipitation and lateral runoff were large enough to compensate the changes to the evaporation rates. As a result the water depth was increased, in areas where topography allows for values larger than one meter, the critical threshold above which methane is thought to be consumed by methanotrophic bacteria, before being released to the atmosphere.

[13] In northern tropical Africa, the area we have chosen is too large to show homogeneous changes. We have therefore split it into two smaller regions, the first one (20°W–15°E, 5°N–20°N) exhibiting drier conditions 21000 years ago than present, the second one (20°W–50°E, 10°N–25°N) exhibiting wetter conditions 126000 years ago (Table 1). At both time periods, the changes in the extent of wetlands and lakes are similar: they

Table 2. Areas occupied by lakes and wetlands, expressed in 10^{10} m^2, together with areas which go from one status to the other, between present-day and the past climates. The arrows indicate the sign of change, with respect to present.

Geographical Regions	Time periods	Wetlands	Lakes	Wetlands becoming lakes	Lakes becoming wetlands
Northern	Present-day	13.5145	44.8837		
South America	LGM (21 ky)	13.5956 ↑	44.0935 ↓		0.5235
(85°W-30°W; 20°S-15°N)	LIG (126 ky)	13.2702 ↓	45.5958 ↑	0.1422	
Africa	Present-day	1.8737	2.2197		
(20°W-15°E; 5°N-20°N)	LGM (21 ky)	1.4768 ↓	1.2618 ↓		0.1201
Africa	Present-day	1.2761	0.7173		
(20°W-50°E; 10°N-25°N)	LIG (126 ky)	4.1426 ↑	8.4023 ↑	0.15491	

Table 3. Integrated annual amount of changes in methane emissions, between present-day and the past climates, from the natural wetlands (total flux), expressed in 10^{12} g of carbone, including the *changes* in emissions from areas which go from one status to the other. '+' ('-') indicate that the change led to more (less) CH_4 emitted at paleo-times.

Geographical Regions	Time periods	Estimated changes in Total flux	Wetlands becoming lakes	Lakes becoming wetlands
Northern South America	LGM (21 ky)	−0.6252		+0.2606
(85°W-30°W; 20°S-15°N)	LIG (126 ky)	−0.0875	−0.0797	
Africa (20°W-15°E; 5°N-20°N)	LGM (21 ky)	−0.32		+0.0576
Africa (20°W-50°E; 10°N-25°N)	LIG (126 ky)	+1.8313	−0.0815	

increase when the water budget increases and vice-versa (Table 2). Even though this common behavior between lakes and wetlands is different from what we obtained for northern South America, we still observe a rather important fraction of lakes at present that were wetlands at the last glacial maximum, and wetlands at present that were lakes during the last interglacial.

[14] These particular areas that do not seem, intuitively, to follow the hydrological changes may be quite important for the methane budget. They may make the total CH_4 flux emitted by the continental surfaces larger (lower) than it would be 21000 years ago (126000 years) if the changes in wetlands extent responded in a straightforward way to the changes in water budget. Using the simplified temperature dependent methane emission model developed by *Fung et al.* [1991], we find that in northern South America, 126000 years ago, the annual flux of methane emitted from natural wetlands was lower than at present, despite the increased water balance and the warmer temperatures, due to the enhancement of lake areas at the expense of wetlands (Table 3).

4. Discussion

[15] *Kaplan* [2001] showed in his modeling study that the extent of wetlands might have been larger 21000 years ago than at present, as a result of the continental shelves that were exposed at that time (particularly in the tropics). Our study shows that there is also potentially another mechanism that may have contributed to an increase in wetland area. Drying, in what are now moist tropical regions (e.g. northern south America and parts of northern tropical Africa), may have been enough to convert deep lakes into shallow wetlands. These wetlands then emitted methane and potentially increased (or limited the decrease of) the total CH_4 flux received by the atmosphere. In semi-arid subtropical regions (e.g. most of northern tropical Africa) drying during the LGM leads to a simulated dessication of wetlands and lakes and a decrease in the CH_4 flux to the atmosphere.

[16] Our results do not allow us to make any synthesis of the changes that have occurred at the last glacial maximum (nor at the last interglacial) because of both our limited areas and the fact that this version of HYDRA does not account for all types of wetland formations. However we feel confident that a bottom-up modelling approach is the appropriate tool to infer such changes because the competition between lakes and wetlands can only be solved if they are explicitely simulated.

[17] At this stage of our work, we cannot validate our conclusion based on field data since, to our knowledge, there is no such information. We encourage paleoclimatologists though to help us confirm (or disprove) our findings by extracting the appropriate informations from their data.

[18] Our approach, before being applied at the global scale, will also need a number of improvements including, as discussed in the 'tools and methods' section, the accounting of saturated soils and flooded plains in the definition of wetlands as described by *Coe et al.* [in review]. We will also need to use a sophisticated model for methane emissions from natural wetlands, such as the one developed by *Walter et al.* [1996].

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