DIRECT CARBON DIOXIDE EFFECT IN CONTINENTAL RIVER RUNOFF OVER THE PAST AND FUTURE CLIMATE

L'EFFET DIRECT DU CO_2 SUR L'ECOULEMENT DES RIVIERES DANS UN CLIMAT PASSE ET FUTUR

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Abstract : Recently, Gedney et al. demonstrated the impact of increase of atmospheric CO_2 during the period of 1960-1994 on global runoff through stomatal conductance process. The aim of this work is first to stress that this important result is also found in the IPSL OAGCM combined with the ORCHIDEE biosphere model prescribed with CO_2 measurements through the 20th century, and second to investigate whether this impact is still an important process in warm and cold climates changes, using simulations for 21st century and last glacial maximum (LGM). Our results focused on the global response of the water cycle and runoff in different climates and atmospheric CO_2 contents. Our set of experiments, described below show that for both, warm and cold climates, the stomatal conductance is an important player in explaining an increase (decrease) in runoff occurring in warm (cold) climate, but is not exceeding a third of global variation and has to be accounted for. The changes in transpiration during the 21st century remain important to explain the runoff increase. For the LGM, the CO_2 decrease and induced stomatal conductance impact on the runoff is much weaker than the change on the temperature produced by Sea Surface Temperature (SST) and ice sheets.

Keywords: river runoff**,** carbon dioxide effect, stomatal conductance

Résumé : L'augmentation du débit global des fleuves, enregistrée au cours du 20ème siècle, est essentiellement expliquée par l'effet direct de l'accroissement du CO_2 (baisse de l'évaporation totale induite par la diminution de la transpiration). En effet, à des taux élevés de CO_2, les plantes ouvrent moins leurs stomates. En conséquence, moins de vapeur d'eau est libérée vers l'atmosphère, ce qui engendre une augmentation du stockage de l'eau dans le sol et ainsi une intensification du ruissellement.

La première partie de notre travail confirme ce lien (CO_2/ruissellement) sur la période du 20ème siècle. Nous avons utilisé le modèle de circulation générale de l'IPSL, couplé au modèle de biosphère ORCHIDEE, forcé par les concentrations mesurées de CO_2 et d'aérosols. La deuxième partie quant à elle évalue l'importance de ce lien pour un climat chaud du 21ème siècle et un climat froid du Dernier Maximum Glaciaire (DMG), il y a 21 000 ans. On a pu réaliser des études plus poussées sur la réponse globale du cycle hydrologique à des climats et de taux de CO_2 atmosphérique, différents. Selon notre jeu d'expériences, la part de la conductance stomatique sur l'augmentation du débit des fleuves pour le 20 et le 21ème siècle est faible (n'excède pas le tiers) mais reste non négligeable. En fait, la majeure partie de l'augmentation du ruissellement est plutôt expliquée par l'augmentation des précipitations. Pour le DMG, l'effet du CO_2 sur la transpiration est beaucoup plus faible que l'effet de la baisse de température (climat froid du DMG).

Mots Clés: écoulement des rivières, effet du dioxyde de carbone, conductance stomatique

INTRODUCTION

Carbon dioxide is the currency of plant photosynthesis: plants take up CO_2 from the atmosphere and incorporate it into their tissues in the form of organic carbon compounds. This uptake of CO_2 is accomplished through plant stomata-small openings in the surface of leaves that open and close to allow the exchange of CO_2 and other gases with the atmosphere. During gas exchange, water was inevitably lost to the atmosphere, again for the stomata openings. This is the process of the plant transpiration, which on a global scale, mediates the transfer of water from the soil into plant tissues, and out through stomata to the atmosphere.

Plants can regulate the opening and closing of stomata in response to changing environmental conditions; in hight-CO_2 atmosphere they are more efficient in their use of soil moisture. The stomata do not open as much or for as long, and less water is lost from leaves to the atmosphere. As consequence, plants acquire enough carbon through their stomata with less water uptake from the soil. The result is that continental evapotranspiration is reduced, more moisture is left in the soil, and this additional surface water can lead to increased continental runoff.

Long term observations and modelling studies have confirmed that global runoff on the continents has increased over the twentieth century (Labat et al., 2004), but unfortunately we know much less about the mechanisms under this increase. A number of studies have revealed that observed increase in global runoff is associated with climatic and anthropogenic factors, increasing atmosphere humidity due to ocean evaporation caused by rising temperature (Labat et al., 2004), precipitation change (Berezovskaya et al., 2004), and land use and land cover change (Sahin et al., 1996; Foley et al., 2005; Costa et al., 2003). Recently, using a powerful method based on observed climate, use of the MOSES land surface/biosphere model and fingerprint analysis, Gedney et al (2006) consistently depicted that the direct effect of CO_2 via stomatal conductance closure was needed to account for the runoff increase observed on most of the continents.

In this study, we used the IPSL GCM and a continental biosphere model (ORCHIDEE) to explore how the global runoff and its temporal variation patterns changes over the last century, 21st century and LGM period.

THE MODEL

The global model

The coupled ocean-atmosphere-sea-ice general circulation model used in the present study is the version 4 of the “Institut Pierre Simon Laplace” (IPSL), Marti et al. 2005. The atmospheric part of the model LMDz (Li 1999), developed at the Laboratoire de Méteorologie Dynamique (LMD, IPSL) is coupled to the ORCHIDEE land-surface model (Krinner et al. 2005). This part is run with a horizontal resolution of 96 points in longitude, 72 points in latitude (2.7° x 2.5°) and 19 vertical levels. While the ocean part, ORCA/OPA (Madec et al. 1998) developed at the Laboratoire d’Océanographie (LODYC, IPSL) is run with 182 point in longitude, 149 point in latitude and 31 vertical levels with the highest resolution (10m) in the upper 150 m. A sea-ice model (Fichefet and Morales Maqueda 1997), which computes ice thermodynamics and dynamics, is coupled with the ocean-atmosphere model. The atmosphere and the ocean component interacts ones per day exchanging heat, fresh water, and momentum.

The biosphere model

ORCHIDEE model is a process based non-equilibrium biogeography-biogeochemistry model, and was developed previously to assess the transient impacts of climate change on the transfer of water and carbon in the vegetation-soil-atmosphere system (Kriner et al., 2005). The model includes parameterizations of canopy physiological responses (photosynthesis and stomatal conductance), and the hydrological and physiological process are intimately linked. Thus, modeled water evapotranspiration is an integrator of meteorological, hydrological, and ecological processes. The seasonal cycles of energy and water exchanges and carbon fluxes from ORCHIDEE model have been extensively calibrated and validated against eddy covariance data from a number of field sites (Kriner et al., 2005).

Our results do not account for irrigation and other features as plant evolution similarly to the approach described by Gedney et al., but focused on the global response of the water cycle and runoff in different climates and atmospheric CO_2 contents. Our set of experiments, which have been performed for larger climate perturbation than those of Gedney et al. intend to quantify whether the stomatal conductance may drastically enhance the first perturbation product either by CO_2 increase (IPCC) or by ice sheet extent and SST decrease extent occurring at LGM

EXPEREMENTS AND DISCUSSIONS

We used the IPSL GCM coupled with ORCHIDEE with the SECHIBA module activated which includes the stomatal conductance. The first experiment reproduces the 1860-2000 climate with prescribed aerosol and greenhouse gas concentrations. The historic changes in atmospheric CO_2 concentration are taken from Rayner et al. (2005). The second experiment covers 21st century using the SRES A2 scenario (fig. 1). To isolate the CO_2 effect, we carried out two other simulations where we drove ORCHIDEE using a monthly climatology averaged from the two first simulations but prescribing CO_2 at pre-industrial value (286 ppm). The first simulation successfully captures the trend of the precipitation through the 20th century (fig. 1).

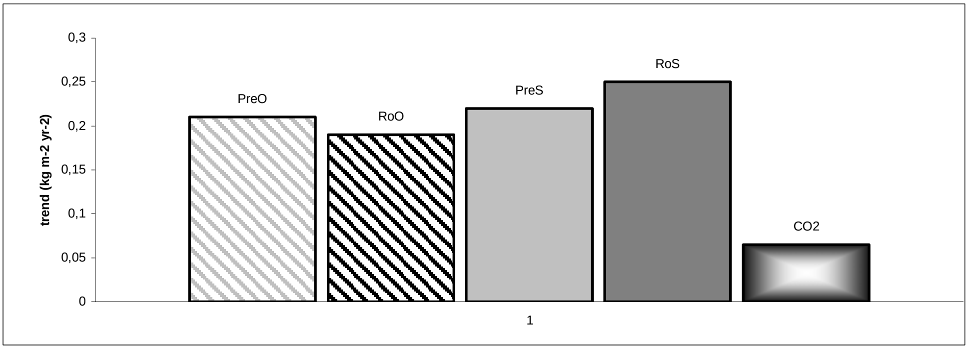
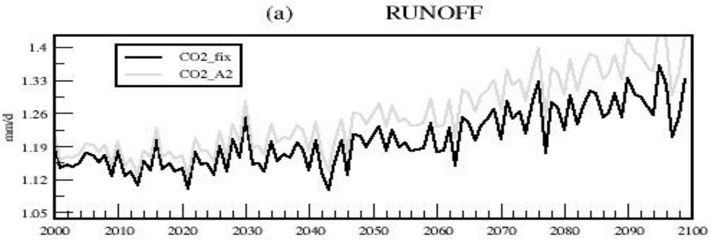


Fig.1. This figure depict the trends in continental water budgets between 1903 and 1994 similarly as defined in Gedney et al. (2006) for annual mean globally average quantities. Observed precipitation (PreO) and runoff (RoO). The three next bars represent our own results using IPSL and ORCHIDEE: precipitation (PreS; red bar), Runoff (RoS) and direct CO_2 contribution due to stomatal conductance which is only 26% of the total increase in runoff (CO_2).

For the 21st century, we show that the first order impact of CO_2 on radiative balance, increased temperature and associated moisture and finally is the major contribution to explain annual runoff increase (fig. 2). While the increase in annual runoff at the end of the 21st century is three times larger than the one obtained for the end of 20th century (15% increase instead of 5%), the contribution of stomatal conductance remains less then a third (fig. 1 &2).



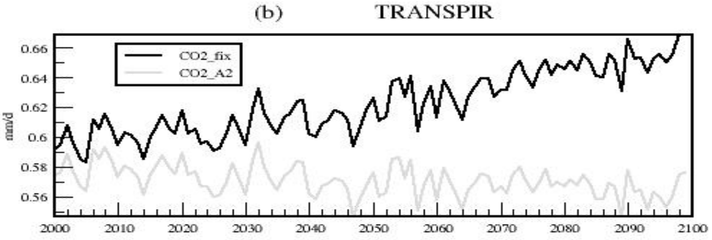


Fig. 2. Evolution of the annual mean globally averaged (a) runoff and (b) transpiration in mm/d in both 21st century simulations the red line shows SRES A2 scenario and black line the simulation with CO_2 fixed at 286 ppm. The relative contribution due to stomatal conductance (difference between these two curves) is weak in comparison with the total runoff increase during the 21st century.

Moreover for LGM, we performed a standard PMIP2 run (Kageyama et al. in press) with the same model than for the 20th and 21st cetury simulations: IPSL OAGCM coupled with ORCHIDEE. In this run the boundary conditions are Ice-5G (Peltier, 2004) for ice sheets reconstruction and CO_2 decrease (185 ppm) from Vostok.

To isolate the direct CO_2 effect from those of Ice sheet and SST we carried out the 20th century simulations using LGM CO_2 value (185ppm). The CO_2 decrease induces, as expected for opposite reasons than in CO_2 warming scenario, an opening of the stomates which reduces the runoff. Hoverer, this direct CO_2 lowering contribution to the global decrease of runoff at LGM remains very weak (0.02 mm/d) in comparison with the much larger impact of ice sheet extent and SST decrease (0.11 mm/d). In conclusion, we argue that in conditions when large perturbations of climate occur either toward warming (21st century IPCC SRES A2 or toward cooling (Last Glacial Maximum) the most important forcing factors acting on runoff increase (warming) or decrease (cooling) are primarily linked to primary to the radiative effect of $CO_{2,}$ for warming or cryosphere or ocean changes for LGM rather than the direct CO_2 effect through stomatal conductance.

CONCLUSIONS

The present study draws attention to hydrologic consequence of changes in climate and atmospheric CO_2 during the 20th and 21st century. We argue that, in fact, the major contribution explining runoff increase in a warm climate (IPCC A2 Scenario) or decrease in a cold climate (LGM PMIP simulation) is driven by the primary forcing factors (CO2 increase or ice sheet extent respectively). We show that the contribution of stomatal conductance is far to be a major player (fig. 1 and 2).

As Gedney et al, 2006, our result should be viewed with caution, because we considered only the effects of CO_2 on stomatal conductance. Other ecosystem structure changes including leaf area index (LAI) are not taken into account in our studies, although previous studies have highlighted the importance of feedback from LAI change on terrestrial hydrologic process (Betts et al., 1997; Levis et al., 2000). Consequently, predicting the role of atmospheric CO_2 rising in current hydrological cycle must include both vegetation stomatal conductions and LAI response to CO_2, and therefore additional study at the global scale is certainly needed.

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