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# Simulation of intense monsoons under glacial conditions

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**Abstract.** Paleoenvironmental and paleoclimatological proxy data indicate that strong continental monsoons took place under glacial conditions during marine isotopic stage 6.5 (175 ka BP). So far, no climate model has explored the possible coexistence of glacial conditions at mid and high latitudes and of interglacial monsoons in the tropics. Here we use an atmospheric general circulation model and clearly demonstrate that high insolation can generate increased monsoon activity even with surface glacial conditions. Our experiments show that Indian and African monsoons at 175 ka were stronger than nowadays and induced an increase in outflow of the Nile river to the Mediterranean sea. This freshwater supply combined with the local low glacial evaporation may explain the stagnation of the Eastern Mediterranean sea leading to the deposit of sapropel S6. Our simulations show also increased surface winds in the northern Atlantic and Pacific oceans which may have affected the bioproductivity in these areas.

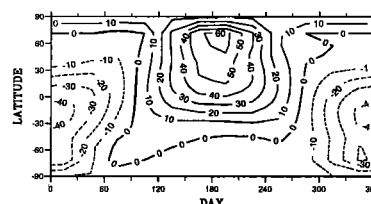
## 1. Introduction

A strong environmental change is documented at 175 ka BP during marine isotopic stage 6.5. The Dole effect [Bender *et al.*, 1994], measured as the deviation between records of mean ocean water  $\delta^{18}\text{O}$  and air oxygen  $\delta^{18}\text{O}$ , exhibits a peak related to changes in marine and/or terrestrial primary productivities [Malaizé *et al.*, 1999]. During this period of glacial conditions at mid and high latitudes, an unusual sapropel event (S6) occurs in the Eastern Mediterranean Sea [Mélières *et al.*, 1997; Cheddadi and Rossignol-Strick, 1995]. Sapropels, organic-rich black sediment layers accumulated under anoxic conditions, have been correlated with maxima in northern hemisphere summer insolation. Large insolation changes may have triggered intense African monsoon rainfalls and massive freshwater discharges in the Eastern Mediterranean from the Nile river [Rossi-

gnol-Strick *et al.*, 1982]. The orbital configuration of stage 6.5 [Berger, 1978] is indeed associated with a strong northern hemisphere summer insolation (7.5% higher than today at  $10^\circ\text{N}$ ) (Figure 1) which may be responsible for stronger northern summer monsoons and drastic changes in marine and terrestrial primary productivities.

In contrast with most periods of strong monsoons and sapropel events, stage 6.5 is characterised by glacial conditions (extensive continental ice volume [Imbrie *et al.*, 1984], 20% lower than during last glacial maximum, hereafter LGM; low atmospheric  $\text{CO}_2$  level [Petit *et al.*, 1999]). Observations and modelling studies have shown that a large Eurasian snow cover has a negative impact on monsoon strength, for present-day [Barnett *et al.*, 1989; Vernekar *et al.*, 1995] and past climates [Prel and Kutzbach, 1987; De Menocal and Rind, 1993]. In this paper, we use an atmospheric general circulation model (AGCM) to determine whether it is possible to simulate strong monsoons under glacial surface conditions with the orbital configuration of stage 6.5.

We have run version 5.3 of the LMD (Laboratoire de Météorologie Dynamique, CNRS, Paris) AGCM [Hazzallah and Sadourny, 1995], with a mean horizontal resolution of  $5.6^\circ$  longitude and  $3.6^\circ$  latitude, and 11 vertical levels. This model is able to simulate many features of the observed modern monsoon system and has been extensively used for paleoclimate studies (e.g. within the Paleoclimate Modelling Intercomparison Project, PMIP) focused on past monsoons [Masson and Jous-



**Figure 1.** Hovmöller diagrams of insolation change at the top of the atmosphere between 175 ka BP and present-day as a function of the day (Day 1 is January 1st) and the latitude ( $\text{W.m}^{-2}$ ). Calculations are from Berger [1978].

**Table 1.** Description of the boundary conditions used for the different simulations. C and LMG are 16 year long simulations; C175 and LGM175 are six year long simulations; the first year corresponds to the model spin-up. Glacial surface conditions include SST from [CLIMAP, 1981] and ice-sheets from [Peltier, 1994].

Name	Insolation	CO <sub>2</sub>	Surface
C	0kBP	345 ppmv	modern
LGM	21 ka BP	200 ppmv	glacial
LGM175	175 ka BP	200 ppmv	glacial
C175	175 ka BP	345 ppmv	modern

saume, 1997; Joussaume et al., 1999] and on the climatic impact of glacial boundary conditions [Ramstein and Joussaume, 1995]. We have evaluated the impact of the insolation change by comparing simulations that differ in values of insolation, CO<sub>2</sub>, and surface conditions (Table 1). Due to the lack of detailed information on ice sheet topography and ocean surface conditions during stage 6.5, we have used extreme surface conditions; modern and LGM. The difference between simulations LMG175 and C shows the climate change resulting from both insolation and surface condition changes. The difference, LMG-C, shows the change resulting only from glacial to modern conditions, while the change due only to insolation change is the difference, C175-C, for modern conditions, or LGM175-LGM for glacial conditions. Finally, the impact of glacial conditions on the sensitivity to insolation change is taken to be (LGM175-LGM)-(C175-C). We discuss below the changes in 1) summer African and Indian monsoons, 2) terrestrial biosphere, 3) wind stress at the ocean surface, and 4) hydrology of the Eastern Mediterranean Sea.

## 2. Results and discussion

1. With modern boundary conditions (Table 1), the higher JJA (June-July-August) 175 ka BP insolation induces a strong continental warming (+6°C in Eurasia) (C175-C, Figure 2). Over African and Asian monsoon regions, stronger precipitation (C175-C, Figure 3) results in colder surface temperatures, due to heat loss by evaporation and convective cloud albedo. The mechanism responsible for insolation-dependent monsoon changes is well known [Prell and Kutzbach, 1987]. The radiative heating of the continental surface warms. The rising air creates a thermal low which draw in moist air from the surrounding oceans. Once over the continent, this moist air also rises and the subsequent adiabatic cooling triggers intense precipitation, enhancing the monsoonal activity.

Within PMIP, [Pinot et al., 1999] have shown that the climatic and hydrological changes of the LMD model (LGM-C, Figures 2 and 3) compare well with observations and other model simulations using the same boundary conditions (reduced CO<sub>2</sub> and surface glacial conditions). Simulations and reconstructions show that glacial conditions decrease the African and Indian monsoon (less precipitation in south eastern Asia and western Africa) and increase the precipitation over the warm

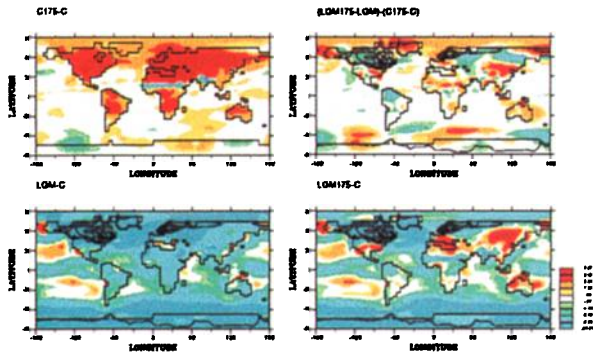
Indian Ocean (including eastern equatorial Africa). Like some of the PMIP models, the LMD model also shows increased precipitation above the Indian Peninsula, for which no data are available. In the Indian ocean, alkenone-based reconstructions [Bard et al., 1997; Sonzogni et al., 1998] suggest cooler than CLIMAP tropical SST which would probably influence the simulated monsoons.

With glacial boundary conditions (LGM175-C, Figures 2 and 3), the same insolation change also produces stronger than present African and Asian monsoons. The northern African (20°W, 60°E, 5°N, 25°N) and Indian (70°E, 100°E, 0°, 30°N) summer precipitation is intensified by 30% and 60% respectively compared to the control simulation. The climatic impact of insolation change is weaker than under modern boundary conditions because 1) the ice-sheet albedo weakens the northern warming (LGM-C, Figure 2); and 2) large convective areas are shifted towards the LGM oceanic warm pools reconstructed by [CLIMAP, 1981] (LGM-C, Figure 3). As a result, the monsoon amplification in northern Africa and India is 25% lower under glacial conditions (LGM175-LGM) than under modern conditions (C175-C) (Figures 2 and 3). However, the strong monsoons simulated under glacial conditions with 175 ka BP insolation (LGM175) are much larger than the sum of the modern precipitation sensitivity to insolation (C175-C) and weak glacial precipitation (LGM), which illustrates the non linearity of the monsoon system.

2. The impact of these large insolation-induced climate changes on the continental biosphere has been evaluated using an equilibrium biome model [Prentice et al., 1992]. The LGM175 simulated vegetation (Figure 4) is characteristic of a cold and dry glacial climate in the extra-tropics, consistent with long pollen records [Tzedakis, 1993; Reille and Beaulieu, 1995; Cheddadi and Rossignol-Strick, 1995]. In central mid-latitudes, warmer and moister summers enable the replacement of dry desert by grasslands in the model. In India and northern Africa, the simulated large increase of the surface occupied by xerophytic woods (replacing dry desert or dry forest) reflects the intensified monsoon rainfall.

3. The LMD model simulates increased annual mean surface wind speeds (Figure 3) above the north Atlantic and Pacific oceans (+8%), the equatorial eastern Atlantic and the tropical western Indian ocean (+5%). Stronger wind surface stresses should intensify coastal and open ocean upwellings, increasing the deepwater supply of nutrients and the primary productivity in nutrient limited oceanic regions. Some paleoproductivity records indicate increased productivity during stage 6.5, for instance in the equatorial Indian ocean [Rostek et al., 1997; Beaufort et al., 1997; Cayre et al., 1999] which may have contributed to the Dole effect signal [Malauzé et al., 1999].

4. The simulated annual mean freshwater balance (precipitation minus evaporation plus continental runoff) for the Mediterranean Sea (13 model grid points) is increased by +0.7 m/yr at 175 ka BP. This is the result of decreased evaporation (+0.4 m/yr) and in-

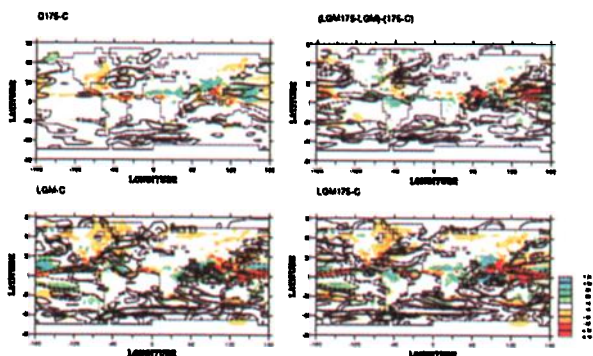


**Figure 2.** Change in summer (June-July-August) surface air temperature (in °C) (color scale) and change in ice-sheet elevation (isolines at 500, 1000, 1500, 2000, 2500 and 3000 m).

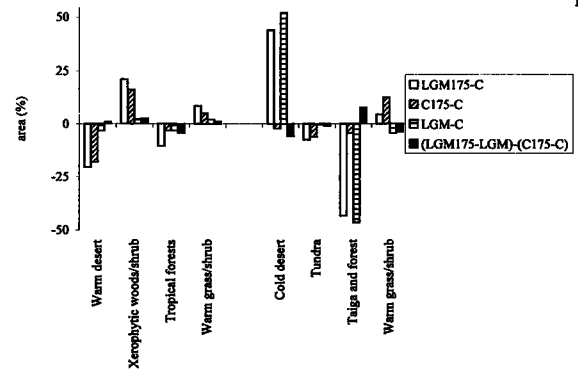
creased outflow from the Nile river (+0.3 m/yr) (Figure 5). Two thirds of the evaporation decrease arises from colder glacial SST (-2°C). The remainder is induced by the summer insolation change: the advection of warm air from the surrounding continents above the Mediterranean sea stabilizes the atmospheric boundary layer and decreases the surface fluxes. According to a runoff model based on modern drainage system [Braconnot *et al.*, 1999b], the increase of outflow from the Nile river results from the African monsoon precipitation increase due to the insolation change. We speculate that the increased Nile river discharge to the Levantine Basin combined with low evaporation above the Eastern Mediterranean Sea may have resulted in a stratification of the water column leading to the formation of sapropel S6.

### 3. Conclusions

Simulations performed with an AGCM demonstrate the possible coexistence of glacial conditions in the middle and high latitudes and strong African and Asian monsoons. Although we have used crude assumptions for the surface conditions (no feedback of the vegetation, modern or CLIMAP glacial ocean conditions), we show that the impact of insolation alone is large enough to explain at least part of the observed environmental



**Figure 3.** Change in summer (June-July-August) precipitation (color scale, in m/year; changes larger than 0.25m/year pass a Student test at 95% confidence level) and change in annual ocean surface wind speed (blue isolines at -5, -2, -1, -0.5, +0.5, +1, +2 and +5 m/s).



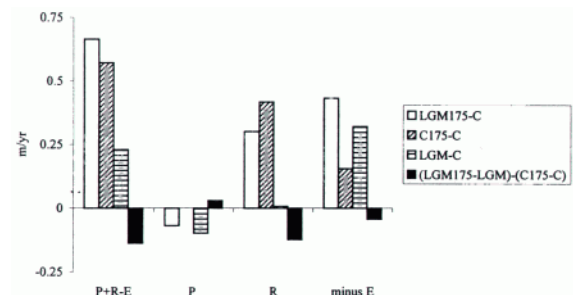
**Figure 4.** Changes in northern hemisphere biome distributions (in percentage of land surface): in the tropics (5°N, 25°N) for the first four biome types; at high latitudes (45°N, 90°N) for the last four types.

changes documented at 175 ka BP (vegetation changes, occurrence of sapropel event S6, higher marine bioproductivity). The simulated increase in monsoonal activity may even be amplified when taking into account the interactions of the ocean and vegetation with the atmospheric circulation [Braconnot *et al.*, 1999a].

A further assessment of our simulations will be provided by the comparison of atmospheric methane emissions and the Dole effect calculated from our simulations with paleoclimatic records. The atmospheric methane concentration recorded in Vostok ice core during stage 6.5 is between glacial and interglacial levels [Petit *et al.*, 1999]. This probably reflects the lowered emission from boreal wetlands (due to the ice sheets and permafrost cover) and the intense activity of tropical wetlands [Chappellaz *et al.*, 1997]. The Dole effect at 175 ka BP [Mélières *et al.*, 1997] corresponds to the largest anomaly of the past two climatic cycles [Malaizé *et al.*, 1999].

Previous periods also show the occurrence of Mediterranean sapropels [Rossignol-Strick, 1989] under glacial conditions (e.g. S8 dated at 224 ka BP). It is probable that similar monsoon increase mechanisms took place during these periods.

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**Figure 5.** Changes in Mediterranean Sea annual mean freshwater balance (in m/year).

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