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Climate sensitivity to wetlands and wetland vegetation in mid-Holocene North Africa

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Abstract Wetland regions are important components of the local climate, with their own characteristic surface energy and moisture budgets. Realistic representation of wetlands, including the important vegetation component, may therefore be necessary for more accurate simulations of climate and climate change. However, many land-atmosphere coupled models either ignore wetlands or treat wetlands as bare, water-saturated soil, neglecting the vegetation present within wetland environments. This study investigates the possible response of the mid-Holocene climate of North Africa to changes in orbital forcing, both with and without the presence of wetlands. The location of these wetlands is guided by analysis of paleovegetation and wetland distribution. In this study, the wetland regime in the land surface component of a climate model was modified to incorporate vegetation. Field measurements have shown that vegetation affects water loss associated with evaporation (including transpiration) within a wetland area. Comparisons between non-vegetated wetland and vegetated wetland revealed an increase in local albedo that produced an associated decrease in net radiation, evaporation and precipitation in the vicinity of the wetlands regions. Based on an analysis of the model surface water balance, the calculated area of mid-Holocene wetland coverage for North Africa closely matches the observed. For the North African region as a whole, the effects of adding vegetation to the wetland produced relatively small changes in climate, but local recycling of water may have served to help maintain paleo wetland communities.

North Africa was covered with grasslands along with scattered lakes and wetlands (Street and Grove 1976; Hoelzmann et al. 1998). The fundamental cause of the wetter North African climate was the change in the Earth’s orbital parameters that amplified the annual cycle of insolation in the Northern Hemisphere. This led to an enhanced land-ocean temperature contrast and a stronger summer monsoon (Kutzbach and Street-Perrott 1985; Prell and Kutzbach 1992). Subsequent modelling studies have shown how land surface feedbacks involving the changed vegetation altered the surface energy and moisture budgets and further enhanced the large-scale monsoon circulation (Kutzbach et al. 1996; Texier et al. 1997). However, models including the observed changes of vegetation, lakes, and wetlands have been unable to simulate the complete magnitude and extent (northern boundary) of the large-scale monsoon enhancement of the mid-Holocene (Kutzbach et al. 1996; Coe and Bonan 1997; Broström et al. 1998).

Broström et al. (1998) conducted modelling experiments to evaluate the specific effect of the observed increase in North African surface water on the climate and found that the expanded wetland regions in the mid-Holocene produced local climate changes but had little effect on the North African climate as a whole. Because of restrictions due to model design, their treatment of wetlands, however, was limited to assuming a saturated soil surface that did not include vegetation. Building on the work of Broström et al. (1998), this study evaluates the climate response associated with including vegetation in the wetland regime.

1 Introduction

Paleoenvironmental data reveals that, compared to the desert that exists today, much of the mid-Holocene

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2 Model and experimental design

for incorporating wetlands

The coupled land-atmosphere model used for this study was Version 3 of the National Center for Atmospheric Research (NCAR)
Community Climate Model (CCM3) (Kiehl et al. 1998). The atmospheric model is a primitive equation spectral model (truncated
at T42 resolution) that utilizes a 2.8° by 2.8° horizontal grid and has 18 levels in the vertical. CCM3 incorporates a land surface
model (LSM) to include vegetation, soil, and surface energy and hydrologic processes (Bonan 1998). The LSM operates on each model land grid cell. Each grid cell is assigned a fractional coverage of inland lakes and wetlands. The remaining fractional area is assigned one of 29 surface types (e.g., savanna, warm grassland, etc.). Each surface type supports up to three plant types (e.g., cool C3 grass, warm C4 grass, bare ground, etc.).

For a land grid cell area containing a mix of coverage by lake, wetland and a non-wetland surface type (e.g. warm grassland), the fractional wetland component is treated strictly as bare saturated soil (Bonan 1998 and personal communication). In order to include vegetation in a wetland, we therefore had to take a different approach by creating a separate category of vegetated wetland surface type. Since only one surface type can be assigned to a land grid point, the vegetated wetland surface type was required to occupy 100% of the grid cell area.

North African wetlands contain C3 and C4 grasses and are generally unforested (Jones 1988). For simplicity, we prescribed an equal mix of C3 grass, C4 grass and bare saturated soil for the vegetated wetland surface type adopted for mid-Holocene North Africa. The prescribed properties of wetland C3 and C4 grasses (e.g., leaf and stem area index, canopy height, albedo, etc.) are the same as those given in Bony (1998). The choice of an equal proportion of C3 and C4 grasses for the wetland vegetation is consistent with the observation that biomass accumulation appears to vary little between C3 and C4 plants in a non-limited water region (Jones and Muthuri 1984). The bare soil part of the wetland area accounts for the shallow standing water component associated with wetland areas (Idso 1983).

Four climate simulations were conducted to examine the response of the climate to prescribed changes in land surface characteristics in the region of North Africa (Fig. 1). The modified region, based upon the paleovegetation, lake and wetland reconstructions by Hoelzmann et al. (1998) stretches between approximately 7°N to 30°N and 10°W to 35°E, where the mid-Holocene wetlands were most prevalent. The experiments used the 1° by 1° distributions of vegetation, lakes, and wetlands of Hoelzmann et al. (1998) extrapolated to the 2.8° by 2.8° grid used in CCM3. The four experiments were: (1) no wetlands (but with more extensive grasslands replacing desert, savannah replacing grassland, darker soil replacing lighter desert soil, and enlarged lakes as in Broström et al. 1998, see Fig. 1); (2) fractional unvegetated wetlands (adding wetlands to the no wetlands case, based upon estimates of Hoelzmann et al. 1998, see Broström et al. 1998); (3) enlarged unvegetated wetlands (wetlands occupying more than 10% of a lake free gridcell in the fractional case were increased to 100% of that cell, see Fig. 1); and (4) enlarged vegetated wetlands (adding vegetation to the enlarged wetlands areas, Fig. 1). Although the fourth experiment incorporates a more realistic wetland structure, the areal coverage of wetland exceeds mid-Holocene observations. As noted, this latter problem was a consequence of model design which did not allow us to add vegetation to a fractional wetland area. Thus the results of the enlarged unvegetated and vegetated wetland experiments (3 and 4) should be viewed as providing insight on the sensitivity of climate to wetland vegetation rather than being an accurate representation of mid-Holocene wetlands.

Each experiment was run for 7.5 years, with an average of the last five years used for the analysis. Broström et al. (1998) and Kutzbach et al. (1996) have shown that this length of experimental run is sufficient to produce statistically meaningful results. The atmospheric CO2 concentration and sea-surface temperature were prescribed as modern values while the orbital parameters were fixed at 6000 years ago: an eccentricity of 0.0187, axial tilt of 24.1° and perihelion occurring in mid-September (Kutzbach et al. 1996).

3 Results

3.1 Surface energy processes

In order to isolate the effects of the various changes in wetland characteristics, differences between the simulations were examined. The analysis of these simulation differences and the associated graphs in Fig. 2 refer to fractional wetlands (fractional unvegetated wetlands minus no wetlands), enlarged wetlands (unvegetated wetlands enlarged to 100% of the associated gridcell minus the fractional unvegetated wetland simulation) and vegetated wetlands (enlarged wetlands modified to contain vegetation minus the enlarged unvegetated wetland simulation).

The surface albedo decreased in the summer as a result of including wetlands in the North African

Fig. 1A-C Map of simulation region. A Represents the extent of modern grasslands and the expanded grasslands associated with 6000 years ago. B. C Represent the distribution of wetlands during the mid-Holocene (Hoelzmann 1998), and the wetland region enlarged to 100% of the gridcell for the vegetation modification, respectively. The area inside the grey line is indicative of the expanded grasslands associated with the mid-Holocene (Hoelzmann 1998). The hatched area in C shows those wetland regions that were enlarged to 100% of the gridcell, treated both as bare, water-saturated soil wetlands (no veg; without vegetation) and subsequently as vegetated wetlands (veg; vegetation)