Effects of soil moisture on the sensitivity of a climate model to earth orbital forcing at 9000 yr BP

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Abstract. The sensitivity of climate to orbitally-related changes in solar radiation at 9000 yr BP (before present) is examined using fixed and interactive soil moisture versions of a low resolution general circulation model. In both versions of the model increased solar radiation for June-August at 9000 yr BP (compared to present) produced enhanced northern monsoons and warmer continental interiors in comparison to present whereas decreased solar radiation at 9000 yr BP in December-February produced weaker southern monsoons. The increased rainfall in the northern tropics in summer increased soil moisture and runoff at 9000 yr BP in the interactive model; in the southern hemisphere decreased rainfall in summer led to decreased soil moisture and runoff. Conditions in summer became drier (decreased soil moisture and runoff) at 9000 yr BP in the northern extratropics.

The experiments showed that the magnitude (but not the sign) of model sensitivity to 9000 yr BP radiation is altered by the effects of interactive soil moisture. Decreased soil moisture (about 20%) over northern Eurasia in the interactive model led to smaller evaporative increases, greater temperature increases and greater reduction of precipitation than for the model with fixed soil moisture. Over northern tropical lands, slightly smaller temperature increases and greater evaporation and precipitation increases in the interactive model are linked to the simulation of increased soil moisture at 9000 yr BP. The differences in sensitivity between the two versions of the model over northern Eurasia are statistically significant at the 95% level whereas those for the tropics are not.

Overall, the results of the simulations are generally supported by the geologic evidence for 9000 yr BP; however, the evidence lacks sufficient precision and the model resolution is too coarse for detailed model/data comparisons and for assessment of the relative accuracy of the two 9000 yr BP experiments.

The computed sensitivities of temperature and soil moisture to 9000 yr BP radiation differ from those simulated under equilibrium conditions in the various general circulation model experiments for increased atmospheric concentration of CO₂. In contrast to the effects of the enhanced seasonal cycle of solar radiation at 9000 yr BP, a CO₂ increase causes a broad warming of both the ocean and land with little modification of land/ocean temperature difference. The experiments for 9000 yr BP indicate a clearer signal for summer drying than is obtained in the experiments for increased CO₂. The results suggest that the 9000 yr BP climate may be of limited utility as an analog to future 'warm' climates.

1. Introduction

Major variations in global climate of the past have been linked to changes in earth orbital parameters (Hays et al., 1976; Imbrie and Imbrie, 1980; Rossignol-
Changes in these parameters (obliquity, eccentricity and season of perihelion) produce changes in the seasonal and latitudinal distribution of solar radiation received at the top of the atmosphere.

Numerical experiments with general circulation models of the global earth-atmosphere system have greatly advanced our understanding of how these changes in orbital parameters produced variations in climate (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982; Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987; Kutzbach and Gallimore, 1988). General circulation models (GCMs) numerically solve the basic equations governing the mass, momentum (motion), energy and water vapor balances in the atmosphere. The basic variables (temperature, wind, water vapor, etc.) are determined on a distribution of gridpoints regularly spaced over the globe; the spacing between grid points determines what modelers refer to as model resolution (the coarser or lower the resolution the greater the distance between grid points). Solutions to the equations require specification of boundary conditions at the earth-atmosphere interface. These boundary conditions may include land-ocean configuration, orography (e.g. mountains), surface albedo and soil moisture. Models vary in the degree of interactive components permitted at the earth-atmosphere interface. Good introductions to the subject of climate modeling are given in Schneider (1987) and Washington and Parkinson (1986).

The GCM experiments have shown that the changes in solar radiation brought about by variation of earth orbital characteristics produce a differential land/ocean thermal response causing major changes in monsoons and the global hydrologic cycle. At 9000 yr BP (before present), enhanced solar radiation in northern summer (about 7% greater than present) produces continental warming and stronger northern hemisphere monsoons than at present. Precipitation and positive precipitation minus evaporation both increase from tropical north Africa to southeastern Asia. In the interior of the northern continents drier conditions at 9000 yr BP are inferred by a more negative precipitation minus evaporation than occurs in the modern (control) simulation.

Most of the experiments have been performed with GCM's using fixed soil moisture (e.g. Kutzbach and Otto-Bliesner, 1982; Kutzbach and Street-Perrott, 1985; Kutzbach and Guetter, 1986; Kutzbach and Gallimore, 1988). In some preliminary experiments, Kutzbach and Guetter (1986) found that tropical lands were comparably sensitive to 9000 yr BP radiation in interactive (predictive) and fixed soil moisture versions of the NCAR Community Climate Model (CCM); summer warming and aridity over the northern middle latitude lands were greater than for the experiments with fixed soil moisture. Recently, Mitchell, et al., (1988) simulated wetter soils and increased precipitation over portions of the northern tropics in a 9000 yr BP experiment using the UK Meteorological Office GCM with interactive soil hydrology and a mixed layer ocean; drier soils were simulated at 9000 yr BP in northern extratropics. A