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UMI®
Changes in the regional hydroclimate of the Midwest United States between the 6-kBP and current climate

by

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For the Major Program
This work is dedicated to my late parents Mr. Raphael Otieno Onyango and Mrs. Alice Otieno who invested all they had in my education but did not live long enough to see their efforts come to fruition.
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ABSTRACT

This study uses the NCAR Mesoscale Model version 5 release 3 (MM5v3) to simulate the climate of North America at 6000 years before present (6-kBP). The experiments are designed to test the ability of the model to simulate past climates (paleoclimates) which differ significantly from the present and are partially verifiable. The paleoclimate simulations are compared to the present, and sensitivity to changes in insolation, CO$_2$ concentration, and vegetation on climate investigated. To limit the influence of Lateral Boundary Condition (LBC) errors on the simulations, the study uses NCEP-DOE Reanalysis II data for both 6-kBP and current climates. The study differs from previous paleo-climate simulations, because it used a regional model instead of GCM, and also includes differences in vegetation between the climates, which have been ignored in previous studies. The simulation results are also compared with proxy records and paleo-climate simulation from General Circulation Models (GCM).

Results from the study show that MM5v3 is capable of simulating the 6-kBP climates. The simulated differences between the present and the 6-kBP climates are consistent with the proxy records and lake level data. The study obtained improved simulations for the Midwest US, most likely due to better representation of the regional land-atmosphere interactions. The results suggest that given realistic initial and lateral boundary conditions, MM5v3 is capable of simulating details of climates (past or future) that differ from present.

The simulated precipitation over Midwest at 6-kBP is less than the present, but the evaporation is higher, resulting in negative precipitation minus evaporation (P-E). This is consistent with observed low lake level at 6-kBP over the region. These changes in (P-E) may
not have adequately been captured by previous GCM studies. The analysis of the results also reveals that less transport of moisture to the Midwest at 6-kBP was the likely cause of the lower precipitation and hence lake-levels. Sensitivity tests show that a change in insolation influences both temperature and precipitation; a change in vegetation affects precipitation; but changes in CO₂ produce less significant changes in both temperature and precipitation.
CHAPTER 1 INTRODUCTION

1.1 General introduction

Climate models are increasingly being used to study and predict future climate scenarios. The efforts are aimed at understanding the impacts of anthropogenic activities on the climate systems. Among the impacts is the potential for an altered hydroclimate (Allen et al. 2000; IPCC 2001; Nearing 2001; Takahashi et al. 2003). However, the need for reliable climate information for planning realistic adaptation or mitigation strategies has raised questions about the ability of models to simulate climates that differ significantly from the present. The questions arise partly because coupled Atmosphere Ocean Global Climate Models (AOGCMs) that have been used to make projections had coarse resolution, and were developed, calibrated for, and primarily tested on the current climate (Johns et al. 1997; Bell et al. 2000; Collins et al. 2004). Even if the predictions from the current state of the art climate models are assumed to be representative of future climate, lack of corresponding observations does not allow for verification of the projections. Some studies have therefore attempted to simulate verifiable past climates (paleoclimates) using AOGCMs (COHMAP 1988; Joussaume and Taylor 1995; Hall and Valdes 1997; Vettoretti and Peltier 2004). These studies examined the consistency between simulated and inferred past climates. They found general consistency between simulations of broad scale patterns of temperature, but large areas of uniform precipitation changes in some cases conflicts with proxy records. Differences also occur depending on model resolution, and whether or not vegetation and sea surface temperature (SST) feedbacks are allowed.

This study simulated the climate of North America using a high-resolution regional climate model (RCM) during a period when the climate was significantly different from
present and proxy records are available to verify the simulation. Proxy records indicate that the Midwest US was dry and warm around 6,000 years before present (6-kBP). The number of existing proxy records provide a basis for model evaluation at this time. The evaluation focused on the water cycle because lake levels in North America are known to have been lower than present at 6-kBP. The water cycle can be influenced internally by atmospheric, land surface and sub-surface changes as well as externally by changes in insolation due to natural variations in orbital parameters (Labitzke and Van Loon 1992).

Anthropogenic alteration of the hydroclimate which may compound problems of natural variability in the Midwest US include changes to land-surface cover, excessive exploitation of sub-surface water resources such as in the Ogallala aquifer in south central US (Rosenberg et al. 1999) and increases in atmospheric green house gas (GHG) concentrations (IPCC 2001). Natural variations such as those of the orbital parameters have in the past been associated with the advance and retreat of glaciers, with substantial impacts on the hydroclimate of North America (Van Geel 1999). However, contemporary climate-change studies have tended to focus primarily on future impacts of current anthropogenic modifications of the climate system. This study examines how the climate of North America simulated by an RCM forced by a combination of natural and anthropogenic changes representative of 6-kBP climates, compares to pollen-inferred climate.

1.2 Climate modeling uncertainty

Uncertainties in AOGCM projections arise in part from coarse resolution and parameterizations based on incomplete understanding of sub-grid atmospheric and terrestrial physical processes. In AOGCMs for instance, the subsurface hydrology does not usually extend into the vadose zone and net changes in aquifer storage along with its influence on
soil moisture and surface runoff are ignored. However, significant regional contribution to the atmospheric moisture from subsurface may occur (Gutowski et al. 2002, York et al. 2002).

AOGCM predictions of future GHG scenario climates suggest likely alterations to the hydroclimate through changes in spatio-temporal patterns of surface temperature, precipitation and soil moisture (IPCC 2001). However, simulated changes in global averages tend to be small and well within the range of inter-annual variation. However, global averages mask regional changes, which may be much larger. AOGCMs were not designed to simulate regional details, yet it is changes at these scales that ultimately influence biotic and physical systems, affecting composition, structure and function of vegetation as well as the regional water balance. The observed decline in lake-levels and eastward expansion of the prairies in the Midwest US around 6-kBP are examples of such response to a global forcing (Webb et al. 1993).

Uncertainties in the simulations of regional climatic features by AOGCMs, especially under different climates have led to increasing application of RCMs. The climate of any region is ultimately determined by the interactions between the various scales of circulations found in the region. In the Midwest US, for instance, the low-level jet and its associated moisture fluxes, lee cyclogenesis east of the Rockies and surges of high-latitude cold air masses interact to give the region a unique climate (Stensrud 1996; Roebber et al. 2004). High resolution that represents these regional circulations may therefore benefit simulations of regional paleoclimate. Also, much of the continental archives of paleoclimate proxies are found in small to medium size lakes with spatial dimensions that are much smaller than typical AOGCM grid spacing (300 km). These lakes are not resolved at the AOGCM resolution. Using an RCM which simulates local features better and also provides a
verification based on a spatial resolution that is closer to scales represented by proxy archives, which are essentially point measurements, may lead to improved simulations. RCMs provide higher spatial resolutions, but they also use parameterizations of physical processes, have been tested, calibrated and developed primarily in the current climate and therefore their simulations still need to be verified for different climates. This was a primary motivation for this study. Given a combination of changes in CO₂, land use and solar forcing representative of 6-kBP, can a RCM simulate the regional climate response of North America that is consistent with proxy records? What potential physical mechanisms explain the warm and dry conditions that have been associated with the US Midwest at 6-kBP? These are the overarching questions addressed in this study. The rationale is that understanding how the regional climate system responds to combinations of natural variability and anthropogenic influence highlights regions of vulnerability, which may have large changes in response to the imposed forcing. This knowledge is useful in minimizing the risk of “climate surprises” from a feedback-driven rapid climate change.

1.3 Approach used in the study

This study focuses on a specific region of the globe with sufficient paleoclimate proxies and current climate observations needed to run a RCM. The National Center for Atmospheric Research/Pennsylvania State University (NCAR/PSU) Mesoscale Model Version 3.6 (MM5v3) was used to simulate current and 6-kBP (scenario) climates of North America. Both the current and scenario simulations were driven at the lateral boundaries by data from the second National Centers for Environmental Prediction (NCEP) and Department of Energy (DOE), Atmospheric Model Intercomparison Project (AMIP-II)
Reanalysis Project (NDA-RPII, Kanimitsu et al. 2002). Using the same lateral boundaries for both climates allowed for the isolation of the effects of CO₂, vegetation and insolation. These were the main differences between the 6-kBP and the current climate. Comparing the results show the effects of 6-kBP forcing on different components of the water cycle and hence hydroclimate.

The main reasons for the period and domain choices above were the agricultural significance of the US Midwest, documented changes in the regional climate at 6-kBP, availability of both current climate data and proxy records in addition to the uniqueness of 6-kBP radiative forcing (Plantico et al. 1990). Observational data over the North American continent provided adequate information needed to drive MM5v3 while the paleo-environment reconstructions provided a basis for verification. Insight into the large-scale circulation at 6-kBP, which could not be determined from proxy records alone, and which was needed for 6-kBP boundary conditions, was inferred from past AOGCM simulations of 6-kBP.

As discussed in Chapter 2, 6-kBP lacked the large ice sheets that characterized the last glacial maxima (LGM) and the summer (June-July-August, JJA) insolation was greater than in the current climate making it a suitable epoch for verifying RCM simulations. The insolation at 6-kBP had little change in annual mean but a large seasonal variation (Kutzbach and Ruddiman 1993). Lack of large ice mass and presence of strong insolation changes provide for a simpler experimental design. Unlike the effect of CO₂, which is uniform in space and time, changes in insolation examined in this study may act more strongly where sunlight reaches the surface and thus enhance regional response.
1.4 Objectives

The study evaluates how well of MM5v3 simulates the climate of North America at 6-kBP, which has been shown in other studies to have been different from the current. The evaluation focused on components of the hydroclimate. Differences between the simulated 6-kBP and current climate were used to assess the model response to 6-kBP forcing. Specifically the study:

(i) Simulates an average current climate warm season (April-September) using MM5v3, with lateral boundary conditions (LBC) and initial conditions (IC) from Reanalysis II (Kanimitzu et al. 2002)

(ii) Performs a series of individual sensitivity experiments to determine regional model responses to individual changes in eccentricity, longitude of perihelion, obliquity, reduced CO₂ and changes in vegetation.

(iii) Performs a scenario experiment in which the changes in (ii) above were combined to represent the 6-kBP scenario forcing.

(iv) Compares the scenario and current climate simulations with each other and against current-climate observation or proxy-derived precipitation and temperature.

(v) Attempts to determine physical mechanisms for the simulated differences.
CHAPTER 2 BACKGROUND

2.1 Simulating different climates

Can numerical models predict climates that are significantly different from those of the present? To answer this question, we need to compare the predictions with observed data from the different climates. It is possible that observations will eventually be available to verify current projections of future climate. However, concerns for potentially irreversible changes to the climate systems by then have prompted climate researchers to attempt to answer this question now, using data from past climates (paleoclimate). The earth's climate is known from geological and proxy records to have been different from present at 6,000 years before present (6-kBP) and as far back as the last glacial maxima (LGM) approximately 18,000 years before present (Kutzbach and Ruddiman 1993). Unfortunately records of standard meteorological observations of climatic elements do not exist for the LGM making it difficult to verify LGM simulations. Although the large Laurentide ice mass chilled the North American continent giving the region a distinctly different climate at the LGM, most proxy records in the continental North America are only available during over the last 10,000 years (Holocene). This study, therefore, focuses on the mid-Holocene period of 6-kBP to make use of the available proxy records. In addition to availability of proxies, the unique radiative forcing at 6-kBP and absence of large ice mass also provided for simpler experimental design, which ultimately helps with the interpretation of simulation results.

Following the COHMAP (1988) approach, the verification here involves determining whether or not simulated temperature, precipitation and evaporation are consistent with pollen-derived vegetation and lake levels. While the COHMAP studies used GCMs, this
study uses an RCM. A further motivation for using an RCM (MM5v3) was the extremely low decreases in lake levels obtained when AOGCM output was used to drive a hydrological model (Filby et al. 2002).

The known changes in the orbital parameters and the climate of North America at 6-kBP based on pollen records, lake level data, and AOGCM simulations are documented in the subsequent sections. The differences in orbital parameters are needed to set up the 6-kBP simulations, while the 6-kBP climates are used for verification. Particular attention is focused on differences occurring within the region where initial conditions (IC) and lateral boundary conditions (LBC) for the 6-kBP simulations are required, that is MM5v3’s forcing frame. Details of the RCM configuration are presented in Chapter 3.

2.2 Variations in orbital parameters

Variations in the earth's eccentricity, axial tilt, and precession affect the seasonality and strength of solar radiation at the earth's surface. These three parameters are collectively known as orbital parameters and their cyclic variations have been called the Milankovitch cycles (Milankovitch 1920). Astronomical computations (Berger 1978) can determine their values at 6-kBP fairly accurately and show differences between 6-kBP and present (Fig.1).

Of the three Milankovitch cycles, the shape of the earth's orbit around the sun or eccentricity varies with a period of 100,000 years. It alters the earth-sun distance and hence actual amount of radiation reaching the top of the atmosphere. The orbital eccentricity at 6-kBP was 0.0187 and is currently near the minimum of its cycle at 0.0167. The current eccentricity puts the earth closest to the sun (perihelion, 153 million km) in January
compared to October at 6-kBP. Hence more radiation is received in June-July-August at 6-kBP compared to present.

The earth's axis of rotation also executes a slow precession with a period of about 23,000 years. This precession of the equinoxes determines the time at the point in earth's orbit when a hemisphere tilts toward the sun, thereby amplifying or damping seasonal climate variability. At 6-kBP the Northern Hemisphere (NH) extra-tropical latitudes received larger insolation during the summer than at present, due in part to the precession of the equinox.

The earth's tilt (obliquity) with respect to the orbital plane (elliptic) also varies from 21.5 to 24.5 degrees with a period of about 41,000 years, larger tilts producing greater seasonality. Fig.1(c) shows that the earth's obliquity was 24.1° at 6-kBP, resulting in greater seasonality compared to the present tilt of 23.5° (Kutzbach and Webb 1993). Thus the earth's eccentricity, longitude of perihelion and orbital inclination at 6-kBP all support increased insolation at the top of the atmosphere during North America summer at 6-kBP.

Understanding how the hydrological cycle in the Midwest North America responded to this increased insolation was one of the main goals of this study.

Transient runs in which the orbital parameters are allowed to evolve over their individual time-scales (thousands of years) would be ideal. However, this would require IC and LBC that do not exist and the cost of computation would also be prohibitive. Therefore, this study adopts a case study approach in which the RCM was setup for a current climate in one case and 6-kBP for the other. To do this, the standard MM5v3 code was modified to account for changes in the earth's orbital eccentricity and inclination as well as longitude of perihelion. The standard MM5v3 specifies obliquity explicitly but combines the eccentricity...
Fig. 1: Variations in the orbital parameters since the last glacial maxima. (a) Eccentricity (b) Obliquity (c) Longitude of perihelion and (d) Eccentricity factor; (function of eccentricity and longitude of perihelion).
and longitude of perihelion into a single eccentricity factor that is a function of time. Fig. 1d shows the annual evolution of the eccentricity factor for the current and 6-kBP climates. Maximum values in the eccentricity factor and hence insolation occurs in October and January for the 6-kBP and current climates respectively, consistent with the earth being at perihelion.

2.3 Reconstructions of paleo-environments

In addition to the 6-kBP orbital characteristics, the vegetation over North America, particularly in the Midwest is known to have been significantly different from present. Differences existed in the distribution of prairies and forests at 6-kBP as determined from fossilized proxy records. These records generally include plant fossils, zoologic records, sediment deposition, eolian dust accumulations and some archeological records. Of the proxy records, the plant fossils are considered the most direct sources of information, especially in well-watered and sheltered places such as basins but they may be unrepresentative in open ridges (Bartlein et al. 1986; Webb et al. 1993; Adams and Faure 1997). Existing physical relationships between temperature, precipitation and vegetation and the availability of fossilized pollen enable past climates and vegetation on land to be inferred. In marine environments, surface water temperatures and other controlling variables such as nutrients and salinity influences the composition of marine plankton and can be used to reconstruct sea-surface temperature (SST) time series (CLIMAP 1981).

MM5v3 is capable of simulating 6-kBP climates at high spatial and temporal resolutions, but pollen inferred precipitation and temperatures only show changes in annual
averages. However, in the Midwest US, vegetation growth and a large fraction of the precipitation occur in the warm part of the year. Therefore changes in pollen and lake-levels are assumed to reflect conditions during the warm and wet part of the year, allowing the inferred climate to be compared with the MM5v3 simulated warm season.

2.3.1 Paleo-vegetation

The reconstructions from COHMAP (1988), the National Oceanic Atmospheric Administration (NOAA) paleo-climatology program (Overpeck et al. 1992), the Quaternary Environments Network (QEN; Adams and Faure 1997), BIOME 6000 (Prentice and Webb 1998) and more recently Garjewski et al. (2000) are representative of past reconstructions of paleo-vegetation. While these studies used different approaches, which include transfer functions, plant functional types (PFT) and also focused on different pollen groups, each reconstruction of 6-kBP vegetation shows similar broad-scale spatial patterns especially for eastern North America.

COHMAP (1988) reconstructed regional vegetation patterns for eastern North America through a temporal synthesis of fossil pollen types collected at sampling sites across the region. Initial work on the pollen data used transfer functions (Bartlein et al. 1986; Prentice et al. 1996) derived from multiple regressions, but these were considered cumbersome at sub-continental scale. Hence, later reconstructions by Webb et al. (1993) used response surfaces that estimate temperature and precipitation from pollen data. Twenty-four pollen types from 270 out of a total of 328 sampling sites across North America were used for reconstructing the 6-kBP vegetation. Infrequently observed taxa, those with indicators of
human disturbance and some over-represented wetlands taxa were not used. Response surfaces illustrating the multivariate nature of the relationships between individual pollen types and certain climate variables from isopoll (constant pollen) maps were developed. Linear combinations of the mean July, January, and annual precipitation were used as climate variables to represent control of plant distribution by summer warmth, extreme winter cold and moisture availability. The use of transfer functions or response surfaces assumes that changes in pollen data over time result from pollen-climate relationships that were comparable to those represented by modern transfer or response functions. The vegetation is also assumed to stay in dynamic equilibrium with climate throughout. While these are plausible assumptions they have not been verified.

The COHMAP reconstruction shows that modern vegetation patterns developed after 9-kBP under a distinct east-west precipitation gradient. Most taxa including spruce and oak trees moved northward, suggesting a general warming of eastern North America (Ritchie 1987), reaching a maximum extent at 6-kBP. A southward retreat thereafter suggests a reversal in climate forcing after 6-kBP. The prairie-forest border also moved eastward before 6-kBP in the northern Midwest and then retreated westward after 6-kBP (Webb et al. 1993).

The maps in Fig. 2a from the NOAA paleoclimate (Overpeck et al. 1992) program are based on 11,700 fossil pollen samples and 1744 modern pollen samples. Twenty-one pollen taxa were included in the analyses. Analog/no-analog vegetation types were assigned to a 100x100 km grid at 1000-year intervals using a three-dimensional, time-space interpolation scheme. To generate maps the paleo-coastline and Laurentide ice sheet were overlain to mask out appropriate portions of equal area grid boxes.
Fig. 2: Reconstructions of 6 kBP vegetation (a) Overpeck et al. 1992 (b) Prentice et al. (1996) and (c) Present-potential (Adams and Faure 1997).
Established in 1994, BIOME 6000 is another project, which developed global paleo-vegetation data sets (Fig. 2b) for the mid-Holocene (5±0.5 $^{14}$C kBP) for use in paleoclimate model simulations (Prentice and Webb 1998). Unlike COHMAP, which used response surfaces, BIOME 6000 used plant functional types (PFTs). These functions were first assigned to taxa represented in the pollen or plant macro fossil assemblages. The assignments were based on the life form, leaf form, phenology and bioclimatic tolerance of the plant species included within the taxon. Combinations of the PFTs were used to define major regional scale vegetation types (biomes). Once relationships between taxa, PFT and biome classifications were made, the affinity of pollen or plant macrofossil for each biome was calculated. Each assemblage was then allocated to the biome for which it had the highest affinity. The difficulties encountered in this approach include lack of taxonomic resolution in
pollen identification, which could cause some taxa to be classified into more than one PFT. Also, some PFTs, which are known to occur, could not be included in the biome definition because they occur in too many biomes to provide discriminatory power.

The quaternary environments network (QEN, Adams and Faure 1997), was operated through a system of informal contacts, wherein expert opinion was solicited on the nature of paleo-vegetation in particular regions for particular time slices, using various relevant paleo-indicators. Their map (Fig. 2c) represented a baseline derived from a coherent interdisciplinary set of global biome maps for 6-kBP. Present-potential vegetation map for North America, representing modern vegetation, as it would be without agriculture, is similar in its spatial distribution of vegetation to those of BIOME 6000 and Overpeck et al. (1992) for 6-kBP over eastern US.

All these studies have uncertainties resulting from making inferences about regional distributions of vegetation based on point measurements at the sampling sites and may be influenced by large gaps between sampling sites. In the western US and across the Rocky Mountains for instance, gaps occur due to large variation in climate and topography. Such gaps are evident in Fig. 2b from Prentice et al. (1996) and also in the COHMAP sample sites (not shown). As a result, the uncertainty in the reconstructed vegetation over western US may be larger than over eastern North America. To address gaps in spatial coverage, assemblages from packrat middens (Betancourt et al. 1990) have at times been used to supplement pollen reconstruction of the paleo-vegetation in the west. However, arid conditions, which favor preservation of packrat middens are not good for stratigraphic pollen records, making it hard to get both sets of proxy data at a single site (Thompson et al. 1993). The use of
heterogeneous sources of proxy data in the reconstruction of paleo-vegetation may be another source of uncertainty, especially when different proxies suggest different climatic regimes at the same time in one region. Across the Colorado plateau and the northern Rocky mountain region, for instance, some proxies indicate wetter climate at 6-kBP compared to present while others indicated drier (Thompson et al. 1993). Paleoclimatologists address variations in proxies by focusing on changes that are consistent across multiple proxies over wide areas, but this procedure may mask regional differences, which may actually have existed.

Note that the paleo-vegetation maps have been smoothed and the location of the vegetation boundaries between the various reconstructed maps may be quite arbitrary. In reality most natural vegetation types either exist as mosaics or merge gradually into one another. A potential source of confusion involves the nomenclature. For instance, the vegetation over the southeastern US at 6-kBP (assumed similar to present-potential), is referred to by various names, i.e. Southeast forest (Overpeck et al. 1992), warm temperate forests (Adams and Faure 1997) and broad-leafed/warm mixed forests (BIOME 6000). Keeping these potential sources of uncertainty in mind, these paleo-vegetation maps were only used as guides. The study focused on the overall distribution of grassland and forests in the Midwest to define representative 6-kBP vegetation distributions for use in MM5v3.

2.3.2 Paleo-climate lake-levels

Lake level data (LLD) are another source of climate information that is independent of the pollen records. Closed-basin lakes are sensitive to climatic changes in hydrologic balance. Buried littoral sediments and microfossils indicate lower lake levels, particularly in
arid areas. LLD need to be standardized to allow for inter-site comparisons because they are derived from many different geomorphologic, sedimentologic and biostratigraphic information sources. Webb et al. (1993) divided the total altitudinal-range changes in lake-level within each basin into low (lower 15% of range), intermediate (15-70%) and high (top 30% of range) which also included overflowing lakes. Lake levels were obtained from 25 basins in eastern North America. Although the spatial distribution of the lakes was uneven, with more sampling sites in the North American Great Lakes region, the lake-level data showed that lake levels in North America decreased steadily from 12-kBP and reached their lowest levels at about 6-kBP (Fig. 3). Almost all the lakes in the Midwest and two lakes in the southeast were low. The lake levels have been rising steadily since then. These data suggest a negative terrestrial water balance over North America, particular in the Great Lakes region, prior to 6-kBP and positive thereafter, making 6-kBP a turning point.

Fig. 3: Lake levels during the LGM (from COHMAP 1988).
The decreases in lake levels may have been driven by increased evaporation from increased insolation discussed previously or a decrease in precipitation. However, high evaporation would result in increased cloud amounts and possibly more precipitation. The former would reflect more solar radiation and hence tend to decrease solar heating, and the later could increase lake-levels. It is not clear from the proxy records what role, if any, was played by such feedbacks and whether decreased precipitation or increased evaporation was primarily responsible for the observed decreases in lake levels. These are among the questions examined in this study.

2.4 Paleoclimate modeling studies

The use of a RCM requires surface and upper atmospheric data within the forcing frame. However, the paleo-vegetation and LLD discussed above give no indication of the surface and upper level circulation at 6-kBP. Therefore, results from past AOGCMs and AGCMs over North America are used to infer representative 6-kBP atmospheric fields necessary to run MM5v3. It is assumed that circulation features common to the various past AOGCM simulations are characteristic of the 6-kBP circulation. Following is a discussion of some of the common features of the past GCM and AOGCM circulations.

The COHMAP simulations (Kutzbach and Ruddiman 1993) were among the earliest paleo-climate modeling studies and used the original NCAR Community Climate Model (CCM0). They simulated 450 days in perpetual January and July simulations at a coarse resolution of 4° x 7.5° lat/lon. SSTs were fixed at modern values for 6-kBP because the observed patterns indicated that by 9-kBP, most oceans had warmed (within the uncertainty
of measurements) to near modern SSTs. Surface albedo and sea levels for 6-kBP were also set at modern values while CO₂ was in the range 265-275 ppmv. No atmospheric aerosols were included and vegetation and SST feedback processes were ignored. Fig. 4 summarizes key boundary conditions for the COHMAP simulations.

Simulated July temperatures were significantly warmer, up to 2°C across central and eastern US. The largest simulated changes in July appeared over the continents but the simulated spatial patterns of temperature were very similar between the 6-kBP and present climates. The initial simulations are in agreement with later results from AOGCMs coupled to mixed-layer ocean models (Kutzbach and Ruddiman 1993).

Fig. 4: Summary of the COHMAP (1988) boundary conditions.
July SLPs were low across the US and a little higher over the surrounding oceans, but the differences were smaller than ±1 mb, and were statistically insignificant. July appeared wetter at 6-kBP than present over the Midwest, contrary to LLD and proxy records.

The 6-kBP simulated July 500 mb wind patterns and storm tracks, derived as standard deviations of surface pressure after 2.5-6 day band-pass filtering, are all similar to present, suggesting little or no change in storm tracks. Later COHMAP experiments (Kutzbach et al. 1993) which included interactive snow cover, soil moisture and a 50-m mixed-layer ocean model with interactive sea-ice, confirmed these result and also showed that orbital induced changes in insolation produced only minor changes in ocean temperatures. This justifies the use of current climate SSTs in 6-kBP experiments. Their use of current CO₂ however introduced a small bias toward warmer conditions in the paleo-climate simulations.

Hall and Valdes (1997) performed two 10-year annual-cycle integrations using the U.K. Universities Global Atmospheric Modeling Programme (UGAMP) AGCM at T42 resolution with interactive land and sea ice and SSTs specified to present day values. The two simulations differed only in the annual cycle of insolation, which varied with orbital parameters (Table 1) and CO₂ concentration. CO₂ concentrations were set at 280 ppmv for 6-kBP and 345 ppmv for present climate. The results show that North America was warmer in June-July-August by up to 2°C. Changes in surface air temperatures occurred over the oceans but magnitudes were within ±1°. The storm tracks over North America show no appreciable change at 6-kBP.
Table 1: Orbital parameters used in UGMAP-AGCM (Hall and Valdes 1997).

<table>
<thead>
<tr>
<th></th>
<th>Present Day</th>
<th>6 kBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentricity</td>
<td>0.016</td>
<td>0.018</td>
</tr>
<tr>
<td>Obliquity</td>
<td>23.44°</td>
<td>24.10°</td>
</tr>
<tr>
<td>Perihelion date</td>
<td>282.04</td>
<td>180.87</td>
</tr>
</tbody>
</table>

Several other modeling studies since COHMAP have used different models and simulated focused on different periods. They also had variations in the 6-kBP boundary conditions, making it difficult to say whether differences in results were due to model or boundary conditions differences. Thus the Paleo-climate Modeling Intercomparsion Project (PMIP-I; Joussaume and Taylor 1995) was setup to establish whether or not key paleo-climatic results were model dependent. Suites of 18 models from various modeling centers (USA, Canada, UK, Germany, France, Australia, Japan and Korea, among others) were driven by identical boundary conditions. Each model was run for at least 10 years. March 21 was used as the date of the vernal equinox but the season definition was kept as present since changes in the length of the seasons are small at 6-kBP and since the models were forced by present-day SSTs (Joussaume and Braconnot 1997). The land-surface characteristics were fixed and thus did not account for vegetation changes. A summary of the PMIP-I experiments, whose design was simplified in order to isolate particular aspects of the model response, appears in Table 2.
Most of the models in the PMIP experiments show a Northern Hemisphere average warming (+1°C) in June-July-August. PMIP experiments are continuing since the launch of Phase II in 1994 to study the role of climate feedback in the different climate subsystems (atmosphere, ocean, land surface, sea ice and land ice) and evaluating the capability of state-of-the-art climate models (Harrison et al. 2002).

Table 2: Summary of key PMIP experiment boundary conditions.

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>CURRENT</th>
<th>6 kBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST and sea-ice</td>
<td>Control run or PMIP dataset</td>
<td>No Change</td>
</tr>
<tr>
<td>Albedo (land-ice free)</td>
<td>Control run</td>
<td>No Change</td>
</tr>
<tr>
<td>Topographic coastlines</td>
<td>Control run</td>
<td>No Change</td>
</tr>
<tr>
<td>CO₂</td>
<td>345 ppm or control</td>
<td>280 ppm or (280/345)</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.01672</td>
<td>0.01868</td>
</tr>
<tr>
<td>Axial tilt</td>
<td>23.44</td>
<td>24.11</td>
</tr>
<tr>
<td>Seasonal cycle</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

2.5 6-kBP Climate summary

The proxy records, LLD and paleo-climate AOGCM simulations reviewed above provided baseline characteristics for defining a representative 6-kBP climate that can be contrasted with the present climate. They show that 6-kBP was warmer and probably drier in the Midwest US. The warm conditions are attributed to the disappearance of the Laurentide ice sheets which allowed insolation to become the main climate forcing, reaching values 4%
higher in July compared to present. While paleo-GCM simulation results show some variations, the large-scale circulation features including the storm tracks show no statistically significant difference between 6-kBP and the present climate suggesting that current-climate large-scale circulation is a fair representation of 6-kBP circulations. The low lake-level data in the Midwest suggest negative precipitation minus evaporation and could be related to increased evaporation or decreased precipitation or even both.

2.6 Experimental design

Based on the preceding reviews, this section provides a framework for the simulation methodology presented in Chapter 3. MM5v3 coupled to the Noah-LSM land surface scheme and driven by initial and lateral boundary data from NCEP-DOE-AMIP Reanalysis-II (NDA-RPll) is used for both the 6-kBP and current climate. The approach is justified because paleo-AOGCM simulations suggested no statistically significant difference between 6-kBP and current climate large-scale circulation and also because current climate SST have been used for 6-kBP. However, specific changes are needed in order to account for the differences in orbital parameters, CO₂ concentrations, and vegetation. Orbital parameters are determined following Berger (1978) as in previous studies while preindustrial CO₂ concentrations are used in 6-kBP simulations. Differences in the vegetation cover over North America between 6-kBP and present, particularly in the agricultural areas of the Midwest is evident in the pollen records. In order to have observationally based land use data, current climate United States Geological Survey (USGS) land-use data is used for the current climate. Replacement of current land use with the present potential from the pollen reconstruction is done for the 6-
kBP in regions showing significant anthropogenic activity such as urbanization and large-scale agriculture in the current USGS data. This preserves the boundaries of natural vegetation and maintains consistency with MM5v3 land use classifications. The impacts of aerosols and methane (CH₄) were not included as in the other studies reviewed.
CHAPTER 3 REGION, MODEL, DATA AND ANALYSIS

3.1 Region of study

The focus of this study is the upper Mississippi river basin in the Midwest US, during the warm season months (June-July-August, JJA). Much of the paleo-evidence and regional responses to past climates including the northward migration of spruce and oak populations, eastward expansion of the prairies and low lake levels at 6-kBP are found here. The region is also among those that suffer greatly from anomalies in the climate system such as the dust bowl drought of the 1930’s, which displaced millions of people, the drought of 1988 and the floods of 1993. Losses in energy water and ecosystem and agriculture during the 3-year drought of the 1980’s were estimated at $39 billion. During the 1988 Midwest drought, low water in the Mississippi grounded more than 800 barges, used for economically transporting coal, petroleum, grain farm products and manufactured goods for several months. In contrast, the Mississippi river peaked at over 15 m, nearly 2 m above the 1973 level during the floods of 1993. The damage was estimated at US$ 15-20 billion (Ross and Lot 2003).

Apart from the natural climate variations, anthropogenic activities discussed earlier are also evident in the large-scale agricultural practices in the Midwest that have altered the regions natural land cover (Fig. 5). A large portion of corn, soybeans, and wheat consumed in or exported from the U.S. originates here. The region is therefore important for this study due to availability of proxy-recorded response to climate forcing, evidence of anthropogenic influence, vulnerability to changes in climate and significance to the US economy.
The simulation domain is based on the standard Project to Inter-compare Regional Climate Simulations (PIRCS) domain (Takle et al. 1999). However, the domain is enlarged by 15 grid points all round to locate the forcing frame over the oceans, include the Gulf of Mexico. This allows the MM5v3 physics to exert greater influence in the domain interior. Locating the forcing frame over the ocean is preferred because SST differences between 6-
kBp and present are small. The Gulf of Mexico is included because it provides a large part of Midwest moisture.

Fig. 6 shows the simulation domain centered at 42.5° N and 97.5° W. The grid has 110 longitudes by 80 latitude points and 23 levels in the vertical. The black dots on the perimeter mark forcing frame where LBC are provided at six hourly intervals.

Fig. 6: Domain of study. Showing the forcing frame (black dots) and the Upper Mississippi Box (UMBX, black rectangle used to define the average climate)
3.2 MM5v3 configuration and physics

3.2.1 Configuration

Version 3.6 release 1 of the Meso-scale Model (MM5v3) is among the latest in the series of RCMs developed by the Pennsylvania State University and the National Center for Atmospheric Research (PSU/NCAR, Grell et al. 1994). The non-hydrostatic version of this model with terrain following coordinates is used in this study. USGS Terrestrial data and NDA-RPII atmospheric fields are initially horizontally interpolated on to the 50 Km high resolution MM5v3 grid followed by vertical linear interpolation of the atmospheric fields to the 23-sigma levels. Table 2 summarizes the various parameterizations used.

3.2.2 Precipitation physics

Precipitation is the net result of many non-linear processes of the climate system. In MM5v3 precipitation is parameterized into large-scale and convective. The parameterizations affect the time space characteristics of simulated precipitation and hence the simulated hydroclimate. During the warm season a large fraction of precipitation in Midwest US results from convective systems. In this study convective process are parameterized using the Grell scheme, which has been shown to be useful at resolution down to 10-30 km (Grell 1994). Furthermore its quasi-equilibrium assumptions, which relate the strength and the location of convection to large-scale destabilization, have been shown to be valid for summertime mid (Grell et al. 1994).

Observed precipitation is not divided into implicit and convective parts, but convective systems contribute a large fraction of the warm season precipitation in the
Midwest. Preliminary analysis of MM5v3 precipitation showed that up to 70% of simulated warm season precipitation was convective and hence the significance of appropriate choice a convective scheme.

Table 3: Summary of key MM5v3 configurations.

<table>
<thead>
<tr>
<th>Land surface Scheme</th>
<th>Noah-LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation scheme</td>
<td>CCM2</td>
</tr>
<tr>
<td>Cumulus Convection</td>
<td>Grell</td>
</tr>
<tr>
<td>PBL</td>
<td>Medium Range Forecasts (MRF)</td>
</tr>
<tr>
<td>Micro-physics</td>
<td>Goddard Flight Center</td>
</tr>
<tr>
<td>Sea Surface Temp.</td>
<td>Varying Reynolds SST</td>
</tr>
<tr>
<td>Model Top</td>
<td>50 mb</td>
</tr>
<tr>
<td>Δx</td>
<td>50 Km</td>
</tr>
<tr>
<td>Δt</td>
<td>120 secs</td>
</tr>
<tr>
<td>Land Use</td>
<td>24-Category USGS</td>
</tr>
<tr>
<td>Grid size</td>
<td>110 x 80 on Lambert Conformal</td>
</tr>
<tr>
<td>Spin-up</td>
<td>October 1-March 31</td>
</tr>
<tr>
<td>Period of simulations</td>
<td>April 1- Sep 30</td>
</tr>
</tbody>
</table>

3.3 Model input data

Fields that need to be provided to run MM5v3 are air temperature, horizontal wind, geopotential heights, sea-level pressure and sea surface temperatures (SST) in addition to terrestrial data. Ideally, a complete set of both the current and 6-kBP climate is needed but not available. In the following subsections procedures used to identify representative LBC
and IC for both current and 6-kBP are discussed. Details of the precipitation and temperature data set that are used for verification are presented.

### 3.3.1 Terrestrial data

Simulations of the current climate, which constitute the control simulation (CTR), are done using the 30-minute (55 Km), 25-category terrestrial data from the USGS. Each MM5v3 grid cell is assigned one land use category (Fig.7a), which determines surface properties such as albedo, roughness length, long-wave emissivity, heat capacity and moisture availability. For 6-kBP, current vegetation in areas with little or no anthropogenic activities is assumed to be representative of the present-potential vegetation depicted in Fig. 2c. As has been done in other studies cited earlier, this study assumes that 6-kBP vegetation is very similar to the present potential vegetation. Agriculture and urbanization, which cause fragmentation of natural land in the present climate USGS land use, are considered markers of anthropogenic influence. Therefore USGS classifications that exhibited these markers, particularly in the Midwest US are modified. The modifications involve replacing the vegetation at these grid points with those indicated in the pollen-reconstructed present-potential vegetation presented in the last chapter. Fig. 7b shows the resulting land use data that is used for the 6-kBP (SCN) simulations. Major differences occur in the Midwest where farmlands have been replaced by forests and grassland. The pattern (Fig.7b) is reasonably similar to the potential natural land use data of Küchler (1964) that was also used in experiments to sensitivity to land use changes by Pan et al. (1999a).
(a) Current land use from USGS-24 categories

(b) Present-potential vegetation used in 6kBP Experiments

Fig. 7: 25-Category USGS derived land use data for (a) current (b) present-potential (6-kPB).
This approach avoids uncertainties related to the problems of paleo-vegetation reconstruction pointed out in the previous chapter.

3.3.2 **Lateral boundaries**

It is not practical to provide detailed observations of IC and LBC in RCM simulations. Two alternative sources currently used are AOGCM output and reanalysis of observations that use data assimilation systems. To simulate climates that are different from present, AOGCM output has been used to drive RCMs in a future climate prediction (Pan et al. 2000) and recently in a paleo-climate simulation of North America (Diffenbaugh and Sloan 2004). These approaches assume that the AOGCM simulation output are perfect representations of the observed large-scale circulation for the different climates. However, AOGCMs do have biases that may influence the RCM. Hence it is preferable in this study to provide LBC and IC from the observational constrained reanalysis data to limit AOGCM bias especially for climates that differ from present.

**3.3.2.1 LBC for current climate experiment**

The mean climate is usually defined as a 30-year average of the relevant field. This definition can not be used to define mean current climate LBCs in this study as it would smooth out disturbances that move along the storm-tracks and whose interaction with the large-scale systems are very important for the hydroclimate of the Midwest. Instead, a year whose mean precipitation in the Midwest is close to a 30-year climatological mean, based on observed station data within the UMBX (Fig. 6) was identified. Fig.8 shows the precipitation
deviation for 1997 compared to 1988 (dry) and 1993 (wet). The deviations are from a 31-year (1960-1990) mean precipitation record from the National Climatic Data Center, Climate Prediction Center (NCDC/CPC) unified precipitation.

![Graph showing time series of UMBX precipitation deviation from mean for 1997, 1988, and 1993.](image)

**Fig. 8: Time series of UMBX precipitate**

Since 1997 had the least deviation in the UMBX during the warm season, 6-hourly NDA-RPII LBCs for 1997 are used to represent the current climate atmospheric fields. Precipitation was chosen in the definition because it represents the net effect of the various interactions between climate systems. Large variations in other climate variables such as the atmospheric circulation are ultimately reflected in changes in precipitation. Inherent in this approach is the assumption that average circulation produces average precipitation. This has been demonstrated in Pan et al. (1999b) for the Midwest US.
3.3.2.2 LBC for 6-kBP experiments

The current climates LBCs are also used in the 6-kBP (SCN) for the following reasons. Several AOGCM simulations of 6-kBP discussed in the previous chapter using multiple models of varying complexity and configurations showed similar large-scale circulation patterns between 6-kBP and present over North America (COHMAP 1988; Joussaume and Taylor 1995; Hall and Valdes 1997, and Harrison et al. 2003). Furthermore, statistical significance tests conducted by COHMAP (1988) and by Hall and Valdes (1997) for their respective simulations showed that the difference between 6-kBP and present climate circulation features were not statistically significant over the domain in this study. The similarity in large-scale circulation features among the diverse models suggested a common response to increased insolation. Hence, to a first order approximation, the current climates LBCs are used for the 6-kBP experiments. Current climate LBCs are also used in order to minimize uncertainties in paleo-AGCM output because of MM5v3’s sensitivity to LBC errors. Another reason for using current climate LBCs is that as in other paleo-climate studies current climate SSTs are used in the IC and forcing frame.

The advantage of this approach is that it allows for the use of realistic LBCs and highlights MM5v3’s response to changes in 6-kBP solar radiation, CO2 and vegetation without the uncertainty associated with AOGCM LBCs. Interannual variations that could affect the results are accounted for by using LBC from the extremely dry 1988 and wet 1993 in addition to those of 1997.
Past AOGCM and GCM modeling results show statistically significant warming of surface temperatures at 6-kBP. In this study, however, the current surface temperatures in the IC and LBC are not increased. This is done to avoid creating spurious temperature gradients and the potential for circularity in which temperatures are first increased in the IC and LBC and then increases in simulated temperatures are sought. Thus the surface temperatures are kept at present and any increases are considered indications of consistent response to 6-kBP forcing.

In summary, present-potential vegetation, pre-industrial CO₂ concentrations and 6-kBP orbital parameters together with current climate large-scale circulation, and surface temperatures (SSTs) are used for the 6-kBP simulation.

### 3.4 Experiments

The study has three main experiments; the control (CTR), 6-kBP (scenario, SCN) and sensitivity (SEN). In the CTR experiments, MM5v3 is driven by current climate LBC, IC, vegetation, CO₂ and orbital parameters. The SCN experiments have CO₂, vegetation and insolation set to correspond to the 6-kBP values. In the SEN experiments, individual changes are made to account for known differences between 6-kBP and current. CTR and SCN are conducted for three years each using LBC from 1988, 1993 and 1997 while SEN is done only for 1997. Attempts are made to identify feedback that may help explain the observed low lake-levels and proxy records in the Midwest. Error characteristics in simulations of current climate using MM5v3 are evaluated using meteorological observations for 1997. SCN and SEN are compared to CTR and subjected to a series of statistical analysis to determine
differences if any between the present and 6-kBP climate simulations. The analysis focuses on differences in the surface air temperature, precipitation, evapotranspiration, soil moisture, and short-wave radiation.

3.4.1 Current climate control (CTR)

These experiments use current climate LBC from 1988, 1993 and 1997. These years were identified to represent the average, dry and wet Midwest climate respectively. The results from these experiments form a baseline against which model differences (simulated minus observed) of MM5v3 are evaluated. The CTR using 1997 LBC minus 1997 observation shows MM5v3 bias in simulating current climate while scenario or sensitivity minus CTR measures the influence of 6-kBP forcing.

3.4.2 Sensitivity experiments

The sensitivity experiments involve changes to the obliquity, eccentricity factor, CO₂ concentrations and vegetation. In the SEN experiments, one of these is changed to its 6-kBP value while the rest are held at CTR values.

3.4.2.1 Sensitivity to obliquity (SEN-OBQ)

The changes in orbital parameters consistent with 6-kBP were discussed in Chapter 2. This sensitivity experiment attempted to determine the effects of increased obliquity alone. Thus, obliquity was changed from 23.4 to 24.1 degrees while holding everything else as in CTR above.
3.4.2.2 Sensitivity to eccentricity factor (SEN-ECF)

In MM5v3, the effects of longitude of perihelion and eccentricity are combined into a single factor (eccentricity factor), which then determines insolation. Thus, in this experiment, the eccentricity factor is changed while keeping everything else as in CTR.

3.4.2.3 Sensitivity to CO₂ concentrations (SEN-CO₂)

All as in CTR except CO₂ concentrations, which are set at pre-industrial levels of 280ppmv.

3.4.2.4 Sensitivity to changes in vegetation (SEN-VEG)

The land use is modified to represent the present-potential, which is assumed for reasons stated earlier to represent the vegetation at 6-kBP.

3.4.3 Scenario experiment (SCN or 6-kBP)

In this experiment, the individual changes in CO₂, orbital parameters and land use consistent with 6-kBP are all combined in the simulation.

3.5 Verification data sets

3.5.1 Precipitation and Air temperature

Gridded observations of precipitation and air temperature from the terrestrial air temperature and precipitation data of Willmott and Matsuura (1995) available through the University of Delaware (UDW) is used to asses model simulation of current climate. This data
uses station records of monthly and annual mean air temperature and total precipitation for 1950-1999 interpolated to 0.5x0.5 degree of latitude/longitude grid.

3.6 Methods and analyses

3.6.1 Modifications to model configuration

To modify the orbital characteristics in MM5v3, the obliquity and eccentricity factor are modified in subroutine solar1. The obliquity is changed from its current value of 23.5° in the CTR to 24.1° in the 6-kBP (SCN) and SEN experiments. Computations for the eccentricity and longitude of perihelion follow the methods of Paltridge and Platt (1976). It involves computing the longitude of the sun from vernal equinox and expressing the time in Julian days as an angle in radians (RJUL). The eccentricity factor is then computed as a function of this angle using equation 1.

\[ ECCF = C_1 + C_2 \cos(RJUL) + C_3 \sin(RJUL) + C_4 \cos(2 \times RJUL) + C_5 \times (2RJUL) \]  

The coefficients in equation 1 differ for 6-kBP and current climates and are obtained by first using the National Aeronautics and Space Administration (NASA) step1_orbpar routines (http://aom.giss.nasa.gov/srorbpar.html) to compute 6-kBP eccentricity, longitude of perihelion and obliquity. The routine step2_orbpar is then used to calculate the coefficients in equation 1 (Vizy and Cook 2003, personal communication) in a procedure involving conversion of the longitude of perihelion from vernal equinox to autumnal equinox (September 22, Julian day 265).
The multiplicative factor, \( eff \) in equation 2 is then used to define the coefficients \( C_1, C_2, C_3, C_4, \) and \( C_5 \).

\[
\begin{align*}
\text{eff} & = \frac{1}{(1 - ecc^2) * (1 - ecc^2)} \\
\text{C}_1 & = \text{eff} \times 1.0 + \text{eff} \times \frac{ecc^2}{2} \\
\text{C}_2 & = \text{eff} \times 2.0 \times ecc \times \cos(2\pi \frac{Julian}{365}) \\
\text{C}_3 & = \text{eff} \times 2.0 \times ecc \times \sin(2\pi \frac{Julian}{365}) \\
\text{C}_4 & = \text{eff} \times \left( \frac{ecc^2}{2.0} \right) \times \cos(4\pi \frac{Julian}{365}) \\
\text{C}_5 & = \text{eff} \times \left( \frac{ecc^3}{2.0} \right) \times \sin(4\pi \frac{Julian}{365})
\end{align*}
\]

where \( ecc \) is the eccentricity and \( Julian \) is the Julian day (as angle in radians).

Changes in CO2 concentration are made in the CCM2 package radini routine and involve changing the volume-mixing ratio from the standard MM5v3 value of 330 ppm to a pre-industrial concentration of 280 ppm. The relevant vegetation changes were discussed under vegetation and involve no additional modifications to MM5v3.
3.6.2 Top of the atmosphere incident short-wave

To determine how the changes in the orbital parameters above altered the amount of solar radiation at the top of the atmosphere the cosine of the zenith and hour angle is used following the formulation in MM5v3 zenith routine.

\[ \cos(\text{zenith}) = \sin(\text{declin}) \cdot \sin(\varphi) + \cos(\varphi) \cdot \cos(\text{declin}) \cdot \cos(\text{hourangle}) \]  

where \( \varphi \) is the latitude and declin is the angle of declination (Paltridge and Platt, 1976). The amount of radiation reaching the top of the atmosphere (TOA) is computed using equation 9.

\[ \text{TOA} = (\text{solarcons}) \cdot \text{ECCF} \cdot \cos(\text{zenith}) \]  

where \( \text{solarcons} \) is the solar constant and was fixed at 1370 Watts/m\(^2\).

3.6.3 Vertically integrated soil moisture and vapor transport

Soil moisture is calculated as a vertically weighted average for the 10, 20, 100 and 200 cm soil layers. The thicknesses of the layers are used for weighting.

Vertical integral of the vapor transport was calculated using equation (10).

\[ qV = \sum_{i=1}^{23} q_i \cdot V_i \cdot d\sigma_i \]  

Where \( d\sigma \) is the thickness of the sigma layer for which \( u, v \) and \( q \) are given in the middle and the summation was over all the model sigma layers.
3.6.4 Low-level jet characteristics

To determine the low-level jet characteristics, the geopotential heights corresponding to the simulated winds are first determined using the formulation of the hypsometric equation (11)

\[ Z = Z_{sfc} + \frac{R_d \overline{T_v}}{g} \ln \left( \frac{P_{sfc}}{P} \right) \]  

where \( Z \) is the geopotential height for which winds are available, \( R_d \) is the gas constant for dry air, \( P_{sfc} \) is the surface pressure and \( P \) is the pressure corresponding to the model sigma level, \( \overline{T_v} \) is the mean virtual temperature and was computed using equation (12).

\[ \overline{T_v} = (1 + 0.61q)T \]  

where \( T \) is the mean layer temperature. Since \( T, q, u \) and \( v \) are all defined in the middle of the sigma-layer, they were assumed to represent the layer average. The pressure corresponding to the actual sigma levels is then used to determine the height above the surface. Having determined the heights corresponding to the simulated winds, the Bonner (1968) classification scheme is used to find the frequencies of occurrence of categories 1, 2 and 3 jets in the SCN and CTR experiments.
CHAPTER 4 RESULTS AND DISCUSSION

4.1 Temperature analysis

4.1.1 Observed temperature climatology

The results focus on changes that occurred in components of the Midwest hydrological cycle. Differences (6-kBP minus current) are considered backward in time and thus indicate how the 6-kBP climate is different from the present. Preliminary analysis indicated that the largest scenario (6-kBP) changes occurred in June-July-August (JJA), therefore only the JJA fields are presented. The simulations are assessed against an observed baseline representing the current climate and a proxy inferred 6-kBP climate. The baseline is defined by averaging the surface air temperatures during JJA for the years 1988, 1993 and 1997. Fig. 9 shows the observed averaged JJA air temperature for the three years and also compares the three-year average to a 50-year (1950-1999) long-term mean (LTM) from observations processed by the University of Delaware (UDW, Willmott and Matsuura 1995). The observed Midwest JJA temperatures are in the range of 290-300 K. Highest temperatures occur in the vicinity of the Gulf of Mexico and California. Comparing the three-year mean to the LTM (Fig. 9d), it is evident that the 3-year average JJA surface air temperature is warmer to the east and colder to the west of domain when compared to the observed LTM. However, the differences are less than ±0.5 K over the region of focus in the Midwest US. The three-year mean can, therefore, be considered a fair representation of the observed LTM and is used to represent a baseline mean current-climate JJA air temperature.
Fig. 9: JJA observed surface air temperature (K) for (a) 1988, (b) 1997, (c) 1993 and (d) 3-year average (shaded) and the difference from LTM (contours) at 0.5 K; zero line is thick; <0 dashed.

LBC and ICs for the three years are, therefore, used in control (CTR) experiments for the respective JJA. Differences between these CTRs and the observed (Fig. 10) are used to assess the model bias in simulations of JJA 2 m air-temperature in the current-climate.
Scenario and sensitivity differences from the CTR are used to assess the impact scenario and sensitivity forcings respectively.

![Map showing averaged JJA surface air temperature (K)](image1)

![Map showing JJA surface air temperature (K) MM5-CTR 2m TEMP.](image2)

Fig. 10: Averaged JJA surface air temperature (K) (a) observed and (b) simulated
MM5v3’s simulated large-scale surface temperature patterns represent the observed field well, showing the north south temperature gradient and the warm areas to the south that also occur in the observation. However, the simulated surface temperature field is much smoother than in the observations (Fig. 10b). The model also shows a cold bias over the Midwest, with the 295 K isotherm running further south in the model compared to the observations. The extent and magnitude of the warmest areas adjacent to the Gulf of Mexico are also diminished in the model simulation.

4.1.2 Scenario minus control

The three-year averaged JJA 2 m air temperatures from the scenario experiments (SCN) were warmer than the control (CTR) over most of continental US (Fig. 11). The warmest areas occurred over the Rockies, the South Central and the Midwest US. Compared to present, averaged SCN JJA temperatures over the Midwest were warmer by at least 0.25 K in the experiments. The magnitude and extent of areas, which show differences greater than 0.75 K varies in both time and space, but warming, is evident in most of the continental interior. The changes in location of greatest warming with LBC suggest that changes in interannual circulation also contribute substantially in determining the degree and extent of the warming in the scenario experiments. The SCN experiment using LBC for the average year (i.e. 1997), show greater warming in the Midwest around Lake Michigan (Fig. 11a). It is possible that a longer simulation with a series of average years could have given the Midwest a warmer climate, but these simulations are too short (3-years) to be conclusive.
Fig. 11: JJA SCN minus CTR differences in surface air temperature (K) simulated with LBCs from (a) 1997, (b) 1993, and (c) 1988.
Fig. 12 shows the time evolution of the area-averaged difference (SCN minus CTR) for three regions over North America. The three rectangular regions, the Rockies (120-95° W, 38-48° N), Central Plains (95-85° W, 38,50° N) and Southern Plains (100-80° W, 30-38° N) are defined based on preliminary analysis of areas showing a consistent sign of SCN minus CTR over a large area in Fig. 11. It is evident that from May-August, most of the regions show some warming.

Fig. 12: Simulated area averaged 2 m air-temperature (K) for the Southern Plains, Rockies and Central Plains regions.
The Central Plains shows increased warming from June-September. In general, the simulated area averaged SCN temperature differences for the three regions is less than 0.5 K except in July and August for the Central Plains.

4.1.3 Sensitivity minus control

Results from the four sensitivity experiments show that the effect of the eccentricity factor (combining longitude of perihelion and eccentricity) results in the largest warming of the three changes. The eccentricity factor appears to be the dominant factor controlling surface air temperature at 6-kBP. The temperature-change pattern with only the eccentricity factor changed (Fig. 13a) is similar to the results from the full scenario with 1997 LBC (Fig. 11a). Largest warming due to changes in eccentricity occur over the West and South Central North America. Although the sensitivity experiments were only conducted using LBC from the average year (1997), changes in surface temperature due to eccentricity factor alone may also show interannual variations as in the full scenario.

Change in eccentricity appears to result in warm scenario while the other changes also show cooling in some areas. In the Midwest the change in vegetation resulted in warmer surface temperatures. In Fig. 14 the relative contributions of changes in the eccentricity factor alone to the full scenario experiment for the three regions discussed previously are investigated.
Fig. 13: JJA Sensitivity minus CTR differences in air temperature (K) (a) Eccentricity-ECF factor, (b) Obliquity-O24, (c) present-potential vegetation-PPV and (d) CO₂.
Fig. 14: Changes in surface air temperature (K) due to eccentricity (ECF) and full scenario.

(a) Rockies, (b) Central Plains and (c) Southern Plains.
The changes in air temperature due to the eccentricity factor alone show a distinct increasing trend from April to September and are larger than those from the full scenario over the Central plains and the Rockies (Fig. 14a and b). Over the Central Plains, the full scenario shows a similar warming, but the eccentricity factor also results in a colder differences in July and August. Suggesting that changes in local circulation in the Midwest may dominate the large-scale solar forcing. Compared to the other two regions, the Southern plains (Fig. 14c) shows a closer correspondence between the full scenario and the sensitivity to the eccentricity factor. However, the temperature differences (SCN-CTR) are all less than 1 K throughout the warm season over the southern plains.

Fig. 15a shows the difference between the full scenario and control (SCN minus CTR) while Fig. 15b shows the difference between a linear sum of the sensitivity differences from control for the four sensitivity cases (i.e. sum of ΔT due to changes in CO₂, eccentricity factor, orbital inclination and vegetation). If the four forcings act linearly, the magnitude of the differences and the signs in the two figures would be identical. However, the presence of feedbacks results in larger or smaller differences and in some areas differences in sign.

The Midwest US exhibits a full scenario ΔT_{scn} > 0.75 K, while the linear sum shows areas of the Midwest that have less. Larger differences can also be seen in the southeast where the full scenario shows warming while the linear sum results in cooler surface temperatures. This result suggest opposite effects resulting from presence of feedbacks between the Midwest and Southeast.
Fig. 15: JJA changes from CTR in surface air temperature (K) from (a) full scenario (b) linear sum of sensitivity experiments.
The effect of feedback appears to result in more warming in both the Midwest and southeast. In both areas the full scenario is warmer than the linear sum suggesting positive feedback.

In Fig. 16, the MM5v3 simulation of surface air temperatures is compared to a sample of ten PMIP AOGCMs. The main criteria used in choosing the AOGCMs were that they had to be the latest in the PMIP suite and have used SSTs fixed at current, as did MM5v3 in this study. Changes in MM5v3 area averaged Central Plains surface air temperature are small (±0.5 K).

Fig. 16: Area-averaged Central Plains SCN minus CTR 2 m temperatures (K).

MM5v3 temperatures are warmer than the AOGCM mean in the Central Plains from April-June and colder from July-September. The smaller changes may be due in part to the
short period (3 years for MM5v3 and at least 10 years in the AOGCM). Another factor is that the same LBC and SSTs, which can exert a strong influence on any RCM simulations is used in both SCN and experiments.

The AOGCMs show temperature differences as large as 3 °C, however, pollen-inferred July temperature differences are less than 2 °C warmer (Thompson et al. 1993) over much of the Midwest. Thus the MM5v3 JJA simulated surface warming may be closer to the proxy than the AOGCM estimates. Since the experimental design eliminated variations in the large scale (same LBC), the differences in simulated surface air temperature are thus most likely related to the changes in isolation as has been reported in other studies as well.

### 4.2 Precipitation analysis

#### 4.2.1 Observed precipitation Climatology

As in the previous section on temperature analysis, the discussion on precipitation in this section is divided into three parts. The analysis of observed precipitation climatology is presented first followed by model-simulated scenario and control and finally results of the experiments on precipitation sensitivity. Fig. 17 shows the mean JJA observed precipitation for the three years, the three-year average and its corresponding difference from a 50-year (1950-1999) long-term mean (LTM). The figure shows the climatological east-west precipitation gradient across North America during JJA. Also evident are the heavy and deficient precipitation in the Midwest US that characterized the summers of 1993 and 1988 respectively. Comparing observed precipitation for 1997 (17d) with the LTM (shading in
Fig. 17: JJA observed precipitation for (a) 1988, (b) 1997, (c) 1993 and (d) 3-year average (shaded) and the difference from LTM (contours) at 0.5 mm/d; zero line thicker; < 0 dashed.

17d), the precipitation in JJA 1997 appears to be fairly representative of the LTM. This was the primary reason for using 1997 LBC for the sensitivity experiments.
As in the temperature analysis, the three-year (1988, 1993 and 1997) average JJA precipitation is used to represent a baseline for the current climate. Fig. 17d shows the LTM (shading) and the difference from the LTM (contours) of the three-year average. The three-year mean compares favorably with the LTM, with differences being within 0.5 mm/d in most places. However the three-year mean is influenced more by the heavy precipitation in 1993.

The average JJA precipitation is compared to the simulated current climate JJA precipitation for the three years to assess how well MM5v3 simulates the observed current-climate precipitation. It is evident from Fig. 18, that MM5v3 is capable of simulating the large-scale precipitation features over North America, in particular the east-west gradient. However, the three-year averaged simulated precipitation is more than the observed precipitation in the Midwest for 1993.

These results show that the model is capable of fairly simulating the observed current climate surface temperature and precipitation. Therefore, the three-year averaged CTR surface air temperature and precipitation for current climate JJA is used as a basis against which scenario and sensitivity forcing precipitation differences are determined.

### 4.2.2 Scenario minus control

To find a physical metric for assessing precipitation differences (SCN minus CTR), the increase in solar radiation incident at the top of the atmosphere is used. Weighted by the cosine of latitude between latitudes 30-50°N (Latitudes encompassing the Midwest), the computed additional energy is determined to be capable of evaporating approximately 0.7
Fig. 18: JJA average precipitation (a) observed and (b) simulated CTR (mm/d).
mm/d of water if it is all absorbed as latent heat. Therefore changes in precipitation and evapotranspiration that are less than 0.7 mm/d are considered to be small and 0.7 mm/d intervals are used in the precipitation contour plots that follow.

The scenario minus control (SCN-CTR) differences shows large variations both in space and time (Fig. 19). Over many areas, the precipitation difference patterns are mixed, showing areas next to each other that have scenario precipitation that are greater or less than control (CTR). The differences are generally within ±1 mm/d. The Midwest, however, shows areas of decreased precipitation in the SCN (6-kBP) simulation particularly for the 1997 case. The area of decreased precipitation in the Midwest is diminished in the wet and dry cases (1993 and 1988 respectively). Changes in scenario precipitation when different LBC are used suggest that circulation changes also contributed substantially in determining the scenario precipitation.

Fig. 20 compares the MM5v3 precipitation with the same ten PMIP AOGCMs used in the temperature discussions earlier. The Southern and Central Plains, which have shown different signs in precipitation (SCN minus CTR) in other past studies, are shown here separately in Figs. 20a and b.
Fig. 19: JJA Scenario minus CTR differences (mm/d) in (a) 1997, (b) 1993 and (c) 1988.
Fig. 20: Monthly mean scenario minus control, AOGCM, MM5v3 and AOGCM 10\textsuperscript{th} and 90\textsuperscript{th} percentiles, precipitation (mm/d) (a) Central Plains and (b) Southern Plains.
The area-averaged change is generally very small (<0.35 mm/d) for the warm season in the Central plains. Recalling that previous AOGCM simulations showed more precipitation in the Southwestern parts of North America at 6-kBP, it is worth noting that MM5v3 shows more precipitation compared to the mean of the AOGCMs in the Southern Plains. This may be due to features of the monsoon that were not resolved by the AOGCMs and which enhance precipitation in this area.

The pollen inferred annual Midwest precipitation is about 1000 mm with a decrease of about 20% at 6-kBP (Thompson et al. 1993). This translates to about 200 mm annually (~0.55 mm/d). Thus changes in area averaged MM5v3 precipitation in the Midwest are smaller than the inferred precipitation. This may be in part due to area averaging of both positive and negative precipitation differences within the region. The mixed pattern may also be related to random errors or the results of local response to the large-scale scenario forcing. However, the proxy records also show variations in space. Hence the simulated pattern may be real.

4.2.3 Sensitivity minus control

Results from the sensitivity simulations show broad scale precipitation patterns that are similar to the full scenario discussed previously. Differences in sensitivity precipitation from control (SEN-CTR) are between ±0.5 mm/d over much of the western half of the domain (Fig. 21). In general, individual sensitivity forcing result in some areas showing decreased precipitation of up to 1.5 mm/d. Unlike in the surface temperature sensitivity to eccentricity factor (ECF), the precipitation sensitivity to change in land use appears to be comparable in magnitude to changes resulting from ECF. Also the change is larger in the
same areas where the vegetation was modified, suggesting a local precipitation response to
local changes in land use.

In spite of the noisy character of the precipitation field, there are some areas in the
Midwest for which JJA precipitation in the sensitivity experiments are smaller than in CTR.
The four sensitivity experiments show decreased precipitation for the Midwest. The potential
for effects of natural (insolation) and anthropogenic influence (CO₂ and vegetation changes)
to add up is examined by comparing the full scenario and linear sum of sensitivity
precipitation differences. Over the Midwest, the full scenario difference in precipitation (Fig.
22a) show smaller differences than the linear sum of sensitivity (Fig. 22b). The changes in
the southeast precipitation in the full scenario are also limited when compared to the linear
sum. Therefore, the existence of feedback effects limits how large the differences between
the full scenario simulation and CTR can be. The simulated scenario precipitation is,
therefore, not simply a linear sum of the sensitivity differences and is determined by both the
scenario/sensitivity forcing and regional circulations.
Fig. 21: JJA Sensitivity minus CTR differences in precipitation (mm/d) (a) Eccentricity-ECF factor, (b) Obliquity-O24, (c) present-potential vegetation-PPV and (d) CO₂.
Fig. 22: JJA changes in precipitation (mm/d) from (a) full scenario (b) linear sum of sensitivity experiments.
4.3 Impact of scenario on Midwest extremes

One of the major concerns from likely changes in climate is the potential for climate extremes to get worse. This study examines whether or not the imposed changes in land use, CO₂ and insolation impact the extreme rainfall events of 1988 and 1993 in the Midwest US. The observed precipitation for June 1988 and July 1993, two periods of extremes in the Midwest, are compared to the simulated control and scenario for the respective months. In Fig. 23, the panels on the left are for 1988 while those on the right are for 1993. The panels in the top, middle and bottom rows are the observed, control and scenario precipitation patterns, respectively. It is evident that the model simulates the broad scale characteristics of extreme precipitation in the Midwest fairly accurately. The simulated CTR precipitation maximum in 1993 is much higher than observed, 15 mm/d in the model compared to 12 mm/d in the observations.

Comparing the control and scenario simulations for 1988 (Figs. 23c and 23e), it is apparent that the scenario forcing had little effect on the spatial patterns and magnitude of the precipitation during this dry period in the Midwest. This may be due to the fact that precipitation could not decrease below zero for 1988. On the other hand, Figs. 23d and 23f show that the scenario for 1993 appeared to increase the aerial extent and intensity of precipitation in flood conditions. Fig. 24, whose layout is similar to Fig. 23, shows the model simulated differences between drought and flood years for both control and scenario simulations and compares these to the observed differences. The reason for taking respective differences between the two controls and the two scenarios was to allow for comparisons of similar simulations.
Fig. 23: Observed and simulated precipitation (a) June 1988, (b) July 1993, (c) CTR June 1988 (d) CTR July 1993 and (e) SCN June 1988 (f) SCN July 1993 in mm/d.
Fig. 24: Observed and simulated precipitation differences (a) June 1988 minus 1993, (b) July 1988 minus July 1993, (c) CTR: June 1988 minus June 1993 (d) CTR: July 1988 minus July 1993 and (e) SCN: June 1988 minus June 1993 and (f) SCN: July 1988 minus 1993 in mm/d.

Taking difference between SCN and CTR involves differences arising from the scenario forcing in addition to changes in circulation in response to the scenario forcing. On the other
hand, comparing the simulations directly with observations inherently assumes that the scenario bias is similar to the current climate bias. There is no justification for making that assumption, hence differences are taken between either two control or two scenario experiments. The drawback here is that model errors of the individual years SCN or CTR may be compounded resulting in much larger differences.

Simulated differences are close to the observed differences in both the control and scenario simulations. In June, the scenario (SCN 1988 minus SCN 1993) has larger differences in the South Central US compared to observed differences. This appears to result from more precipitation in the SCN 1988 compared to CTR 1988. In the Midwest, however, the differences between control and scenario simulations do not appear to change substantially.

4.4 Precipitation minus evapotranspiration

Evapotranspiration increases of about 0.5 mm/d occur over much of the domain with different LBCs suggesting that insolation and local features influence simulated evapotranspiration more strongly compared to the large-circulation. The difference between precipitation and evaporation (P-E) represents the amount of atmospheric vapor convergence and ultimately terrestrial water available for runoff and changes in storage. Reductions in (P-E), therefore, represent a deficit in the amount of vapor convergence and hence water available to the surface and subsurface. Fig. 25 shows the difference between (P-E) in the scenario and (P-E) in the control simulations. Some areas in the Midwest show a decrease in
(P-E). These areas are therefore likely to exhibit drying of the surface and decreasing lake-levels if the pattern persists.

Fig. 25: Changes in (P-E) (mm/d) between SCN and CTR.
While these result also appear consistent with the LLD, we note that the area of greatest
decrease in (P-E) occurs south of the area from which the lake-levels used in the COHMAP
sites were located. This may be an indication that MM5 does not locate the differences in the
same locations as seen in the proxy records.

4.5 Soil moisture, surface and sub-surface runoff

4.5.1 Soil moisture

The changes in lake-levels and expansion of warm climate vegetation that are seen in
the proxy records (Webb et al. 1993) suggest changes in the terrestrial water balance. Fig. 28
shows that changes in vertically integrated soil moisture are larger than 10% over most of the
domain. In the 1997 case, the Midwest shows a distinct decrease in the integrated soil
moisture. The averaged changes (Fig. 26d) appear small but show a decrease west of lake
Michigan.

4.5.2 Surface and sub-surface runoff

The surface and subsurface runoff represents the amount of water that ultimately goes
into lakes and are therefore capable of altering lake-levels. Figs. 27 and 28 show that the
similar spatial patterns of surface and subsurface runoff differences (SCN – CTR). However,
magnitudes are larger for the subsurface. In the experiments using 1997 LBC, the Midwest
shows decrease in both surface and subsurface runoff. Larger increases in subsurface runoff
occur in the Midwest for SCN using 1993 LBC. Although, the mean pattern show decreased
runoff at both the surface and subsurface around Central Plains increases are evident south of this area.

Fig. 26: JJA SCN minus CTR differences in vertically integrated soil moisture using LBCs from (a) 1988, (b) 1997, (c) 1993 and (d) 3-year mean (mm).
Fig. 27: JJA SCN minus CTR differences in surface runoff with LBCs from (a) 1988, (b) 1997, (c) 1993 and (d) 3-year mean (mm).
In general, the changes in runoff are larger over the eastern part of the domain compared to the west and mostly reflect the changes in precipitation. It is evident that
changes in simulated precipitation strongly influence the soil moisture and runoff and ultimately the vegetation that depend on the soil moisture.

4.6 Surface downward shortwave radiation

The increase in simulated surface temperature and evapotranspiration are both consistent with increased summer insolation, which is the most distinctive characteristic of the 6-kBP climates. However, a warm atmosphere has the potential for holding more moisture from increased evapotranspiration, which may result in increased cloud cover and possibly precipitation. Surface incident short-wave radiation is used to diagnose potential changes in cloud cover. Fig. 29 shows the difference (SCN minus CTR) for the three years. The results show that more insolation reaches the surface over large areas in the SCN experiments. Over much of the domain, the increase in the amount of JJA shortwave incident at the surface is about 15 Watts/m². Only in the Southeast are the changes less than 7.5 Watts/m². This may be due to an increase in cloud cover over this area because the same area also shows increased precipitation (Fig. 19).

Fig. 30 shows that average increase in the amount of insolation at the top of the atmosphere (TOA) between 30°N and 50° N was about 20 Watts/m². This is the amount of increase in incident surface short-wave that would reach the surface if there were no clouds present. The SCN increases, (i.e.15 Watts/m² at the surface and 20 Watts/m² at the top) suggest that no substantial change in cloud effects and probably amounts occurs. The areas showing increase in incident short-wave > 22.5 Watts/m² (Fig. 29) may have experienced reduced cloud cover in the SCN experiments.
Fig. 29: JJA SCN minus CTR differences in surface incident shortwave radiation with LBCs from (a) 1988, (b) 1997, (c) 1993 and (d) 3-year mean (Watts/m²).
Change in TOA incident solar radiation

Fig. 30: June-July-August top of the atmosphere short-wave-down cos-latitude-weighted-averaged between 30°N and 50° N. (day 1 is Oct 1 of preceding year)

4.7 Moisture transport

4.7.1 Vertically integrated moisture transport

The relatively small increases in evapotranspiration (0.5mm/d) are probably insufficient to account for changes in simulated precipitation. Furthermore, comparable increases in both top and bottom of the atmosphere incident shortwave suggested little or even decreases in cloud cover. Thus changes in moisture transport are examined for associations with the simulated decreases in precipitation. Fig. 31 shows vectors representing the JJA vertically integrated moisture fluxes for 1997 and 1988. The patterns are similar for 1993.
Fig. 31: Vertically integrated vapor transport for average year 1997 (a) June, (c) July, (e) August and for dry 1988 (b) June, (c) July, (f) August.
It can be seen that the flux in the region of the low-level jet contributes substantially to vapor transported into the Midwest US. The flux was particularly intense in the CTR 1993 experiment.

Changes in vertically integrated moisture transport are depicted in Fig. 32 for the experiments with 1988, 1993 and 1997 LBC. Due to variable characteristic of the winds, JJA averages are very small. It is seen that larger differences in the vapor transport are evident in the low-level jet region. The direction of the differences vector suggests decreases in vapor transported into the Midwest in the SCN experiments especially for the 1993 and 1997 cases.

4.7.2 SCN minus CTR Low-level jet frequencies

Fig. 33 shows the difference (SCN minus CTR) in number of category 1 jets for the average year (1997), which also had the largest precipitation change in the Midwest US. The results from the three scenario experiments show increases in the low-level jet frequencies for almost all categories. The largest changes are centered close to the where the jet originates over Texas and are largest at 0600 UTC which corresponds to midnight local standard time (Fig. 33). The increased frequencies appear to contradict the decrease in vapor transport. However strong heating during the day followed by a rapid decay of the planetary boundary layer and stronger shear would result increased low level jet frequency even in the absence of vapor. The largest frequency increases also occur at night (Fig. 34) when evapotranspiration is at its minimum. Thus whereas there is potential for transporting more vapor, little vapor may be available in the atmosphere. Also, a stronger association between precipitation and
low-level jets has been suggested only for the strongest jets (category 3), but there were fewer category 2 and 3 and hence smaller differences (not shown).

Fig. 32: Change in JJA vertically integrated vapor transport (kg/ms).
Fig. 33: Change in JJA LLJ frequencies for category 1 for 1997 CTR.
Fig. 34: Changes in diurnal characteristics of the low-level jet frequencies (a) 1993 and (b) 1997 experiments.
CHAPTER 5 SUMMARY AND CONCLUSIONS

5.1 Summary

This study simulated the climate of North America at 6-kBP and compared it to a simulated current climate control using MM5v3. The focus was on the Midwest US hydrological cycle during JJA because most of the precipitation in this region occurs at this time and preliminary analysis showed that largest changes in the components of the hydroclimate occurred at the same time. A baseline current climate was defined using observations for the years 1988, 1993 and 1997. The baseline was then used to assess the MM5v3 simulations of current and 6-kBP climates. Differences between MM5v3 simulated current climate and observed, indicated model bias, while differences between simulated scenarios (sensitivity) showed effects of scenario (sensitivity) forcings. The results of the simulations were also compared with a sample of ten PMIP AOGCMs and proxy records where possible.

5.1.1 Surface air temperature

The simulations of surface air temperatures show that MM5v3 is capable of simulating the large-scale patterns although the MM5v3 shows a cool bias in simulations of the Midwest. The three-year average JJA surface temperatures are close to the long-term mean with differences within ±0.5 K and are considered representative of the current climate mean. The scenario minus control show warmer temperatures at 6-kBP over the continental US in all the years but only the average year, 1997, shows warming exceeding 1 K in the Midwest. Different regions show different amounts of warming, but from May to August, the
Southern Plains, the Central Plains and the Rockies all show warming, the highest occurring in August. The temperature sensitivity results show that changes in eccentricity and longitude of perihelion (together the eccentricity factor) had the most influence in determining the scenario surface temperature but the effects of these changes appear to be different for different areas. The presence of nonlinear feedbacks results in smaller differences in the full scenario compared to the linear sum of changes produced by adding the differences from individual forcing factors. The Southeast shows a warm difference that is opposite to the cooling shown by the linear sum. Over the Southern Plains the eccentricity factor and full scenario differences are both small but the effect of eccentricity factor was larger than the full scenario in the Central Plains. Compared to the AOGCMs MM5v3 area averaged temperature increases are small. However, the proxy records also showed temperature increases at 6-kBP that were less than 2 K over the Midwest. Thus the MM5v3 surface temperature simulations are close to the pollen-based estimates than the AOGCM estimates.

5.1.2 Precipitation

The three-year averaged precipitation is also close to the observed long-term mean, but may have been strongly influenced by the heavy precipitation in 1993. Differences between the three-year average for most of the Midwest are less than 0.5 mm/d. Simulations of the current climate shows that the model had more precipitation than observed in the 1993 flood region. The SCN minus CTR field was very variable but areas in the Midwest received less precipitation at 6-kBP, consistent with the proxy records. As in the surface temperature results, nonlinear feedbacks in the full scenario appear to limit the precipitation differences between the scenario and control. Over the Southern Plains, MM5v3 shows more
precipitation than the AOGCMs mean. The mixed patterns in precipitation difference may be associated with differences in local response to the large-scale forcing or may be the results of random noise. These results are also consistent with pollen record estimates of precipitation for the Midwest. Changes in scenario minus control (P-E) showed negative values, which indicate decreased convergence of atmospheric vapor and are consistent with observed low lake levels at 6-kBP. However, the negative changes occur south of the area where lake-level data were available.

The sensitivity minus control shows that unlike temperature, precipitation changes are also substantially influenced by changes in vegetation in addition to the eccentricity and longitude of perihelion. There are no indications that the different changes are additive in their effects on precipitation. The scenario forcing does not also substantially influence the precipitation extremes in 1988 and 1993.

5.1.3 Short-wave radiation

Simulated increases in surface temperature and evapotranspiration are both consistent with increases in solar radiation that characterized the 6-kBP climates. The differences (SCN minus CTR) shows increases in incident surface short-wave over much of the domain. The increase in incident surface short-wave radiation beyond the scenario increases at the top of the atmosphere suggests decreases in cloud cover. The simulated decrease in precipitation is thus consistent with possible decreases in cloud cover
5.1.4 Soil moisture, run-off and vapor transport

Changes in both surface and underground run-off between SCN and CTR show some decreases but the latter were larger and are more distinct for 1997. The 1993 experiments show increased runoff in areas where precipitation increased and may have been a response to the heavy precipitation in those experiments. The pattern of runoff changes is also reflected in the vertically integrated soil moisture, which shows drying of the soil in SCN experiments.

The mean patterns show substantial vapor fluxes originating in the Gulf of Mexico and flowing into the Midwest, suggesting that a large portion of the water vapor available for Midwest precipitation is transported by flow in the low-level jet region. The vapor-transport vector differences between scenario and control experiments suggest decreases in the amount of vapor transported in the scenario experiments. Changes in the low-level jet frequencies were small (<10%) for the strongest category 3, which has been associated with precipitation.

5.2 Conclusion

This study successfully met its objective of simulating a climate representative of 6-kBP that verifies well against proxy records. It shows that given realistic IC and LBC MM5v3 can simulate details of climates that differ significantly from present. The results suggest that increased insolation resulted in warmer temperatures and increased evapotranspiration across North America, but decreased atmospheric moisture convergence most likely resulted in substantial decrease in Midwest precipitation. Changes in Midwest precipitation due vegetation appear comparable to those resulting from changes in insolation.
However, longer simulations are necessary in order to account for inter-decadal variability and the role of sea-ice needs further investigation.

This study differs from many previous ones in its use of a regional climate model to investigate the combined effects of changes in CO₂, vegetation and insolation in forcing the climate of North America at 6-kBP. The previous studies were limited to investigating the role of the increased insolation and therefore ignored differences between 6-kBP and current climate vegetation and CO₂ concentrations. They ignored current climate vegetation, which shows large areas under agriculture. Vegetation characteristics such as roughness length and albedo influence the amount of absorbed insolation and evapotranspiration respectively and can cause changes in the atmospheric circulations through the turbulent fluxes of heat and momentum. Therefore the past studies neglected vegetation feedbacks and their coarse resolution did not allow them to simulate the regional details. Since land-atmosphere interactions occur on scales that are smaller than the GCM grids, using high resolution in this study enabled regional details to be adequately represented.

The work of Diffenbaugh and Sloan (2004) is among the few published work that attempted to use an RCM in a 6-kBP simulation of North America. However, they obtained LBC for the regional climate model (RegCM2.5) from a GCM and their main focus was in western North America. Furthermore, current climate vegetation was used in both their current and 6-kBP climates. They observed warming of up to 2°, but the simulated precipitation conflicted with the proxy records in their region of focus.

The smaller size of the North American land mass and influence of adjacent oceans have been used to explain the mid continent drying observed in the proxy records. Harrison et al. (2002) proposed a dynamic response to 6-kBP insolation involving subsidence in the
interior to explain the aridity in the Midwest. The results here show that existence of regional feedbacks may also contribute substantially to the climate of the Midwest at 6-kBP. In particular the role of vegetation and moisture flux off the Gulf of Mexico appears to be almost as important as the orbital parameters in determining the precipitation in the Midwest. Although the low-level jet frequency shows some increase, the vapor transport decreases in the scenario.
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