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MODELLING MIDDLE PLIOCENE WARM CLIMATES OF THE USA

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ABSTRACT

The middle Pliocene warm period represents a unique time slice in which to model and understand climatic processes operating under a warm climatic regime. Palaeoclimatic model simulations, focussed on the United States of America (USA), for the middle Pliocene (ca 3 Ma) were generated using the USGS PRISM2 2° x 2° data set of boundary conditions and the UK Meteorological Office's HadAM3 general circulation model (GCM).

Model results suggest that conditions in the USA during the middle Pliocene can be characterised as annually warmer (by 2° to 4° C), less seasonal, wetter (by a maximum of 4 to 8 mm/day) and with an absence of freezing winters over the central and southern Great Plains. A sensitivity experiment suggests that the main forcing mechanisms for surface temperature changes in near coastal areas are the imposed Pliocene sea surface temperatures (SST's). In interior regions, reduced Northern Hemisphere terrestrial ice, combined with less snow cover and a reduction in the elevation of the western cordillera of North America, generate atmospheric circulation changes and positive albedo feedbacks that raise surface temperatures. A complex set of climatic feedback mechanisms cause an enhancement of the hydrological cycle magnifying the moisture bearing westerly wind belt during the winter season (Dec., Jan., Feb.). Predictions produced by the model are in broad agreement with available geological evidence. However, the GCM appears to underestimate precipitation levels in the interior and central regions of the southern USA.

KEY WORDS: Middle Pliocene, GCM, USA, evaluation.

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INTRODUCTION

The middle Pliocene has been described as the last period of geological time that displayed greater sustained warmth and reduced climatic variability over a time period greater than any Quaternary interglacial (Dowsett and Poore 1991; Dowsett et al. 1996). Geological proxy evidence supporting this assertion includes sea surface temperatures (SST) reconstructed from planktonic foraminifera (Dowsett and Poore 1991; Dowsett et al. 1992; Dowsett et al. 1996; Raymo 1994), ostracods (Cronin 1991; Forester 1991), siliceous microfossil records (Morley and Dworestzky, 1991; Barron 1992, 1996), terrestrial vegetation records (Thompson 1991; Heusser and Morley 1996; Thompson and Fleming 1996) and numerous records of higher-than-present sea levels (Dowsett and Cronin 1990; Brigham-Grette 1994; Zubakov and Borzenkova 1990). As a result, the middle Pliocene represents a unique time period in which to examine the behaviour of the Earth's climate system under a regime of greater-than-present warmth.

A relatively precise stratigraphy, wide geographical distribution of sample sites, and numerous extant climatic boundary conditions all combine to make the middle Pliocene an ideal time period for palaeoclimatic modelling studies using general circulation models (GCM; Dowsett et al. 1999). With anthropogenic greenhouse gas emissions forcing greater warmth (IPCC 1995), significant potential benefit exists in the careful investigation of past warm periods in Earth's history, such as the middle Pliocene. Furthermore, palaeoclimatic modelling investigations of this interval provide us with an opportunity to assess the validity and robustness of predictions produced by GCM that are being used to model past, present, and future climates alike (Chandler et al. 1994; Sloan et al. 1996; Haywood et al. 1999, 2000a, 2000b).

This paper describes the results of a new palaeoclimatic modelling study, focused on the USA, for the middle Pliocene using a state-of-the-art GCM. Previous GCM studies of the middle Pliocene have been carried out by Chandler et al. (1994), Sloan et al. (1996), and Haywood et al. (1999, 2000a, 2000b). However, this is the first to examine, in detail, the nature and dynamics of the palaeoclimate and the validity of model predictions on a regional scale.

The geological record of the USA during the middle Pliocene is diverse and well suited for the regional assessment of GCM predictions (Figure 1). A wealth of geological data are available, derived from tectonic basins that contain long sedimentary records of palaeoenvironmental change. In addition, numerous localities display evidence for Pliocene lacustrine, fluvial, and shallow marine environments (Thompson 1991; Thompson and Fleming 1996).

MODEL DESCRIPTION

The HadCM3 GCM

The HadCM3 GCM used in this study was developed at the Hadley Centre for Climate Prediction and Research, which is a part of the UK Meteorological Office. This GCM consists of a linked atmospheric model, ocean model,and sea ice model. However, for the present study we use only the atmospheric component of the model (HadAM3).

The horizontal resolution of the model is 2.50 degrees of latitude by 3.75 degrees of longitude. This gives a grid spacing in the mid-latitudes of 278 km in the North-South direction and 417 km East-West, comparable to a T42 spectral resolution model. The HadAM3 atmospheric model consists of 19 layers.

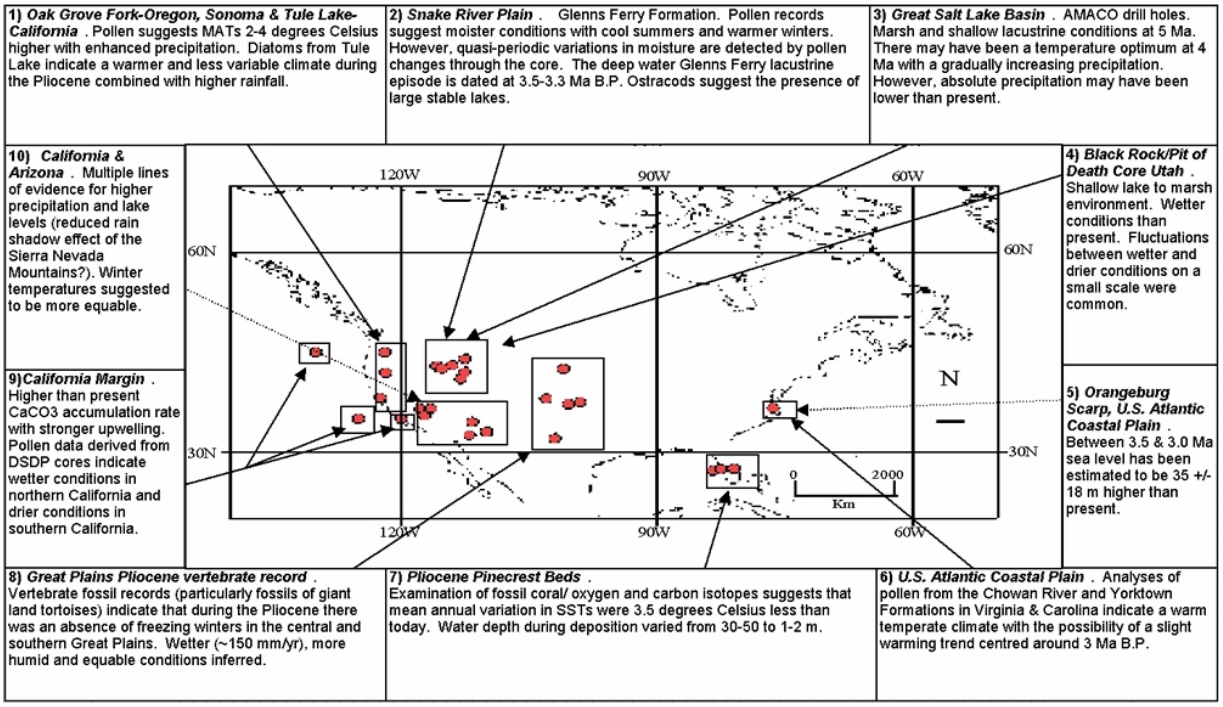


Figure 1. Summary of middle Pliocene palaeoclimatic/palaeoenvironmental evidence derived from the geological record of the United States.

Pope et al. (2000) describes the impact of the new physical parametrizations used in the HadAM3. The land-sea mask and orographic details used do not differ from HadAM2 (Johns et al. 1997; Johns 1996). The model has a timestep of 30 minutes and a new radiation scheme that can represent the effects of minor trace gases (Edwards and Slingo 1996). Parametrizations of simple background aerosol climatology discussed by Cusack et al. (1998) are also included. The model convection scheme has also been improved according to Gregory et al. (1997). A new land-surface scheme includes the representation of the freezing and melting of soil moisture. The representation of evaporation now includes the dependence of stomatal resistance on temperature, vapour pressure, and CO_2 concentration (Cox et al. 1999). The above changes have increased the ability of the HadAM3 model to perform a realistic simulation of surface heat flux.

Boundary Conditions

For this modelling study the required boundary conditions for the HadAM3 model were supplied by the United States Geological Survey's (USGS) Pliocene Research Interpretations and Synoptic Mapping (PRISM) Groups, PRISM2 enhanced 2° x 2° digital data set, or they were specified as current values. Carbon dioxide was set at 315 ppm, a value in line with previous modelling studies for the middle Pliocene (i.e., Chandler et al. 1994). In practice, using prescribed SST means that the model is relatively insensitive to the precise choice of CO_2 concentration. Prescribed boundary conditions integrated into the model that are specific to the middle Pliocene include: (1) continental configuration, modified by a 25 m increase in global sea level, (2) modified present-day elevations (elevation of the western cordillera of North America reduced by 50 per cent; 950 m), (3) reduced ice sheet size and height for

Greenland (50%) and Antarctica (33%), (4) Pliocene vegetation distributions, and (5) Pliocene SST and sea ice distributions (see Haywood et al. 2000a and Dowsett et al. 1999 for more detailed descriptions of PRISM2 boundary conditions and their integration into the UKMO GCM).

The PRISM2 data set is the latest in a line of data sets generated by the USGS that reconstruct the palaeoenvironment of the middle Pliocene. The PRISM2 reconstruction consists of a series of 28 global scale data sets on a 2° latitude by 2° longitude grid, and as such, represents the most complete and detailed global reconstruction of climate and environmental conditions older than the last glacial (Dowsett et al. 1999). PRISM2 evolved from numerous studies that summarised conditions at a large number of marine and terrestrial localities (e.g., Cronin and Dowsett 1990; Poore and Sloan 1996). A detailed description of the new PRISM2 data set, that fully documents the construction of PRISM2 and how it differs from earlier PRISM data sets, is now available as a USGS Open File Report (see Dowsett et al. 1999).

MODEL EXPERIMENTS

Model Experiments, Integration, and Statistical Testing

Two modelling experiments are described in this article. The first (middle Pliocene control experiment) uses the full set of PRISM2 boundary conditions to investigate the nature of the middle Pliocene palaeoclimate and its relative difference to the present-day climate of the USA. The second experiment (Pliocene sensitivity experiment) utilises global PRISM2 Pliocene SST estimates, sea level and vegetation distributions while setting terrestrial ice cover and orographic parameters to modern conditions. Specifically, this increases ice volume over Greenland and Antarctica by 50 percent and 33 percent respectively, and raises the elevation of the western cordillera of North America by 50 percent. The aim of this approach is to investigate the relative importance of certain climatic boundary conditions in producing the climate changes predicted by the HadAM3 model for the middle Pliocene over the USA.

For both experiments the HadAM3, GCM was integrated for 12 years and climatological means were compiled for the final 10 years only. Time-series analysis of all climate variables for the whole of the 12-year simulation show that disregarding the first two years of simulation is sufficient for the model climatology to reach a dynamic equilibrium. Furthermore, the slowest component to reach equilibrium is soil moisture. An examination of global mean soil moisture showed no significant trend in the upper layers after two years. However, there was a small residual trend in the deepest layer that lasted for approximately five years. Overall, the length of the model run is comparable to previous modelling studies for the middle Pliocene (e.g., Sloan et al. 1996). In the results, statistical tests of the Pliocene control-run model predictions are based on the Student *t*-test described by Chervin and Schneider (1976). Although this statistical test has many limitations (see Wigley and Santer 1990), it is commonly used and is a simple test. Moreover, the changes in climate between the middle Pliocene and present-day are generally large and so clearly exceed the statistical test.

BIOME 4

An important feature of our simulations with the HadAM3 model is that we use a Biome model (BIOME 4) to translate climate model output from the Pliocene control experiment, (specifically the seasonal cycle of temperature, precipitation, and solar radiation) into biome distributions. Such an approach has two specific advantages. The first is that it condenses multivariate climate data into a small number of biomes producing an effective and informative summary of the middle Pliocene simulations produced by the HadAM3 model. Secondly, it greatly improves our ability to compare model-simulated climate with estimations of palaeoclimate derived from fossil pollen. In this study we use the BIOME 4 model, which is the latest in a series of mechanistically based models that were developed from physiological considerations that place constraints on the growth and regeneration of different plant functional types. These constraints were calculated via the use of limiting factors for plant growth. These factors include the mean temperature of the coldest and warmest months, the number of growing degree days (GDD) above 0° and 5°C, and via the calculation of a coefficient (Priestley – Taylor coefficient) for the extent to which soil moisture supply satisfies atmospheric moisture demand. GDD are calculated by linear interpolation between mid-months and by a one-layer soil moisture balance model (Prentice et al. 1993) independent of the HadAM3 model hydrology.

The BIOME 4 model is representative of a gradual evolution of biome models (see Prentice et al. 1992; Prentice et al. 1993; Prentice et al. 1998) and differs from earlier BIOME models by the addition of additional plant functional types for tundra climates and by factoring in the importance that differing atmospheric CO_2 concentrations have on plant growth (Kaplan 2001). To minimise any model bias,the BIOME 4 model, like its parent models, has been validated and calibrated to vegetation distribution, productivity and other biogeochemical data for the present-day and the recent past. Known biases in the BIOME 4 model relate to the precise location of the forest-grassland boundary in temperate and subtropical latitudes (Kaplan 2001).

As an equilibrium vegetation model, BIOME 4 is an ideal tool for assessing vegetation distribution at a particular time in the past. However, plant assemblages heavily influenced by short-term dynamic processes (e.g., fire, recurrent extreme weather events) may be incorrectly simulated in model. In this application, we have run BIOME 4 using a 2.5° by 3.75° grid corresponding to the same resolution as the HadAM3 GCM. Absolute values for monthly mean surface temperature, precipitation, and cloud cover derived from the ten-year climatological means from the HadAM3 Pliocene control run were used to provide the climatic information necessary for the BIOME 4 model.

MODEL RESULTS - PLIOCENE CONTROL

Surface Temperature Difference

The HadAM3 model predicts a distinct warm anomaly over the USA during the middle Pliocene (Figure 2). This anomaly is visible over the annual cycle and during winter (DJF) and summer (JJA) intervals. The geographical distribution of the warming is remarkably continuous. Annual mean temperature (ΔT) changes show an average increase of 2° to 5°C. Surface temperature increases are highest during the DJF period with DT values of + 5° to 10°C common over most interior regions of the USA. Temperature variations of above 20°C during DJF are also predicted for the Hudson Bay region of NE North America. Surface temperature changes during JJA reveal a less consistent pattern of change. Overall, a warming of 2° to 5°C is predicted over many areas of the USA. However, larger DT variations of 5° to 10°C are restricted to the Great Plains region. Predicted sporadic cooling over isolated areas of the USA during the mid-

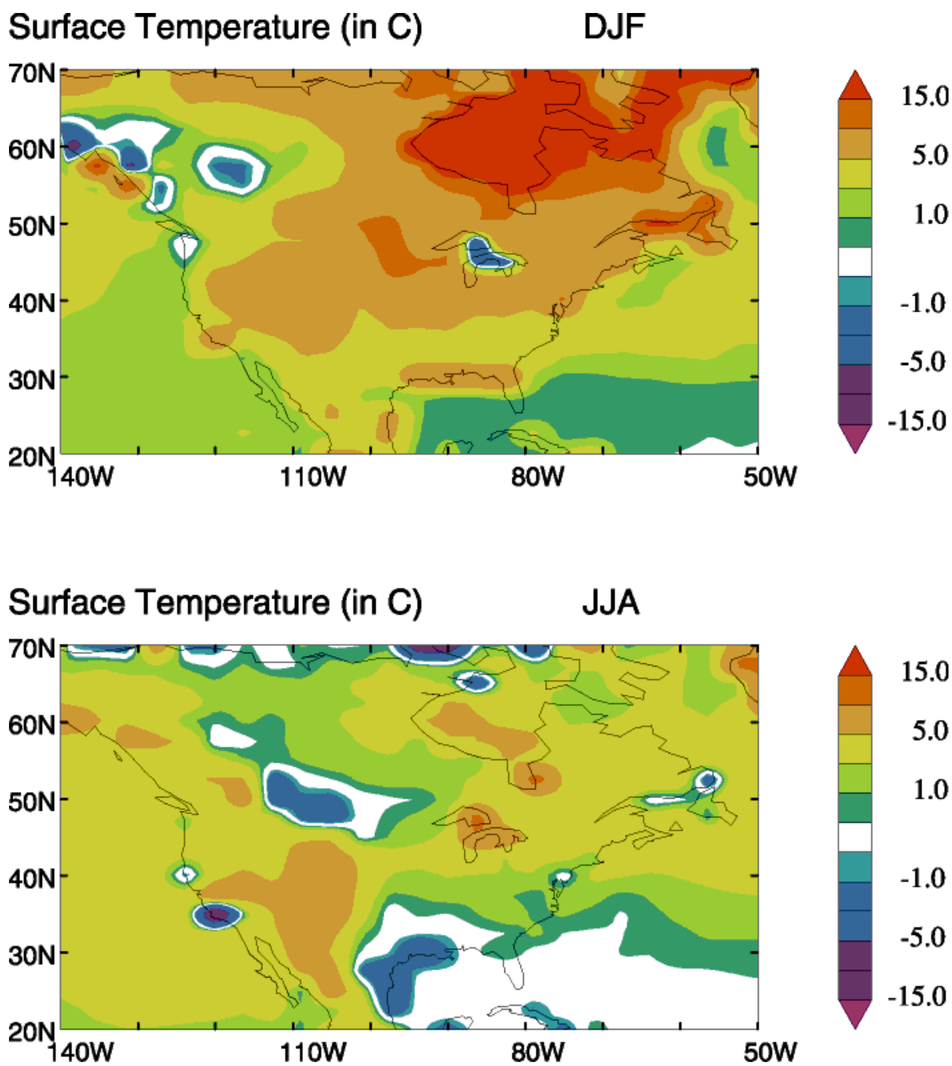


Figure 2. HadAM3 model prediction: difference in surface temperature (°C) during the middle Pliocene over North America for both the winter (DJF) and summer (JJA) seasons.

dle Pliocene is caused by differences in the assigned position of the coast specified in the PRISM2 data set.

Temperature Forcing and Feedbacks

Lower terrestrial ice cover in the Northern Hemisphere and higher SST in the North Atlantic-North Pacific provide the initial forcing mechanism behind the predicted surface temperature increases over the USA at 3 Ma B.P. However, reductions in albedo, particularly during DJF generated by reduced snow cover and altered Pliocene vegetation distributions, would have caused an increase in the absorption of solar radiation promoting further warming. The snow depth decrease occurs over the USA despite a general increase in wintertime precipitation. An increased proportion of precipitation during the warmer middle Pliocene simulation falls as rain and not as snow. Comparison of absolute temperature patterns for present-day and the middle Pliocene over the annual cycle, DJF and JJA, reveal interesting differences (Figure 3). During the middle Pliocene, the freezing line over the annual period and DJF is positioned further to the

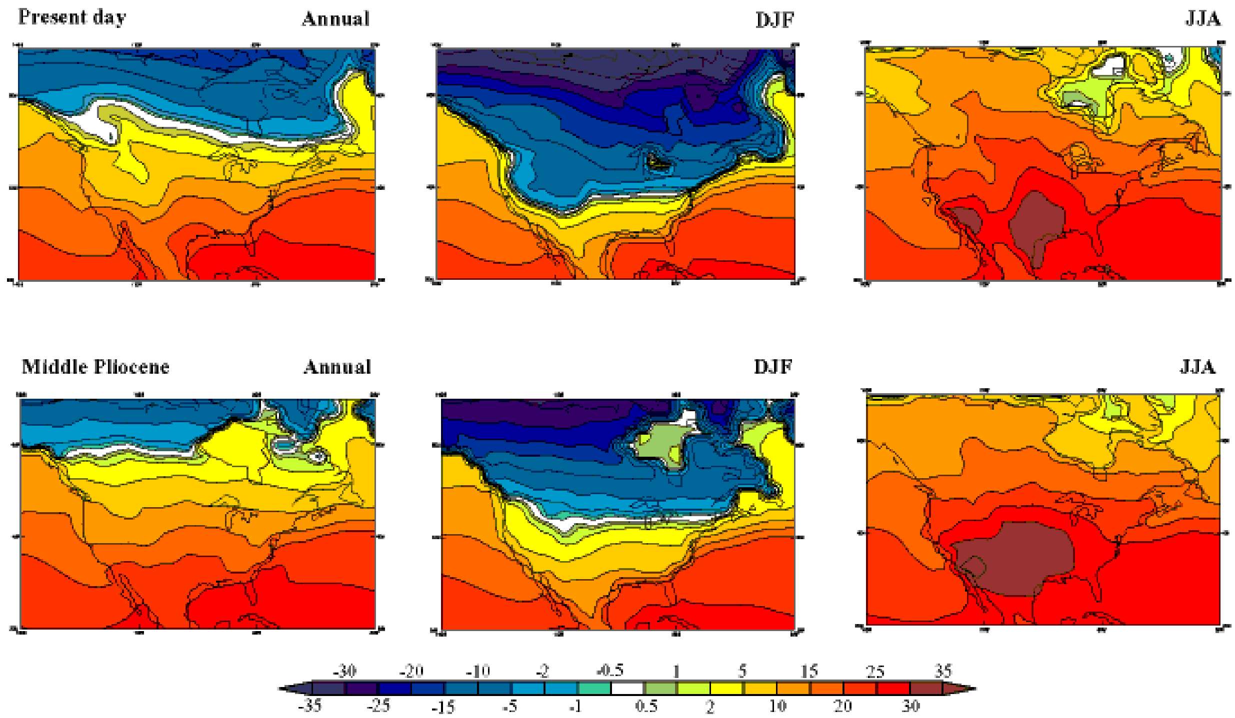


Figure 3. HadAM3 model prediction: present-day and middle Pliocene absolute surface temperatures (°C) over North America for the annual period, winter (DJF), and summer (JJA) seasons.

north of the present-day position (~10°N). Furthermore, the pattern of decreasing temperatures with increasing latitude during the middle Pliocene is less spatially variable than for present-day. This is a function of the prescribed reduction in elevation (by 50%) of the western cordillera of North America within the PRISM2 boundary conditions.

Variations in Precipitation and Evaporation Rates

A clear signal of changing precipitation rates over the USA during the middle Pliocene is predicted by the HadAM3 model (Figure 4). Two zones of change are evident. Over the annual cycle and during winter (DJF), northern parts of the USA experience more rainfall (+ 4.00 to 8.00 mm/day). This increase in precipitation occurs as a broad belt across North America between 40° to 60°N. This increase of precipitation is consistent with an enhancement of the moisture bearing westerly winds over the USA during the middle Pliocene. In the southern and central areas of the USA, particularly during JJA, total precipitation rates decrease by an average 2.00 mm/day.

Changes in the pattern and amount of evaporation and humidity over the USA are mainly a reflection of the altered precipitation distribution and warmer surface temperatures. Areas experiencing enhanced precipitation via moisture bearing westerly winds in the northern USA have elevated evaporation rates by as much as 0.50 to 1.00 mm/day. This reflects the greater moisture availability for evaporation and the warmer surface temperatures. Conversely, central and southern parts of the USA have lower evaporation rates relative to present-day (by a maximum of 4.00 mm/day during JJA) due to a decreased availability of moisture. Humidity values also show a corresponding decrease by as much as 30 percent in this area during JJA.

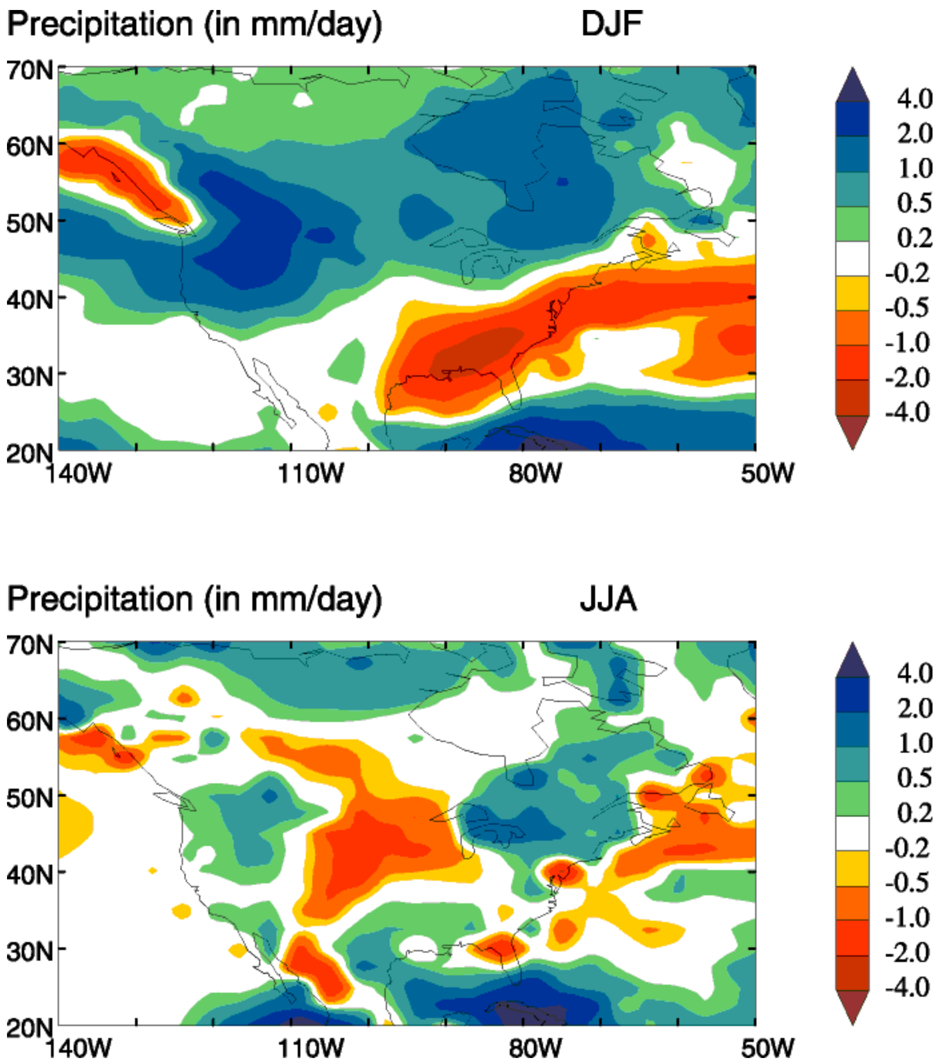


Figure 4. HadAM3 model prediction: difference in the total precipitation rate (mm/day) during the middle Pliocene over North America for both winter (DJF) and summer (JJA) seasons.

Precipitation minus evaporation (P-E) changes over the USA, for the Pliocene control simulation, indicates small anomalies compared to present-day model simulations during JJA. However, significant anomalies are observed for the winter (DJF) season (Figure 5). The model suggests that for the northern USA, during the middle Pliocene, a substantially greater (0.00 to 4.00 mm/day) precipitation flux existed compared to present-day. In contrast, the southeast of the USA during DJF has a greater evaporative flux (0.50 to 8.00 mm/day) compared to model simulations for the present, which extends further south into the Gulf of Mexico. These P-E anomalies are a product of the predicted Pliocene precipitation changes over the USA during DJF (see Figure 5).

Precipitation Forcing and Feedbacks

The primary forcing mechanism, producing the altered precipitation pattern over the USA during the middle Pliocene, is a strong increase in westerly wind strength (Figure 6). These enhanced westerly winds aid the transport of moisture that falls mostly as rain because of the higher annual surface temperatures. The westerly wind increase is brought about by

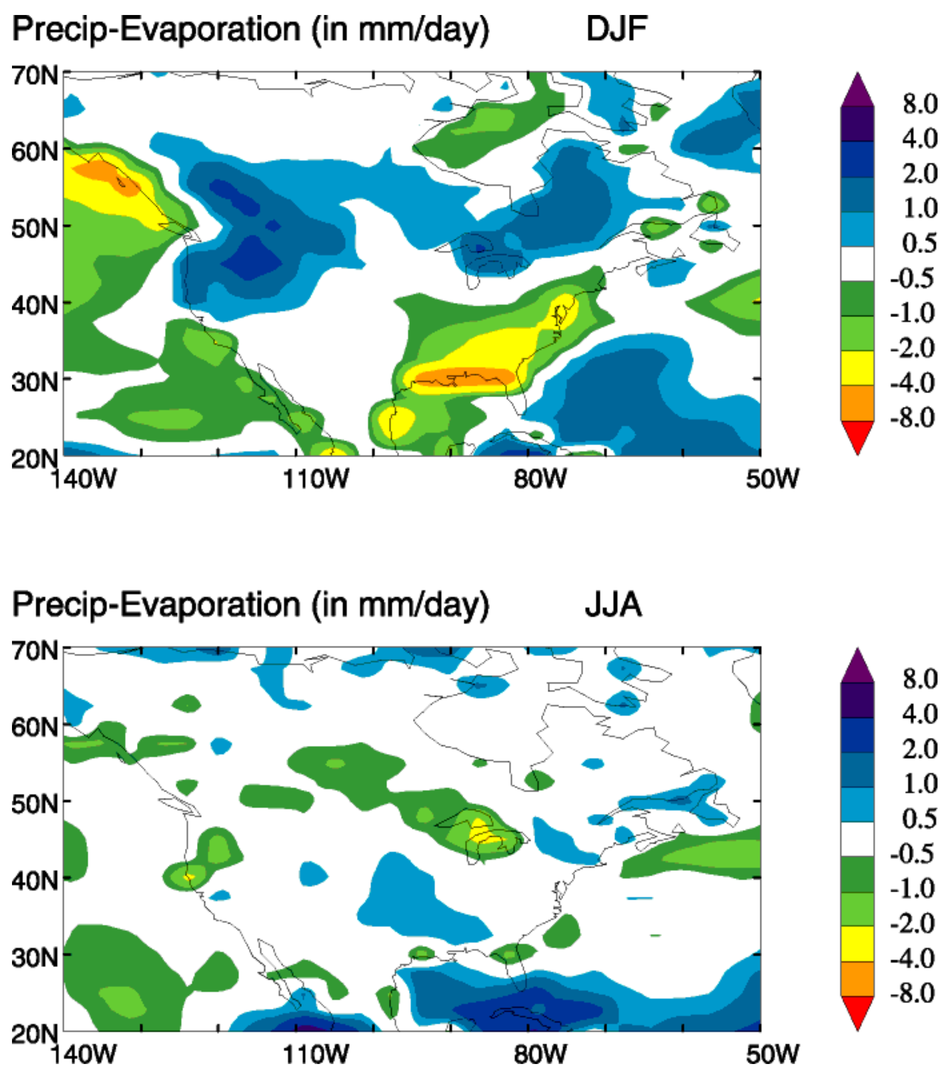
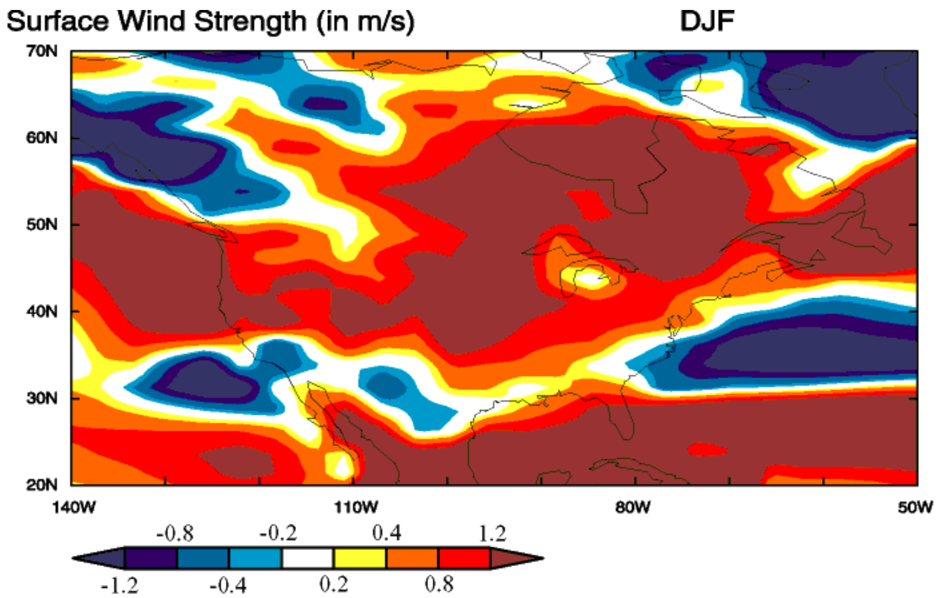


Figure 5. HadAM3 model prediction: difference in P–E values (mm/day) during the middle Pliocene over North America during both winter (DJF) and summer (JJA) seasons.

a complex set of climatic feedbacks. Higher SST in the North Atlantic-Pacific, combined with reduced ice cover in the high latitudes of the Northern Hemisphere, deepen the Aleutian and Icelandic low-pressure systems. This generates an enhanced pressure gradient between the high latitude low pressure cells (Aleutian and Icelandic low-pressure systems) and the subtropical high pressure cells (i.e., Azores high-pressure system) intensifying westerly wind strength in the Northern Hemisphere, particularly during winter. This aids in both the transport of heat and moisture and explains why the highest magnitude changes in surface temperature and precipitation during the middle Pliocene over the USA are predicted for the winter season.

The feedbacks generating the precipitation pattern in central and southern regions of the USA during the middle Pliocene are subtler. A possible explanation for the drying in these areas is the reduced SST at lower latitudes prescribed during certain months in the PRISM2 digital data set. This has the effect of decreasing southerly wind strength in the middle Pliocene simulation over the Gulf of Mexico while reducing the flow of moist mari-



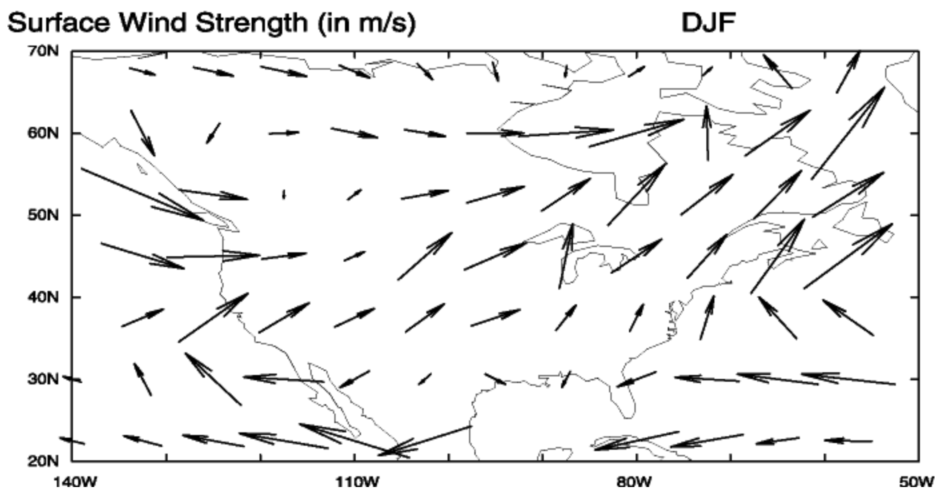


Figure 6. HadAM3 model prediction: difference in surface wind strength (m/s^{-1}) and vector mean winds during the middle Pliocene over North America for the winter (DJF) season.

time air into the continental interior of the USA, particularly during JJA.

The reduced height of the western cordillera of North America by 50% in the middle Pliocene simulation should have the effect of reducing the rain shadow effect to interior parts of the USA. Intuitively, this should also increase precipitation in this area. Discrimination of the effects of such a change from other factors, such as increased SST that also increase precipitation in the region, will be addressed in the following section.

PLIOCENE SENSITIVITY EXPERIMENT

Surface Temperature Difference and Forcing

In response to the altered boundary conditions imposed in the Pliocene sensitivity experiment, the HadAM3 model predicts reduced surface temperatures compared to the Pliocene control over wide regions of the USA during both winter and summer seasons (Figure 7). The magnitude of this cooling varies spatially with severest cooling (>5°C) concentrated over the western United States, associated with the western cordillera. However,

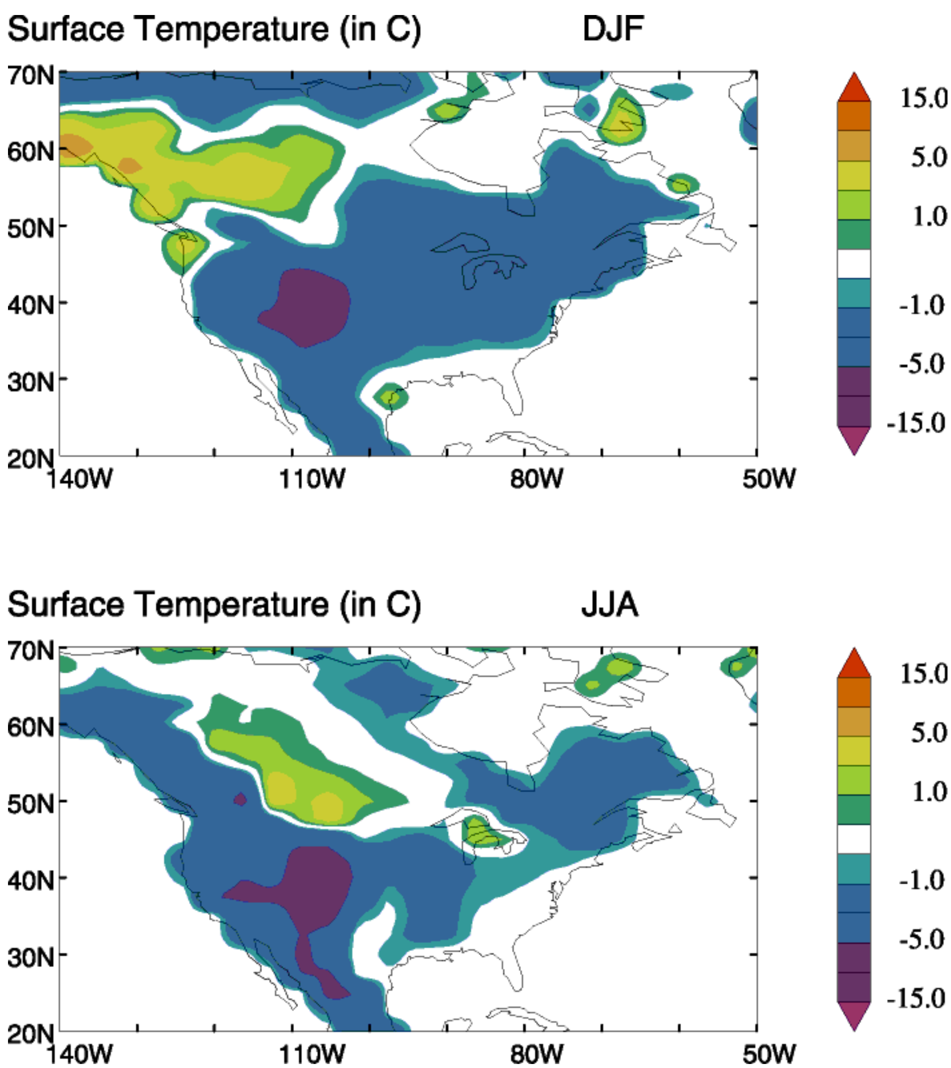


Figure 7. HadAM3 model prediction: difference in surface temperature (^{O}C) over North America between the Pliocene sensitivity experiment and the Pliocene control simulation for both winter (DJF) and summer (JJA) seasons.

areas in close proximity to the coast, peninsulas (e.g., Florida) and bays (e.g., Hudson Bay) do not exhibit a cooling trend. This is due to the warmer SST imposed from the PRISM2 data set. This model suggests that in these regions the simulated warming observed from the Pliocene – present-day control experiment are solely attributable to the warmer Pliocene SST. Conversely, the increase in Northern Hemisphere terrestrial ice and snow cover combined with the regional specified increase (~50%) in the elevation of the North American western cordillera primarily drove the cooler temperatures over western and central parts of the USA observed in the Pliocene sensitivity experiment. Therefore, the primary forcing mechanisms for the simulated warmer conditions in the Pliocene – present-day control experiment are reduced Northern Hemisphere terrestrial ice and snow cover (via an ice albedo feedback) and the lowered elevation of the western cordillera of North America.

Precipitation/Wind Strength Difference and Forcing

Overall, the HadAM3 model predictions for the Pliocene sensitivity experi-

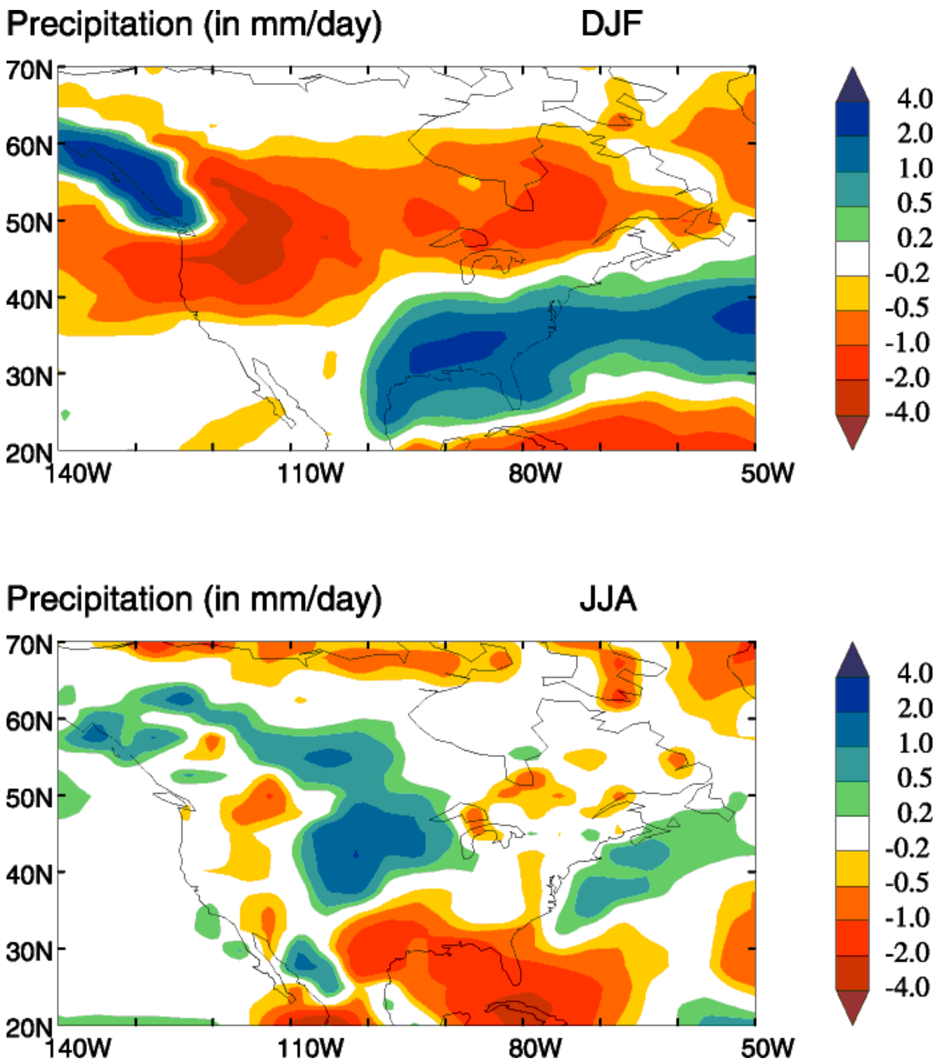


Figure 8. HadAM3 model prediction: difference in the total precipitation rate (mm/day) over North America between the Pliocene sensitivity experiment and the Pliocene control simulation for both winter (DJF) and summer (JJA) seasons.

ment suggest a pattern of reduced precipitation levels over the USA for the Pliocene sensitivity experiment (Figure 8). The largest reductions are observed during the winter (DJF) season in a latitudinal range corresponding to the westerly wind belt. This reduction in precipitation is generated by a number of feedback mechanisms. Increased Northern Hemisphere snow and ice cover, combined with the increased elevation of the western cordillera of North America, reduces surface temperatures, evaporation, and the moisture available for precipitation. Enhanced terrestrial ice cover and lower surface temperatures, which occur generally in the Northern Hemisphere, weaken the Icelandic low and Azores high-pressure systems. This has the effect of weakening the moisture-bearing westerly wind belt in the Pliocene sensitivity experiment (Figure 9). Therefore, increased precipitation levels simulated for the Pliocene – present-day control experiment for the region result from reduced snow and ice cover in the Northern Hemisphere and the reduced elevation of the western cordillera of North America.

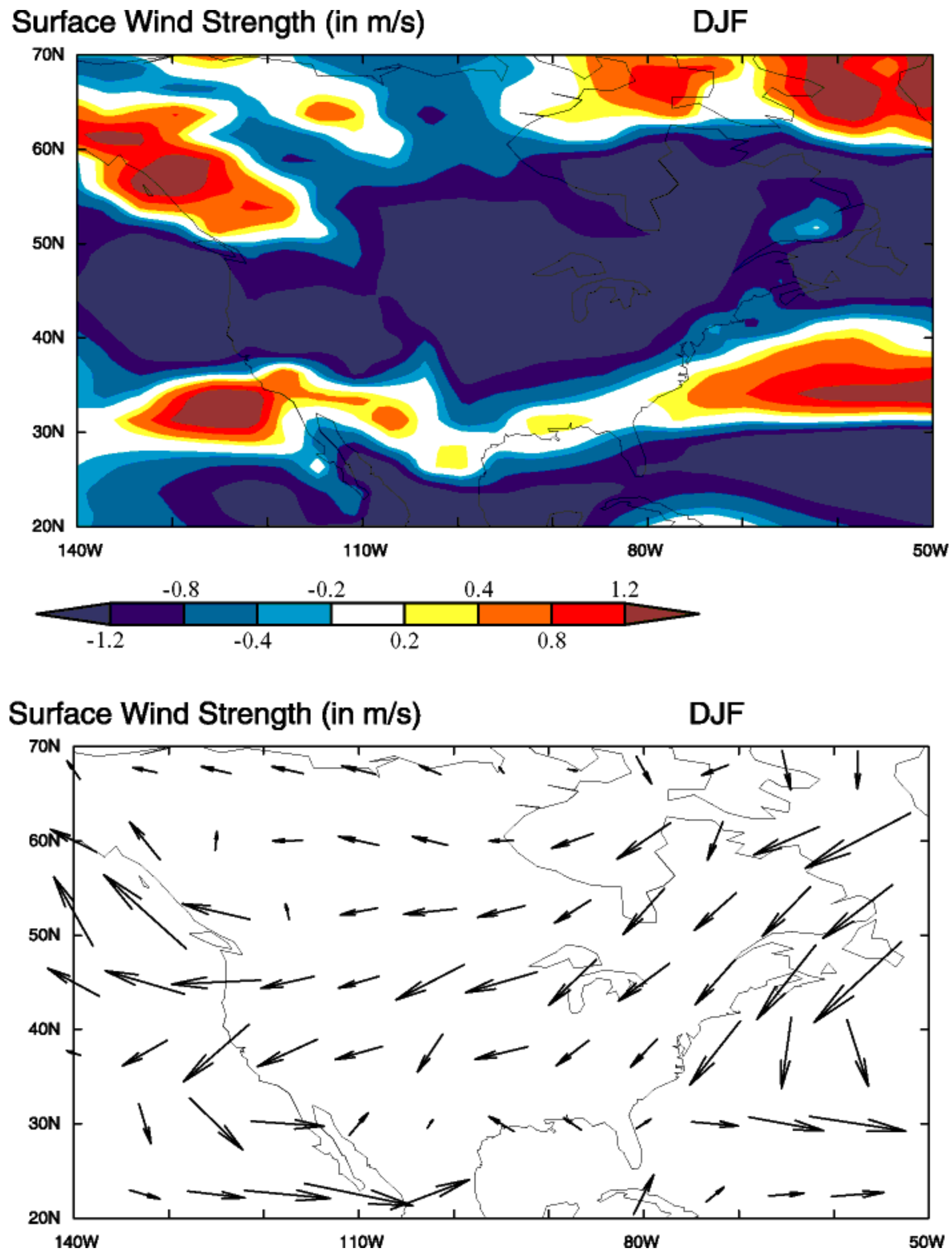


Figure 9. HadAM3 model prediction: difference in surface wind strength (m/s^{-1}) and vector mean winds over North America between the Pliocene sensitivity experiment and the Pliocene control simulation for the winter (DJF) season.

EVALUATION AND DISCUSSION OF MODEL RESULTS

Statistical Analyses of Pliocene Control Results

Statistical analyses of the model output for the middle Pliocene control run is a necessary step in trying to determine how much of the change in climatic variables are truly due to the imposed Pliocene boundary conditions (PRISM2 data set), or inter-annual variability within the model itself. In this study, a threshold of 95 percent is considered significant. This does not automatically imply that any simulated changes that do not achieve a 95 percent significance level are not true representations of differences in the middle Pliocene

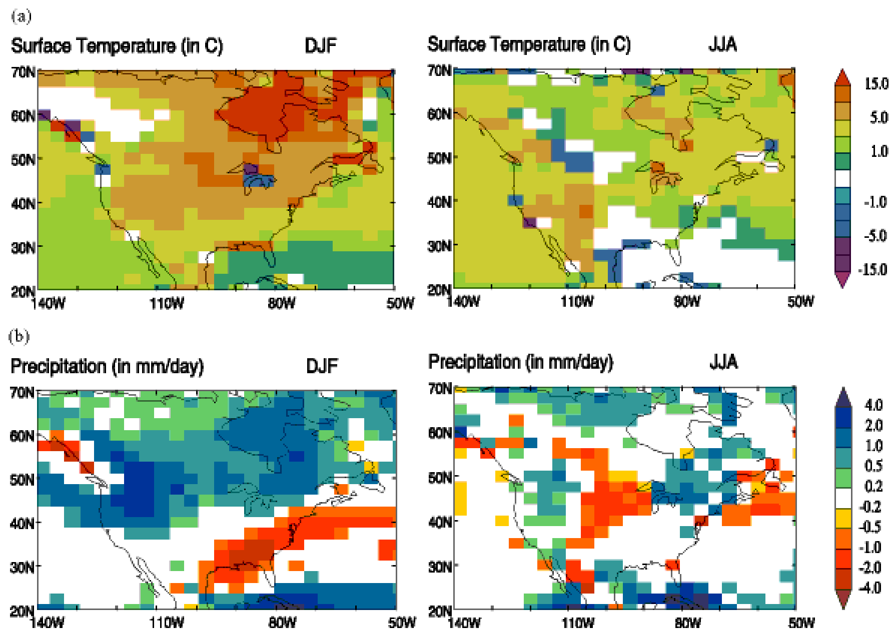


Figure 10. Statistical significance test results for middle Pliocene model simulations of (a) surface temperature (°C) change and (b) total precipitation rate change (mm/day) over North America. Shaded areas show the geographical coverage of statistically significant results (tested to a 95% significance level).

climate. Rather, they could represent either true variations or inter-annual variability. Statistical results for surface temperature changes (°C), total precipitation (mm/day) are summarised in Figure 10.

Statistical results for surface temperatures over North America as a whole suggest that much of the modelled differences in middle Pliocene surface temperatures from present-day are significant, especially during DJF. The improved significance during DJF can be attributed to the higher magnitude of surface temperature change predicted by the HadAM3 model during that season.

Statistical results for changes in total precipitation suggest that most of the predicted changes are significant. During JJA the geographical coverage of significant results is diminished compared to DJF. The difference between seasons can again be attributed to larger changes in precipitation occurring during DJF.

The geographical distribution of significant results for surface pressure (not shown in Figure 10) and wind strength changes is widespread over North America during DJF. This is, once again, a reflection of the magnitude of change in these variables during winter that are driven by changes to the high latitude, low and sub-tropical high-pressure cells.

Comparison to Geological Record

Comparison of the simulated regional climatic features produced by the GCM with Pliocene geological palaeoclimatic data has been carried out in a semi-quantitative fashion and is summarised as Table 1. Broadly, the comparison suggests that the climatic predictions generated by the HadAM3 over the USA are robust and agree with the data. The geological evidence of surface temperature warming of between 2° to 4°C and enhanced winter-warming over many areas of the USA (see boxes 1, 2, 3, 6, 8, and 10 on Figure 1) closely approximates the simulations of surface temperature changes predicted by the HadAM3 model. Furthermore, the simulated retreat of the freezing line during the middle Pliocene accords well with the

Table 1. Semi-quantitative comparison of middle Pliocene GCM outputs for areas 1 to 10 of the United States (see Figure 1) compared to geological data for the same areas.

Area of U.S. (referring to box numbers from Fig. 1).	**Annual model temp. change from PD (°C)**	**Statistically significant to (%)**	**Geological data estimate (°C)**	**Quality of comparison (G/M/P)**	**Annual model precip. change from PD (mm/day)**	**Statistically significant to (%)**	**Geologica l data estimate (mm/day)**	**Quality of comparis on (G/M/P)**
Area 1	+ 2 to 5	>99	+ 2 - 4	G	+ 0.2 to 2	>99	Wetter	M
Area 2	+ 2 to 10	>99	Warmer	M	0 to 2	>99	Wetter	M
Area 3	+ 2 to 10	>99	Warmer	M	0 to 2	>99	Wetter	M
Area 4	+ 2 to 10	>99	Warmer	M	0 to 2	>99	Wetter	M
Area 5			Comparison not possible					
Area 6	+ 2 to 5	>99	Warmer	M	-1 to 0	>95	N/A	-
Area 7			Comparison not possible					
Area 8	+ 2 to 10	>99	Warmer	M	- 2 to 0	>99	+ 150 mm/ yr.	P
Area 9			Comparison not possible					
Area 10	+ 2 - 10	>99	Warmer	M	- 2 to 0	<90	Wetter	P

fossil vertebrate record (Hibbard 1960; Auffenburg 1974; Graham 1986; Thompson 1991) of the USA, which suggests that freezing winters were absent on the central and southern Great Plains (Box 8: Figure 1). A simulated northward regression of the freezing line is not a unique feature produced by the HadAM3 model. Sloan et al. (1996) detected the same northward shift of the freezing line using the NCAR Genesis GCM and the PRISM1 data set.

In contrast to surface temperature, geological evidence for middle Pliocene hydrological characteristics exhibit great variability within the USA itself, thus making the assessment of the GCM predictions substantially harder. Furthermore, the weakness of the statistical testing results reduces our ability to evaluate the model predictions. Nevertheless, geological evidence from northern offshore, central, and interior regions of the USA (boxes 1, 2, 4, 8, and 10: Figure 1) including palaeolake levels and pollen support the assertion of an enhanced hydrological cycle during the middle Pliocene (Thompson 1991; Forester 1991; Thompson and Fleming 1996). Moreover, the geographical location of sites supporting higher precipitation levels in the northern USA coincide with the model-predicted zone of enhanced precipitation associated with the moisture bearing westerly wind belt. This suggests that the primary cause of the existence of large stable lakes or higher lake levels in northern areas of the USA suggested by the geological record (boxes 1, 2, and 4, Figure 1) is related to the higher winter precipitation level generated by the enhancement of westerly winds.

Evidence from fossil pollen, vertebrates, and soil carbonates support a pattern of enhanced precipitation in the southern USA on the eastern side of the western Cordillera of North America as well as further north (Box 10, Figure 1). This change in precipitation may have resulted from a reduced rain-shadow effect, produced by the lowered elevation of the mountain chain (Smith 1993; Thompson 1991; Thompson and Fleming 1996). Specifically, increases in rainfall have been suggested for Texas, Arizona, Nevada, and southern California. The HadAM3 model's simulations of the middle Pliocene climate do not detect this trend of wetter conditions reconstructed from geological evidence.

There are numerous possible explanations for this data-model inconsistency. Firstly, the GCM may be incorrectly simulating the small scale effects on condensation and precipitation rates resulting from the change of orography associated with lowering the western Cordillera within the Pliocene control simulation as specified in the PRISM2 boundary conditions. However, this is unlikely as the model correctly simulates precipitation increases in the northern parts of the USA. Therefore, the simulated reduction in southerly winds that reduces the transport of moisture into southern and central areas of the USA is the most likely source of the data-model inconsistency.

Present-day predictions of precipitation amounts over the same area by the model show no dry anomalies when the outputs are compared to observed climatic data. Therefore, the reduced strength of southerly winds and consequent moisture transport in the southern and central areas of the USA must be linked to either an incorrect model response or deficiencies in PRISM2 boundary conditions. Any error in PRISM2 SST in the low latitudes and Gulf of Mexico region would lead to the GCM incorrectly representing changes in atmospheric circulation during the middle Pliocene for the area in question.

Heating or cooling air over mountaintops can produce strong density contrasts in the atmosphere compared with air masses over adjacent regions. This may result in strong rising or sinking motions in the atmosphere (Norris et al. 2000). Summer heating over a large mountain range produces a rising, low-density air mass, low atmospheric pressure over the mountains and thus strong winds blowing towards the mountain front. In the Northern Hemisphere, the winds blow counter clockwise around the range due to the Coriolis force. During winter, cooling of the mountain surfaces produces dense falling air masses that spread out away from the mountain front. In this case, Northern Hemisphere winds blow in a clockwise direction (Norris et al. 2000). The strength of the winds around mountains depends upon the breadth of the range and the strength of cooling produced by radiation from the land surface. Thus, the pattern of air movements around the western cordillera of North America will act to enhance the movement of southerly winds into the interior of the USA during JJA. However, PRISM2 specifies a 50 percent reduction in the elevation of this mountain chain. This will reduce the strength of counter clockwise air motion around the mountains and potentially affect the strength of southerly wind strength and hence precipitation over southern and central areas of the USA. The data-model inconstancy may therefore be a reflection of more sluggish counter clockwise air motion around the western cordillera of North America. Furthermore, it may indicate that the elevation of this mountain chain has been reduced in the PRISM2 data set erroneously or by a magnitude that is too great.

Data-model comparison of precipitation characteristics over the Great Plains region of the USA identifies another clear discrepancy between the geological record (Box 8, Figure 1) and the predictions of the HadAM3 model. While the model predictions mimic the geological record in terms of temperature changes in this area, simulated precipitation changes are opposite to the more humid conditions suggest by fossil vertebrates (Hibbard 1960; Auffenburg 1974; Graham 1986; Thompson 1991). The model simulations for precipitation change are not statistically significant over the Great Plains. However, with the uncertainties surrounding the statistical technique, these results alone are insufficient to ascribe the cause of the discrepancy to the model and not to our interpretation of the geological record. Firstly, the chronological control on the Pliocene vertebrate record of the USA is less robust than for other areas. Furthermore, the palaeoenvironmental interpretation derived from the Great Plains may be erroneous. Specifically, the existence of giant land tortoises on the Great Plains during the Pliocene may not be a reflection of enhanced temperatures and moisture levels. If the model predictions are robust, then this would suggest that temperature and the absence of freezing winters alone are the most significant driving forces in allowing the advancement northward of giant land tortoises in the USA. If not, then the most likely cause of the error relates to the deficiencies discussed in the last paragraph, namely the model's underestimation of the strength of southerly winds that transport moisture inland from the Gulf of Mexico.

High resolution core records taken from the Glenns Ferry Formation in Idaho (Thompson 1996) and the Black Rock and Pit of Death in Utah (Thompson et al. 1995), all suggest that warmer and wetter conditions existed during the middle Pliocene in the USA, and as such support the simulations provided by the HadAM3 (boxes 2 and 4, Figure 1). However, within the overall trend, significant and frequent variations in moisture and temperature are detected via pollen and magnetic susceptibility changes within the respective cores. For the Glenns Ferry Formation, the periodicities of these variations do not appear to match any known Milankovitch astronomical time frame (Thompson 1996). However, oscillations in the Milankovitch-band frequencies, specifically the 41 kyr obliquity cycle, have been detected for the Pliocene from marine records (Tiedemann et al. 1994) and also from terrestrial diatom records at Tulelake in northern California (Adam et al. 1990).

The palaeoclimate modelling results presented in this paper reflect a simple snap shot for the middle Pliocene. Clearly, this approach is insufficient in the light of geological evidence suggesting climatic variation within the middle Pliocene. Future modelling studies should aim to address the issue of climatic variability within the middle Pliocene by the use of sensitivity experiments that alter orbital parameters. Results from such model experiments can then be evaluated against geological evidence to better assess the predictions of the GCM.

BIOME 4 Result

The biome map for the North American continent during the middle Pliocene, generated by BIOME 4 and the climatic output of the HadAM3 model, can be compared to the PRISM2 distribution of vegetation types over the region. The aim of such an approach is to assess how well the simulated climate produced by HadAM3-BIOME 4 for the middle Pliocene mimics the boundary conditions imposed into it. If the model predictions are robust, then the biome distributions that are predicted by BIOME 4 should closely approximate those in PRISM2 that were used as part of the boundary conditions for the GCM.

Several difficulties are implicit with such an approach. The first centres around the accuracy of the PRISM2 boundary conditions imposed in the model. If certain boundary conditions within the PRISM2 reconstruction are erroneous or out of phase with one another

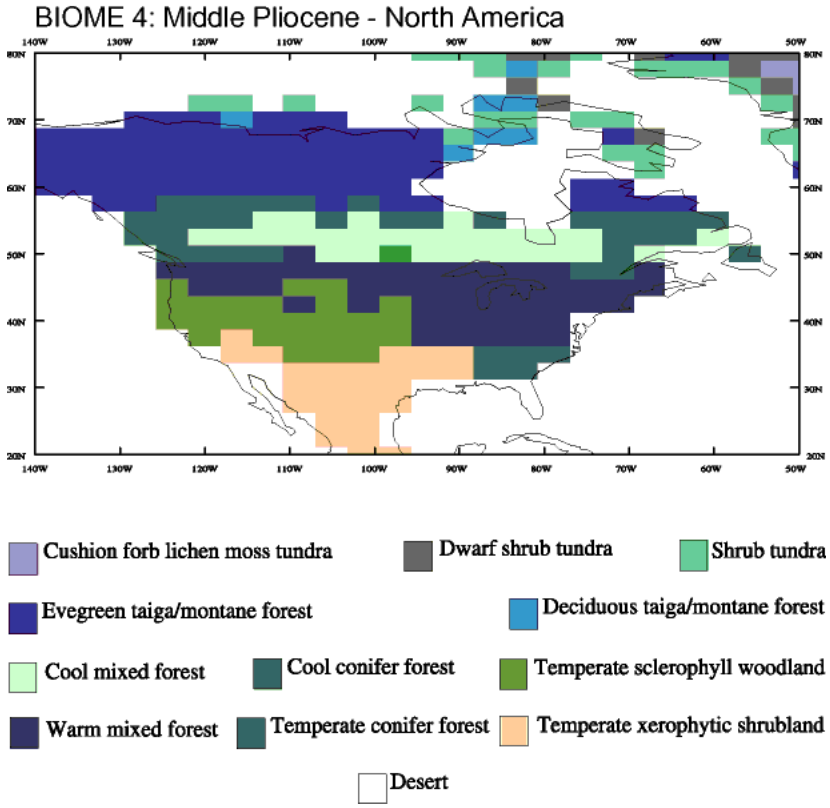


Figure 11. Map of 12 biomes as simulated by BIOME 4 from HadAM3 model's seasonal cycle of temperature, precipitation, and cloud cover over North America for the middle Pliocene.

then the resulting climate and biome simulation will be wrong. Under these circumstances it is very unlikely that the biome distribution for North America produced by BIOME 4 will match that described in PRISM2.

Secondly, great care is required in determining whether any observed discrepancies are related to the model, or differences in the biome classification schemes used in BIOME 4 and PRISM2. PRISM2 uses a simplified seven-stage classification of the Hansen et al. (1983) biome scheme. Grassland, steppe, and savanna type vegetation are all incorporated into one classification due to difficulties in distinguishing between them with pollen evidence (Thompson and Fleming 1996). In contrast, BIOME 4 uses an advanced classification of 23 different biomes. It is important to remember that the BIOME models, just like the HadAM3, represent simplifications of reality and therefore are open to potential sources of error just as any other models (Williamson et al. 1998).

At first sight, the HadAM3-BIOME 4 models predicted only a few biomes in locations generally similar to PRISM2 biome distributions (Figure 11). However, most of this discrepancy is attributed to the differing classification schemes between BIOME 4 and PRISM2. BIOME 4 does correctly capture the expansion of forested areas north and the concurrent retreat of barren and tundra areas that is a key characteristic of the reconstructed middle Pliocene vegetation distribution, compared with present-day (Thompson and Fleming 1996; Dowsett et al. 1999). Comparison of the locations of biome boundaries between the BIOME 4 and PRISM2 is virtually impossible due to the different classification schemes used in both biome reconstructions. However, the latitude boundary at which tundra climates become common is similar between both biome reconstructions, as is the latitude when forest types switch from warm or cool mixed to colder forms.

Nevertheless, the BIOME 4 results show significant variation from the imposed PRISM2 biomes that cannot be explained by the classification problem alone. Firstly, BIOME 4 predicts a significant advance of biomes representing desert or arid areas compared with PRISM2 in eastern and central areas of the southern USA. Specifically, the geographical distribution of xerophytic shrubland moves northward and eastward compared to the reconstructions of desert areas in PRISM2. We believe that this discrepancy reflects the dryer than expected conditions predicted by the HadAM3 for this region in the Pliocene control experiment.

Secondly, BIOME 4 completely fails to predict the presence of grassland in the western USA. In contrast, PRISM2 suggests that grasslands cover a significant geographical area of that region. This may suggest that the HadAM3 model could be over estimating precipitation levels in the higher latitudes of the western USA.

Thirdly, BIOME 4 predicts temperate conifer forest over parts of the southeast USA where PRISM2 identifies deciduous woodland. The results of our Pliocene sensitivity experiment have demonstrated that, at least for this area of the USA, the prescribed PRISM2 SST are primarily responsible for forcing the simulated changes in the middle Pliocene climate. PRISM2 SST reconstructions for coastal areas around this region of the USA are slightly warmer (1° to 2°C), the same or slightly cooler (0.5° to 1°C) than present during certain months of the year (see Dowsett et al. 1999). In this case, the available evidence suggests that the PRISM2 biomes and SST could be out of phase with one another leading to an underestimation of surface temperature change in the middle Pliocene control experiment over this region by the HadAM3 model.

CONCLUSIONS

The UK Meteorological Office's HadAM3 GCM has been used to produce a regional climate simulation of the middle Pliocene over the USA that is in broad agreement with available geological palaeoenvironmental evidence. Generally, a warmer, less seasonal and wetter climate is simulated for the USA during the middle Pliocene. However, according to the geological record and outputs from a biome model (BIOME 4), the HadAM3 model appears to misrepresent changes to the intensity of the hydrological cycle in the southern USA. This inconsistency is related to the way in which the HadAM3 model represents changes to the dynamic circulation of the atmosphere (changes in southerly wind strength) during the middle Pliocene. This problem may arise due to an incorrect response of the model to the imposed boundary conditions. Alternatively, incorrectly prescribed boundary conditions (elevation of western cordillera of North America or SST) in the PRISM2 data set could also be capable of generating the data-model inconsistency.

Future work will continue to evaluate the robustness of the HadAM3 model predictions for the middle Pliocene. Specifically, we aim to evaluate the reliability of the model by comparing its outputs to proxy geological data from other regions and perhaps more significantly attempt to model climate variability within the PRISM2 time slice itself.

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