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Earth system models: a test using the mid-Holocene in the Southern Hemisphere

Robert J. Wasson^{a,*}, Martin Claussen^b

^aCentre for Resource and Environmental Sciences, W.K. Hancock Building, Australian National University, Canberra, ACT 0200, Australia

^bPotsdam Institute for Climate Impact Research, Telegrafenberg C4, P.O. Box 60 12 03, 14412 Potsdam, Germany

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Abstract

Palaeoclimatic reconstructions from proxy data have been compared with climate model outcomes for three decades. It has become evident that explanations of past climates can rely on neither data source alone, the former often being descriptive tools and the latter dependent on model structures and parameterisations. The status of vegetation changes, either as a follower of climate changes or as a modulator of insolation–terrestrial system responses, is vital if proxy records are to be effectively interpreted in climate terms and if models are to be more robust in appropriately incorporating vegetation roles. We use an earth system model (CLIMBER) and proxy data from Southern Hemisphere locations to compare postdictions of mid-Holocene climates. It is concluded that climate simulations and predictions are likely to be inaccurate if vegetation is not properly incorporated, and appropriate models can allow hypotheses to be developed that better explain atmosphere–earth system linkages. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Global, hemispheric and regional syntheses of palaeoclimate reconstructions for different periods of the Late Quaternary have been compared with global climate model simulations to provide powerful insights into the behaviour of the earth system; since the 1970s (e.g. Kutzbach, 1981; Kutzbach and Street-Perrott, 1985; COHMAP, 1988). While palaeoclimatic reconstructions, using pollen, ice limits and lake levels, have been used to test the veracity of global climate models (see for example Gasse, this volume), insights into processes of climate change have come slowly as models of the atmosphere, oceans and cryosphere have been coupled in increasingly successful ways. It has become clear that explanations of past climates cannot rely solely upon either proxies of past climate, which are generally descriptive tools, or model simulations which are to some degree dependent upon model structure and parameterisation.

Two ideas underly most analyses of past climate using proxies and models. The first is that climate sets the

boundaries to vegetation types, and therefore vegetation types are in equilibrium with climate except during the most rapid periods of climate change. Pollen-climate transfer functions can therefore provide reliable estimates of past climate. Secondly, on long time scales, climate changes are driven by solar insolation changes modulated by changes of atmospheric chemistry, extent of ice and snow cover, and biogeochemical changes in the oceans.

These ideas have evolved over the last two decades to begin to form a body of theory about past global climate and biospheric change. While increasingly sophisticated, the emerging theory has usually treated terrestrial vegetation change as a response to climate rather than being an active feedback force in the global system. This is at least partly the result of a lack of appropriate tools of analysis.

Emerging views of the global system take greater account of the biosphere as a dynamic component that both reacts to climate change, and, to some degree, alters climate by feedback from the land surface to the atmosphere. Gradually, it is being widely realised that the general circulation of the atmosphere, and regional patterns of climate, are affected by evapotranspiration from the biosphere, surface roughness, and albedo. There appears to be a strong synergism between the atmosphere and vegetation types, vegetation cover,

*Corresponding author. Tel.: +61-2-6249-4588; fax: +61-2-6249-1037.

E-mail addresses: robert.wasson@anu.edu.au (R.J. Wasson), claussen@pik-potsdam.de (M. Claussen).

ocean temperature and sea ice in modulating (particularly amplifying) insolation changes (Ganopolski et al., 1998b).

Hayden (1998) quoted Walter and Breckle (1985) as representing the dominant modern paradigm about the relationship between climate and the biota, namely that climate influences soil, vegetation and, to a lesser extent, fauna. Climate is only slightly influenced by the soil and biota. Hayden argued that the scientific pendulum has swung to the view first articulated by Christopher Columbus that the land surface has a large effect on the climate, and argued that models that purport to explain climate ‘...are not thought to work without proper specification of the biosphere’ (p.6). Minimum and maximum temperatures are partially controlled by evapotranspiration and the emission of radiatively active biogenically produced trace gases, evapotranspiration contributes as much as half of precipitable water, biogenic condensation and ice nuclei contribute to cloud formation and therefore precipitation, biogenic gaseous emissions modulate solar and terrestrial radiation, spatial heterogeneity of vegetation modulates the distribution and type of weather systems, and large-scale climates are sensitive to evapotranspiration, albedo and surface roughness.

Mid-Holocene climates of the northern tropics are seen primarily as a response to solar insolation (Kutzbach and Street-Perrott, 1985). Changes in insolation between 6 kyr BP and today should produce increased seasonality in the Northern Hemisphere and a decreased seasonal cycle in the Southern Hemisphere, if no other factors are important (Wasson, 1995). While this hypothesis was noted by COHMAP (1988), it has not received sufficient attention by examining Southern Hemisphere palaeoclimates in relation to Northern Hemisphere palaeoclimates. Other factors, such as vegetation—climate feedbacks, also need examination. This is the purpose of this paper, in a model-data comparison. It is recognised, however, that the results presented here represent hypotheses that at the moment are very difficult to test empirically. Broad agreement between model results and data are only one step towards testing the hypotheses.

2. Model results for 6 kya

An earth system model CLIMBER (CLIMate and BiosphERE) of intermediate complexity has been used by Ganopolski et al. (1998a, b) to simulate the mid-Holocene climate of the globe. The low spatial resolution of the model, 10° latitude and 51° longitude, allows both coarse comparisons of simulations with palaeodata and inclusion of feedbacks from vegetation that are missing in higher resolution models. CLIMBER does not use flux adjustments between atmosphere and

oceans. It uses a 2.5-dimension dynamical–statistical atmosphere model, and includes sea ice and vegetation models. Vegetation is simulated by the model, in contrast to biome-type models (e.g. Claussen and Gayler, 1997; Claussen et al., 1998).

Four simulations for 6 kya allowed identification of the hypothetical effect of vegetation. The simulations, shown in Fig. 1 (for a changed mean annual temperature in °C 6–0 kya) and Fig. 2 (for changed mean annual precipitation in mm/day 6–0 kya), are as follows:

- A Atmosphere model only; prescribed SSTs, sea ice and vegetation; vegetation cover from the control simulation which uses a fully coupled model, pre-industrial CO₂ and modern solar insolation.
- AO Coupled atmosphere–ocean model, vegetation fixed as in A; mid-Holocene orbital parameters; pre-industrial CO₂.
- AV Interactive vegetation, ocean characteristics fixed as in A; orbital parameters and CO₂ as in AO.
- AOV Fully coupled atmosphere–ocean—vegetation model; orbital parameters and CO₂ as in AO.

The fully coupled system (AOV) simulation showed pronounced annual warming in both hemispheres. In the Northern Hemisphere, temperature increased by about 1°C in both summer and winter compared to atmosphere–ocean (AO). Winter is warmer despite lower solar insolation. The warming in the model results from a decreased planetary albedo as the boreal forests expanded and subtropical deserts decreased in area. Warming in high northern latitudes was amplified by the sea–ice albedo feedback; annual sea–ice decreased by 25% compared to the control simulation. The ocean therefore absorbs more heat in summer and releases it to the atmosphere in autumn and winter; in the model.

This so-called biome paradox, which includes both vegetation and sea–ice feedbacks via albedo, indirectly affects the Southern Hemisphere because of annual mean global warming. While orbital forcing alone (A), as well as AO interaction, and atmosphere–vegetation (AV) interaction yield a marginal cooling in austral winter, and a slight cooling in austral summer, the AOV predicts a warming in austral winter and summer, mainly over the southern oceans. The link between Northern and Southern Hemispheres arises partly through the Atlantic thermohaline circulation and partly through increased global atmospheric water vapour concentration. In the Atlantic, the model reduces northward heat transport from the South to the North Atlantic by about 0.1PW owing to a reduction in the maximum oceanic overturning of up to 2Sv (see Fig. 4 of Ganopolski et al., 1998a, b). Also, Antarctic bottom water penetrates further north. The reduced thermohaline circulation is a result of freshening of the North Atlantic because of increased runoff

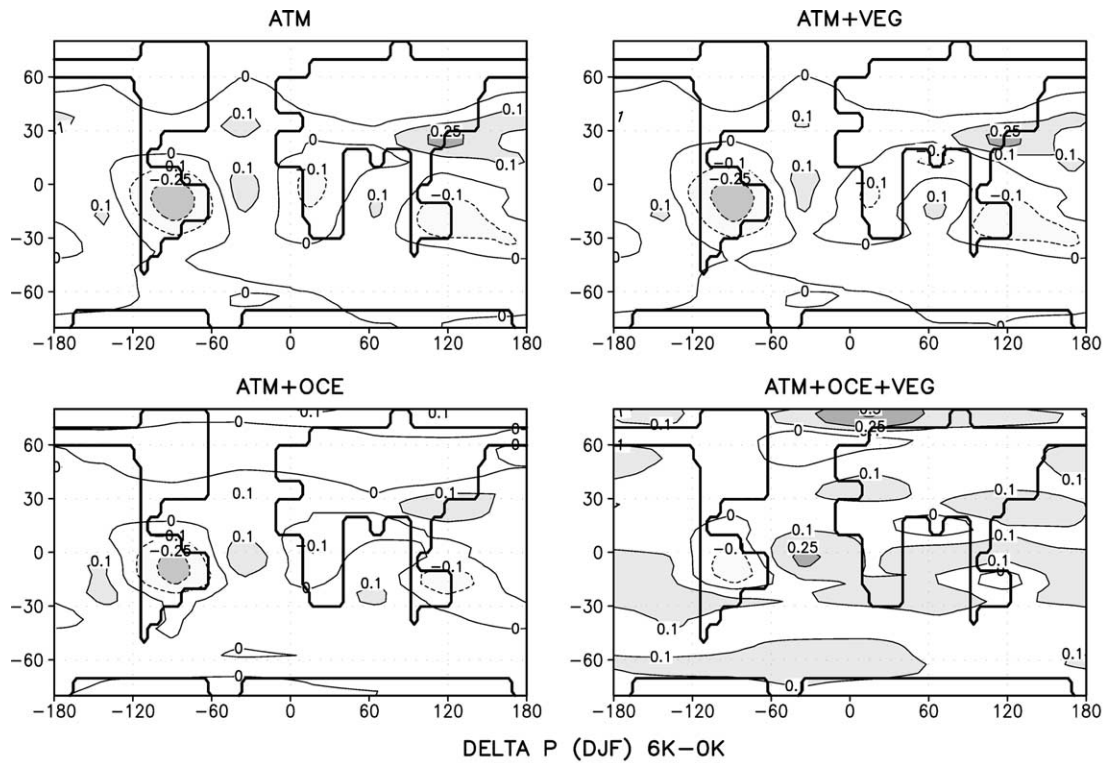


Fig. 1. Differences in boreal winter (December, January, February) mean temperatures between mid-Holocene (6000 years before present) and pre-industrial climate. The figure labelled ATM depicts results of the atmosphere-only model. For ATM+VEG and ATM+OCE, the atmosphere-vegetation model and the atmosphere-ocean model, respectively, was used. ATM+OCE+VEG refers to results obtained with the fully coupled model.

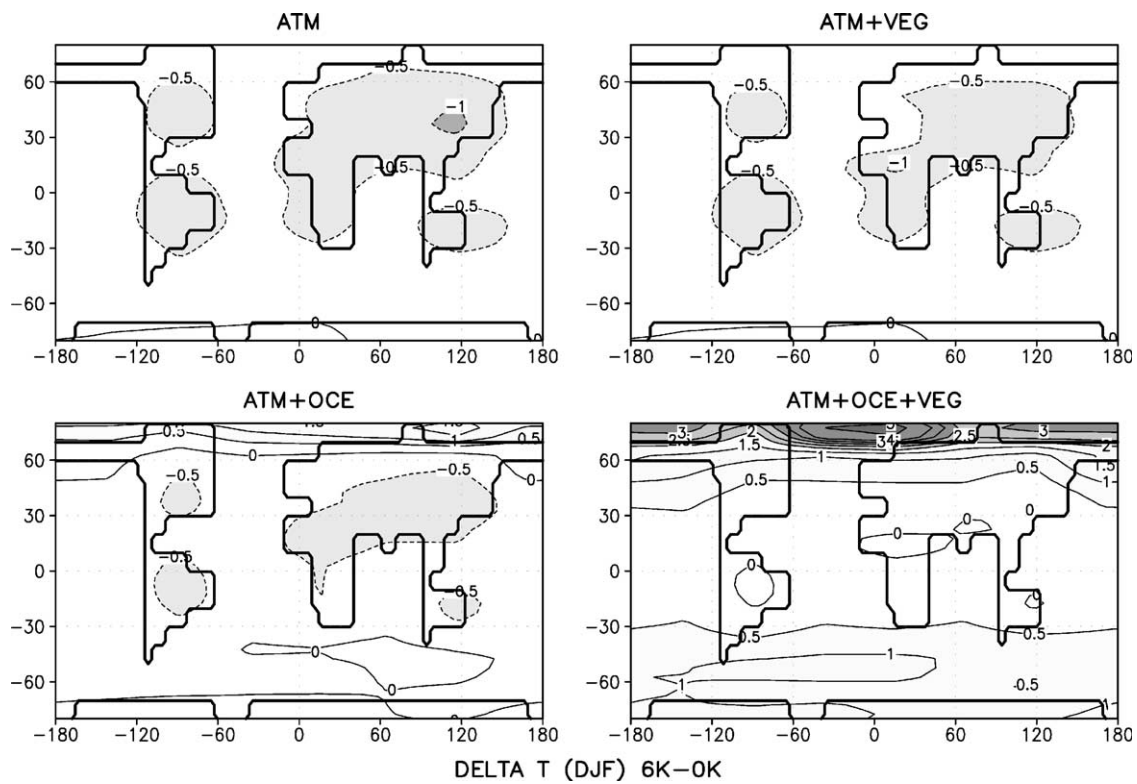


Fig. 2. Differences in boreal winter (December, January, February) mean precipitation between mid-Holocene (6000 years before present) and pre-industrial climate. The figure labelled ATM depicts results of the atmosphere-only model. For ATM+VEG and ATM+OCE, the atmosphere-vegetation model and the atmosphere-ocean model, respectively, was used. ATM+OCE+VEG refers to results obtained with the fully coupled model.

from the continents. Southern Hemisphere warming by 0.7°C in the annual mean results, with a maximum of more than 2°C near Antarctica.

Mid-Holocene insolation changes alone (AO) produce a global annual precipitation increase caused mainly by intensification of Northern Hemisphere summer monsoon in N. Africa, South and East Asia. The Southern Hemisphere continents become drier in annual averages in A and AO. In AOV, the Southern Hemisphere landmasses receive more precipitation, although in austral summer the Amazon Basin is drier in all simulations. In austral winter, the Amazon and Congo basins are considerably wetter than today, while only marginal differences from today can be seen for other Southern Hemisphere landmasses.

While further analysis of the model results is warranted, it appears that the increased precipitation over the Southern Hemisphere in austral summer in AOV is mainly caused by the summer warming of the southern oceans. $P-E$ is more negative over the southern Atlantic and Indian oceans, although precipitation changes little and may increase slightly over these areas on average. Hence evaporation in these regions of the southern ocean was stronger than today.

3. Palaeoclimate reconstructions

Detailed regional comparisons between palaeoclimate reconstructions and CLIMBER results are not warranted because of the coarse resolution of the model; as noted above. Broad patterns of past climates are therefore sought.

Wasson (1995) reviewed palaeoclimate reconstructions for the Asian Monsoon region. Results from Australian locations affected by the austral monsoon, from India, Arabia and the Arabian Sea, Tibet, China, Taiwan, Japan and SE Asia were summarised. Those sites which allowed estimates of $P-E$, or at least estimates of the sign of change of $P-E$ from today, were compiled in a histogram to allow comparison with lake level data compiled earlier by Kutzbach and Street-Perrott (1985) for the Northern Hemisphere tropics.

Both sets of data show the same broad features: rising moisture in the post-glacial to a peak in the early to mid-Holocene, followed by a drier period to the present. In both cases, the early to mid-Holocene was distinctly different from today, leaving clear evidence in lake shorelines and pollen spectra.

The Northern Hemisphere tropical lake level record shows a peak between ~9.5 and 6.5 kya, while in monsoonal Australia the peak is between 4 and 7 kya. In the Asian monsoon region the peak is between 5 and 7 kya, with a peak between 5 and 8 kya for the combined Australian–Asian monsoon region. With an uncertainty of 1.5 kya (Wasson, 1995), these records are statistically

identical. The null hypothesis, that the Northern and Southern Hemisphere records of $P-E$ are synchronous, cannot be rejected. Therefore, the expected strong hemispheric anti-phase relationship, if orbital forcing were the major factor in Holocene climate change, is not found.

Palaeotemperature records in Australia are not widespread for the Holocene, but pollen records from the Eastern Uplands show values ~1°C above present mean annual temperature in the mid-Holocene (Ross et al., 1992).

Building on earlier reviews, Partridge et al. (1990) compiled Holocene palaeoclimate reconstructions for Southern Africa as far north as 22°S. Their compilation is differentiated according to regions, showing geographic variations of both signs and apparent magnitude of change for different periods of the Holocene. Post-glacial warming continued during the early Holocene in some areas, culminating in a period when temperatures rose above the present mean. This is clearest in the Southern Cape and Eastern regions where warming peaked between 5 and 8 kya. Between 1 and 8 kya, wet conditions occurred in both of these regions, when drier conditions prevailed in both the Kalahari and the Namib Deserts (see Lancaster, and Thomas and Shaw, this volume). During the 5–8 kya temperature maximum, the Southern Cape and Karoo were drier than present, but the Kalahari and Eastern Cape were wetter. The Namib remained dry. Small changes in wetness occurred in all regions during the last 5 kya, and temperature varied by $\pm 2^\circ\text{C}$ from the present mean.

According to data available to Partridge et al. (1990), during the mid-Holocene, temperatures were generally higher than present; the southern-most areas were dry and the more northern regions were wetter; the Namib remained dry. Gingele (1996) presents additional evidence of an increase of river-derived clays in marine sediments, showing a marked period of increased river runoff from 9 to 5 kya, with a maximum between 6 and 5 kya.

Partridge et al. (1990) and Gingele (1996) interpret the increased moisture from 8 to 5 kya as a result of increased summer precipitation in the more northerly regions, with decreased winter precipitation at the same time. Gingele (1996) draws attention to synchronicity in overall climate between the Namib, South Africa, and the arid belts of Northern Africa. Gasse et al. (1989) draw attention to the same phenomenon.

Reconstructed palaeoclimate in South America, the third large Southern Hemisphere landmass, is more geographically diverse than elsewhere; perhaps because of the strong climatic influence of the Andes Mountains. Based upon 20 pollen records, supplemented by lake level records, Markgraf (1991) synthesised the Holocene palaeoclimate for most of South America south of 30°S. By 9 kya, west of the Andes, climate was drier than

today, with lakes at their Holocene minimum. East of the Andes, and at lower latitudes, moister conditions indicate that a summer precipitation regime had begun. At 6 kya, in the southern Andes at least, climate deteriorated to drier conditions. At low latitudes summer precipitation was higher. Overall, however, 5–6 kya was drier than present, but there is a hint of a similar latitudinal gradient of moisture regime change (between 6 kya and today) in both Southern Africa and South America. In southwestern Australia, there is some evidence for a mid-Holocene dry period in the present-day winter rainfall zone (Ross et al., 1992).

4. Discussion and conclusions

The hypothesis of insolation-driven changes in seasonality being out of phase in the two hemispheres during the mid-Holocene is not supported by palaeoclimatic reconstructions. Put another way, more suitable to those who prefer falsifiability as the key to science, the hypothesis that the climatic history of the two hemispheres was synchronous cannot be rejected on currently available evidence. A peak of moisture and, in many regions, temperature occurred in both hemispheres between 8 and 6 kya. There are significant regional departures from this pattern (the southern-most parts of Southern Africa and South America, southern India and eastern China) but the overall pattern is clear.

Orbital forcing alone is insufficient to explain Holocene climate changes. CLIMBER results indicate that global warming from albedo changes, induced by both vegetation change and sea-ice reduction, and greater heat transport to the southern oceans as a result of slowed thermohaline circulation, contributed to the synchronicity of climate change in the two hemispheres. Of course, solar insolation changes induced both vegetation and sea-ice changes in the Northern Hemisphere, but responses in the earth system were not a simple result of insolation changes.

A high resolution record of CO₂ in Taylor Dome ice, Antarctica (Indermühle et al., 1999) shows that CO₂ concentration in the atmosphere fell from 11 kya to a minimum at 8 kya, since when it has risen to its pre-industrial value. Indermühle et al. argue that these changes were driven by a combination of: growth of terrestrial biomass from 11 to 7 kya, then reduced terrestrial biomass from 6 to 1 kya as the globe's climate cooled and dried; increased sea-surface-temperature (SST) of ~0.5°C between 9 and 6 kya; and possibly slow re-equilibration between the ocean and sediment systems following deglaciation.

Broecker et al. (1999) explain the same rise of atmospheric CO₂ from 8 kya as a result of CaCO₃ compensation in the deep ocean. As vegetation spread rapidly after deglaciation, atmospheric CO₂ would have

declined, as shown in the Taylor Dome core, until at about 8 kya this regrowth phase ended. At this time, CaCO₃ compensation in the oceans would have re-established the steady state depth of the lysocline, thereby lowering the CO₃²⁻ concentration in the deep ocean and raising the CO₂ concentration of the atmosphere. This is consistent with the ice core CO₂ data.

The explanations offered by Indermühle et al. and Broecker et al. of the ice core data cannot be distinguished at the moment. As Broecker et al. point out, a high resolution and precise reconstruction of the δ¹³C for Holocene atmospheric CO₂ is required to make the distinction.

If, however, biomass changes explain the CO₂ changes in the Taylor Dome record, they must have occurred over a large part of the globe. Accompanying SST changes must also have been global, and CLIMBER may help us to understand the processes that led to these global changes. Or more accurately, CLIMBER allows hypotheses to be generated to more completely explain the changes.

Returning to Hayden (1998), it can be concluded that climate simulations, and therefore predictions, are likely to be inaccurate if vegetation is not properly considered. The extent to which this statement is correct deserves close attention, particularly in relation to deforestation in recent centuries and 'predictions' of climate over the next century.

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