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Separation of atmosphere-ocean-vegetation feedbacks and synergies for mid-Holocene climate

J. Otto,[1,2] T. Raddatz,[1] M. Claussen,[1,3] V. Brovkin,[1] and V. Gayler[1]

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[1] We determine both the impact of atmosphere-ocean and atmosphere-vegetation feedback, and their synergy on northern latitude climate in response to the orbitally-induced changes in mid-Holocene insolation. For this purpose, we present results of eight simulations using the general circulation model ECHAM5-MPIOM including the land surface scheme JSBACH with a dynamic vegetation module. The experimental set-up allows us to apply a factor-separation technique to isolate the contribution of dynamic Earth system components (atmosphere, atmosphere-ocean, atmosphere-vegetation, atmosphere-ocean-vegetation) to the total climate change signal. Moreover, in order to keep the definition of seasons consistent with insolation forcing, we define the seasons on an astronomical basis. Our results reveal that north of 40°N atmosphere-vegetation feedback (maximum in spring of 0.08°C) and synergistic effects (maximum in winter of 0.25°C) are weaker than in previous studies. The most important modification of the orbital forcing is related to the atmosphere-ocean component (maximum in autumn of 0.78°C). **Citation:** Otto, J., T. Raddatz, M. Claussen, V. Brovkin, and V. Gayler (2009), Separation of atmosphere-ocean-vegetation feedbacks and synergies for mid-Holocene climate, *Geophys. Res. Lett.*, *36*, L09701, doi:10.1029/2009GL037482.

1. Introduction

[2] The mid-Holocene, around 6000 years before present (6 ka), is a common reference period to examine the climate response to changes in incoming solar radiation caused by variations in the Earth's orbit [*Braconnot et al.*, 2007a, 2007b]. The mid-Holocene orbital changes led to an increase in insolation during summer and beginning of autumn and a decrease in winter in the Northern Hemisphere compared to present day [*Berger*, 1978]. As a consequence, during the mid-Holocene the Northern Hemisphere summers were warmer than at present day as shown, e.g., by *Davis et al.* [2003] with pollen-based climate reconstructions. These reconstructions also indicate higher mid-Holocene annual mean temperatures for the high northern latitudes. The annual mean insolation, however, changed only marginally. Thus, the seasonal insolation changes amplified by feedbacks may have caused this annual mean signal. To test this assumption, we present results of a factor-separation technique applied to a state-of-the-art climate model.

[3] The climate of the high northern latitudes are controlled by several feedbacks involving, e.g., changes in the hydrological cycle, heat-flux or albedo. Two positive albedo-related feedbacks presumably have the strongest impact on climate in response to orbitally-induced changes: the taiga-tundra feedback and the sea ice-albedo feedback. The taiga-tundra feedback, includes that forest effectively masks out high albedo in comparison with tundra. A replacement of tundra by forest decreases the surface albedo during the snowy season which leads to a warming and favours further growth of boreal forest. The sea ice-albedo feedback functions in a similar way: a reduction in sea-ice cover in response to increasing temperatures leads to less sea ice and thus to lower surface albedo and further warming [*Harvey*, 1988]. The taiga-tundra and sea ice-albedo feedback may amplify each other and cause a more pronounced warming [*Claussen et al.*, 2006].

[4] However, such climate sensitivity to orbital forcing is not well understood. Previous studies on the impact of feedbacks altering the response of climate to mid-Holocene orbital forcing have shown differing results. A factor-separation technique [*Stein and Alpert*, 1993] can be used to estimate the role of feedbacks. So far, it has been applied only by studies with Earth system Models of Intermediate Complexity (EMICs). With the CLIMBER-2 model [*Ganopolski et al.*, 1998] showed that the synergy between the atmosphere-ocean and atmosphere-vegetation feedback is stronger than their pure contributions and that this synergy leads to an annual mid-Holocene warming.

[5] There are only few mid-Holocene simulations with General Circulation Models (GCMs) including dynamic representations of the global atmosphere, ocean and vegetation [*Braconnot et al.*, 2007a]. Using a GCM asynchronously coupled with a vegetation model and applying partly the factor-separation technique, *Wohlfahrt et al.* [2004] depict warmer mid-Holocene than pre-industrial climate throughout the year. They suggest that atmosphere-vegetation feedback and the synergy between atmosphere-vegetation and atmosphere-ocean feedback produce warming in all seasons. Their results suggest a stronger atmosphere-vegetation feedback but a weaker synergy than analysed by *Ganopolski et al.* [1998]. Results from the Paleoclimate Modeling Intercomparison Project (PMIP2) with EMICs and GCMs [*Braconnot et al.*, 2007a, 2007b] corroborate that the atmosphere-ocean feedback plays a major role in altering the response to insolation change. It is not possible to conclude on the relative role of the atmosphere-vegetation feedback from PMIP2-simulations. Notwithstanding, *Braconnot et al.* [2007b] assume that the magnitude of the atmosphere-vegetation feedback is smaller

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[1] Max Planck Institute for Meteorology, Hamburg, Germany.

[2] International Max Planck Research School on Earth System Modelling, Hamburg, Germany.

[3] Meteorological Institute, University of Hamburg, Hamburg, Germany.

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Table 1. Setup of Experiments

Experiment Name	Prescribed From Which Experiment	Length
	Pre-industrial	
0kAOV	–	620 years
0kAO	vegetation, *0kAOV*	620 years
0kAV	SST, sea ice, *0kAOV*	360 years
0kA	SST, sea ice, *0kAOV* vegetation, *0kAV*	140 years
	Mid-Holocene	
6kAOV	–	620 years
6kAO	vegetation, *0kAOV*	620 years
6kAV	SST, sea ice, *0kAOV*	360 years
6kA	SST, sea ice, *0kAOV* vegetation, *0kAV*	140 years

than previously discussed. None of the previous studies with GCMs followed consistently the factor-separation technique. We apply this technique to a complete set of simulations with a coupled atmosphere-ocean-vegetation GCM to separate the atmosphere-vegetation feedback and the atmosphere-ocean feedback from their synergy term.

2. Setup of Model Experiments

[6] We performed our numerical experiments with the atmosphere-ocean GCM ECHAM5-MPIOM including the land surface scheme JSBACH with a dynamic vegetation module. The spectral atmosphere model ECHAM5 was run in T31 resolution (approx 3.75°) with 19 vertical levels, the ocean model MPIOM in a resolution of roughly 3° and 40 vertical levels [*Jungclaus et al.*, 2006] without any flux adjustment. The land surface scheme JSBACH is presented by *Raddatz et al.* [2007]. It was extended with a dynamic vegetation module [*Brovkin et al.*, 2009]. The experiment set-up was designed to follow the factor-separation technique by *Stein and Alpert* [1993]. By applying this technique we are able to determine the contributions of interactions between different components of the climate subsystem and their synergistic effects to a climate change signal [*Berger*, 2001]. In this study, we focus on two interactions: the atmosphere-ocean and the atmosphere-vegetation feedback.

[7] Firstly, the four pre-industrial climate simulations were performed: an equilibrium atmosphere-ocean-vegetation simulation (*0*kAOV), an equilibrium atmosphere-ocean simulation (*0*kAO) with vegetation prescribed (as fraction of each vegetation type and of desert) from *0*kAOV, a simulation with interactive atmosphere and vegetation dynamics (*0*kAV) with sea-surface temperature (SST) and sea-ice cover prescribed as monthly mean values of the *0*kAOV-simulation, and an atmosphere-only simulation (*0*kA) preformed as *0*kAV but with vegetation prescribed from this run *0*kAV. Secondly, the mid-Holocene simulations were performed: *6*kAOV, *6*kAO, *6*kAV, *6*kA. These simulations were carried out in an analogous manner to the pre-industrial simulations but with respective mid-Holocene orbital parameters, and vegetation cover, the seasonal cycle of SST and sea-ice cover, if prescribed, were taken from the pre-industrial simulations (Table 1). Because of non-linearity in our model, we do not refer to only one control run in contrast to studies with EMICs.

[8] All simulations were performed with atmospheric CO_2 concentrations set to 280 ppm. The simulations with dynamic ocean were run for 620 years, with prescribed ocean accordingly shorter (Table 1). For the analysis, the last 120 years of all experiments were considered.

[9] With these simulations, we quantify the contribution of interactions between the atmosphere-ocean and atmosphere-vegetation dynamics to the mid-Holocene climate. The deviation between the fully coupled runs in terms of temperature (ΔAOV) contains all feedbacks and synergistic effects. It is obtained by

$$\Delta AOV = 6kAOV - 0kAOV. \tag{1}$$

The response of the atmosphere (ΔA) is determined as follows

$$\Delta A = (6kA - 0kA). \tag{2}$$

By comparing the results in AV and AO with those from A, it is possible to assess the contribution of the atmosphere-vegetation (ΔV) and the atmosphere-ocean feedback (ΔO):

$$\Delta V = (6kAV - 0kAV) - (6kA - 0kA) \tag{3}$$

$$\Delta O = (6kAO - 0kAO) - (6kA - 0kA). \tag{4}$$

The synergistic effects (ΔS) between atmosphere-vegetation and atmosphere-ocean feedback can be quantified as the difference between ΔAOV and the sum of the three components atmosphere ΔA, ocean ΔO and vegetation ΔV:

$$\Delta S = \Delta AOV - \Delta A - \Delta O - \Delta V. \tag{5}$$

In order to keep the definition of seasons consistent with insolation forcing in pre-industrial and mid-Holocene climate, an astronomically based calendar is necessary [*Joussaume and Braconnot*, 1997]. Accordingly, we considered the seasons defined by astronomical dates: vernal equinox, summer solstice, autumn equinox, winter solstice. Since an astronomical calendar is not implemented in our model, we calculated the seasons from the daily output according to the model's astronomical parameters for pre-industrial and for mid-Holocene climate respectively [*Timm et al.*, 2008]. In previous mid-Holocene studies, seasons have been determined by monthly means which were computed with the present-day calendar. To compare our results with previous studies we shifted the seasons backwards by three weeks relative to the astronomical season. Seasonal averages are then computed from the daily output of the model for the pre-industrial and the mid-Holocene period, respectively.

3. Results

[10] Despite the small annual mean insolation anomalies in the northern latitudes (1.40 W/m^2, $\geq$40°N), the annual mean mid-Holocene temperature is distinctly increased in comparison to pre-industrial climate, which is in general agreement with, e.g., climate reconstructions for Northern Europe [*Davis et al.*, 2003]. The fully coupled model

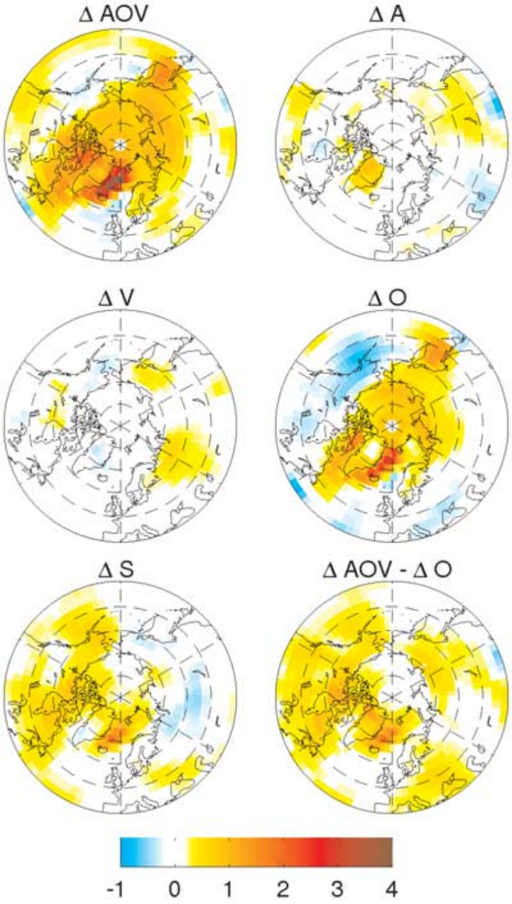

Figure 1. Annual mean 2m-temperature anomalies (°C) between 6 ka and 0 ka according to ΔAOV, ΔA, ΔV, ΔO and ΔS.

including all feedbacks and synergies shows a general annual mid-Holocene warming with values of up to 4°C around Greenland (Figure 1, ΔAOV). The temperature pattern in Figure 1 (ΔA) shows the response of the atmosphere only to the orbital signal without atmosphere-ocean and atmosphere-vegetation feedbacks. It results in a slight warming but only for the continents with maximum values in Greenland of up to 1°C (Figure 1, ΔA). This reveals that the larger obliquity results in a weak annual temperature increase. Vegetation dynamics also leads to continental warming (Figure 1, ΔV), however it is less pronounced. Compared to ΔA, vegetation dynamics leads to a warming of west Siberia with maximum values of up to 0.6°C and a cooling of Greenland. The atmosphere-ocean feedback ΔO (Figure 1, ΔO) however shows a slightly cooler but similar temperature pattern as the fully coupled model (Figure 1, ΔAOV and $\Delta AOV - \Delta O$). The synergy ΔS (Figure 1, ΔS) between atmosphere-vegetation and atmosphere-ocean feedback adds additional warming with maximum values of up to 2°C around Greenland. The separation technique reveals that mean annual warming is not only caused by larger obliquity and changes in precession but rather by the atmosphere-ocean feedback and the synergy between the atmosphere-ocean and the atmosphere-vegetation feedback.

[11] To analyse the climatic response to change in orbital forcing more closely, we focus on the seasonal cycle of temperature. Figure 2 depicts the seasonal cycle of the 2m-temperature of ΔAOV together with contributions of the single feedbacks ΔA, ΔO, ΔV and their synergy ΔS. Our results show an amplification of the seasonal cycle of the Northern Hemisphere 2m-temperature ($\geq 40°$N), as expected from the orbital-induced change in insolation. This is characterised by increased 2m-temperature in summer, autumn and winter, and its decrease in spring (Figure 2a). The direct response of the atmosphere (ΔA) to the change in insolation produces a summer warming of 1.18°C which slightly decreases in autumn to 0.75°C. However, winter and spring seasons show a cooling of −0.18°C and −0.19°C respectively. The atmosphere-vegetation feedback ΔV is rather marginal. In spring and summer it leads to a slight warming of 0.08°C and 0.06°C respectively counteracting to the insolation changes. Atmosphere-ocean feedbacks amplify the response to the orbital forcing in spring and autumn and counteract the direct response slightly in summer and more strongly in winter. The ocean's influence on the warming of the northern latitudes is strongest in autumn (0.78°C), reflecting the orbitally induced increase in summer and autumn insolation. The atmosphere-ocean contribution continues with 0.30°C in winter, resulting likely from the thermal inertia of the ocean that introduces a lag between the season cycle of insolation and oceanic response by approximately one season. The synergy between the atmosphere-ocean and atmosphere-vegetation feedback results in slight warming for all seasons. The maximum contribution of the synergy occurs in autumn and winter with warming of 0.24°C and 0.25°C respectively; the weakest in summer with 0.09°C.

[12] In summary, the seasonal temperature pattern shows that the atmosphere-ocean feedback modulates the mid-Holocene insolation forcing whereas the amplifying prevails over damping. The contribution of the atmosphere-vegetation feedback remains marginal throughout the year. The synergy between the atmosphere-ocean and atmosphere-vegetation feedback however leads to a slight warming in all seasons.

4. Discussion

[13] Our results reveal that atmosphere-ocean and atmosphere-vegetation feedback and their synergy modify the orbitally-induced pattern of seasonal temperature considerably. The modification leads to an annual mean warming in the high latitudes of 0.44°C (Figure 2a). Results of the model CLIMBER-2 for the Northern Hemisphere [*Ganopolski et al.*, 1998] and the IPSL model [*Wohlfahrt et al.*, 2004] north of 40°N show a considerably stronger annual warming of up to 1°C. Besides, the seasonal temperature signals differ in phase and magnitude. Our model shows that the maximum warming occurs in autumn, contrary to previous studies [*Gallimore et al.*, 2005; *Wohlfahrt et al.*, 2004] which suggest a maximum warming in summer. Figure 2a shows that the atmosphere autumn response is doubled by the amplification of the atmosphere-ocean interactions. *Wohlfahrt et al.* [2004] however suggest a cooling of the atmosphere already in autumn. One important factor influencing the differing results is that we

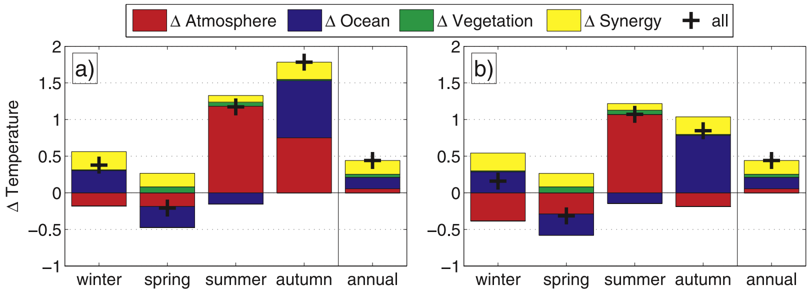

Figure 2. Seasonal temperature anomalies (°C) between 6 ka and 0 ka of the coupled simulations ΔAOV (+) and the contributions of the factors ΔA (red), ΔV (green), ΔO (blue) and ΔS (yellow) to the signal in seasonal temperature, NH $\geq$ 40°. (a) Seasons are defined on an astronomical basis. Note: Because of the astronomically based calendar, the length of the seasons differ between 0 k and 6 k. Thus the annual mean is not the linear average of the seasonal means. (b) Seasons are defined by present-day calendar but the date of the vernal equinox is fixed on the 21 March (as done by PMIP2-simulations).

define our seasons on an astronomical basis [*Timm et al.*, 2008]. Analyses by *Wohlfahrt et al.* [2004] for instance followed the PMIP set-up with the date of the vernal equinox fixed on 21 March. Seasonal values based on this method underestimate changes in the Northern Hemisphere in autumn [*Braconnot et al.*, 2007a] which amounts to 0.9°C according to our data processed with the PMIP-method (Figure 2b).

[14] The atmosphere-vegetation feedback in our model is weaker than in previous studies [*Gallimore et al.*, 2005; *Wohlfahrt et al.*, 2004]. In general, this feedback on temperature is induced by a northward shift of forest due to warmer mid-Holocene summer and autumn. It can be expected to be strongest in spring time through the snow masking of forest. Both the AOV-model (1.4×10^6 km^2, $\geq$60°N, see auxiliary material[1]) and the AV-model (1.2×10^6 km^2, $\geq$60°N) show a considerable northward extension in forest for mid-Holocene which is in general agreement with previous results [*Wohlfahrt et al.*, 2008] and reconstructions [*Bigelow et al.*, 2003]. Despite this shift of forest, the atmosphere-vegetation feedback counteracts the insolation reduction in spring only marginally. During this season the change in forest leads to a reduction in albedo on average of 0.02 ($\geq$60°N) which is due to the snow masking of trees. This area shows a warming between 0.4 – 1.3°C, other regions with no change in land cover (e.g., Greenland) show cooling (not shown). The mean over the whole area results in such a weak warming. This result corroborates the conclusions of the PMIP2 study [*Braconnot et al.*, 2007b], that the magnitude of the atmosphere-vegetation feedback is smaller than previously discussed.

[15] Concerning the atmosphere-ocean feedbacks including the sea ice-albedo feedback, the mid-Holocene simulations show less sea-ice cover compared to the pre-industrial simulations (see auxiliary material), which is in agreement with previous studies [*Ganopolski et al.*, 1998; *Braconnot et al.*, 2007b]. The orbitally induced increase in solar radiation during summer and autumn melts more sea-ice and warms up the ocean more strongly than in the pre-industrial climate. During autumn and winter, the ocean releases this heat to the atmosphere, resulting in higher air-temperatures compared to pre-industrial autumn and winter.

[16] The positive taiga-tundra feedback and the positive sea ice-albedo feedback may strongly reinforce each other as both work at high northern latitudes. Despite the weak atmosphere-vegetation feedback, our simulations feature some positive synergistic effect between the atmosphere-ocean and atmosphere-vegetation feedback. However, the magnitude is smaller than simulated by *Ganopolski et al.* [1998] and *Wohlfahrt et al.* [2004]. This corroborates results obtained with the EMIC MoBidiC for 9 ka [*Crucifix et al.*, 2002]. They suggest that a key point for this low synergy may be the differing sea-ice sensitivities between models. Another explanation for our ocean model with higher resolution may be that the main changes in sea-ice and forest cover occur spatially separated.

5. Summary and Concluding Remarks

[17] We determine the response of climate to mid-Holocene insolation and the impact of atmosphere-ocean and atmosphere-vegetation feedbacks and their synergy on the northern latitude climate. Our model reproduces the basic picture of differences between the pre-industrial and mid-Holocene climate obtained from previous model studies but relates these changes to the components of the climate system in quite a different way. It simulates the mid-Holocene climate as follows: The direct atmospheric response to the orbital forcing is the most important cause of summer and autumn warming in the northern latitudes. The spring cooling is amplified by the atmosphere-ocean feedback most strongest. In autumn, the ocean duplicates the atmospheric warming and in winter, the ocean plays the most important role for the warming in this region. The contribution to the temperature signal from atmosphere-vegetation feedbacks is marginal and leads to a weak synergy between the atmosphere-vegetation and atmosphere-ocean feedback. To summarise, the warming of the northern latitudes during mid-Holocene can only be understood if all components of the Earth system model are taken into account. The atmosphere only explains a marginal warming of 0.05°C annual mean temperature. The contribution of the atmosphere-ocean and atmosphere-vegetation feedback and their synergy, however, lead to an additional

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL037482.

warming of 0.39°C. The most important modification of the orbital forcing can be related to the atmosphere-ocean interactions, likely as a consequence of its thermal inertia and the sea-ice albedo feedback. However, it should be kept in mind that feedbacks and their synergy are presumably strongly influenced by climate variability [*Rimbu et al.*, 2004]. Thus, the magnitude of the feedbacks may depend on the length of the analysis period.

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V. Brovkin, M. Claussen, V. Gayler, J. Otto and T. Raddatz, Max Planck Institute for Meteorology, Bundesstraße 55, D-20146 Hamburg, Germany. (juliane.otto@zmaw.de)