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Detecting vegetation-precipitation feedbacks in mid-Holocene North Africa from two climate models

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Abstract

Using two climate-vegetation model simulations from the Fast Ocean Atmosphere Model (FOAM) and the Community Climate System Model (CCSM, version 2), we investigate vegetation-precipitation feedbacks across North Africa during the mid-Holocene. From mid-Holocene snapshot runs of FOAM and CCSM2, we detect a negative feedback at the annual timescale with our statistical analysis. Using the Monte-Carlo bootstrap method, the annual negative feedback is further confirmed to be significant in both simulations. Additional analysis shows that this negative interaction is partially caused by the competition between evaporation and transpiration in North African grasslands. Furthermore, we find the feedbacks decrease with increasing timescales, and change signs from positive to negative at increasing timescales in FOAM. The proposed mechanism for this sign switch is associated with the different persistent timescales of upper and lower soil water contents, and their interactions with vegetation and atmospheric precipitation.

1 Introduction

Vegetation interactions/feedbacks have received tremendous attention in modern climate (Charney et al., 1975, 1977; Schlesinger et al., 1990; Pielke et al., 1998; Brovkin 2002) and paleoclimate (Kutzbach, 1981; Kutzbach et al., 1996; Ganopolski et al., 1998; Claussen et al., 1999, 2003; Foley et al., 2003; Wang et al., 2005a, b; Wang and Mysak, 2005) studies. Previous understanding (Charney et al., 1975, 1977; Woodward et al., 1998; Box 2-6 in Ruddiman, 2001) largely emphasized that those interactions played an important role in amplifying initial climate perturbations (i.e., positive feedbacks). Using a statistical method (see Liu et al., 2006a, Notaro et al., 2006 for detailed methodology), we present a negative vegetation-precipitation feedback at the annual timescale from two mid-Holocene simulations with FOAM (Galimov et al., 2005), and CCSM2 (Levis et al., 2004), both of which are coupled with

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the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM, Sitch et al., 2003).

In semiarid areas, the dynamics of the simulated hydrologic cycle is partially governed by the interplay between transpiring water in vegetated areas and surface evaporation from bare soils (Dirmeyer, 1994; Sellers et al., 1997). One of the two underlying processes is that when vegetation cover increases, ground evaporation decreases (mainly because there is less energy reaching the soil) and transpiration increases (because there is more vegetation). In our experiments, the imbalance of a large bare ground evaporation over transpiration under fully wet soil conditions in mid-Holocene can produce a local enhancement of rainfall for bare soil condition compared to vegetated condition (i.e., negative feedback). A previous study (Doherty et al., 2000) with the GENESIS climate model (Thompson and Pollard, 1997) detected weak or insignificant vegetation feedback in amplifying precipitation in eastern North Africa. Furthermore, Levis et al. (2004) also mentioned in their 50-year “6K6V” simulation that there may have been a weak negative precipitation feedback in North Africa. Furthermore, a recent observational study (Wang et al., 2006) detected that at different timescales, the sign of vegetation-precipitation interactions may change with their statistical model. Previous mid-Holocene studies (Cooperative Holocene Mapping Project (COHMAP), 1988; BIOME 6000, Prentice and Webb, 1998) indicated that soil in mid-Holocene North Africa was wetter and darker than that in pre-industrial and present-day conditions. Vegetation, mainly grassland, extended farther north into the present-day Sahara Desert (Gasse, 2000, 2002). Under such a distinct climate background, vegetation feedbacks are quite different than present-day (Liu et al., 2006a).

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2 Model description, experimental design and outline of methodology

2.1 Model description and experimental design

The coupled atmosphere-ocean component is FOAM version 1.5. The atmosphere module has a horizontal resolution of R15 (48 longitudes, 40 latitudes) and 18 vertical levels. The ocean component has a horizontal resolution of 128×128 and 32 vertical levels. The LPJ module has been synchronously coupled with FOAM (see Gallimore et al., 2005 for more details). The simulated vegetation pattern agrees with satellite observation (Notaro et al., 2005) and other vegetation model simulations (Cramer et al., 2001). The mid-Holocene simulation of CCSM2 (Holland, 2003) consists of a 350-year integration with orbital forcing prescribed at 6000 years before present (hereafter 6 ka) with atmospheric CO₂ fixed (280 ppmv), which was extended from the “6K6V” simulation in Levis et al. (2004). The CCSM2 is a fully coupled atmosphere-ocean-land surface-vegetation climate model (see Holland, 2003; Levis et al., 2004 for more details), and is run at T31 (3.75 in longitude by 3.75 in latitude) resolution. A typical difference between FOAM and CCSM2 is their soil modules. CCSM2 has ten soil layers, while FOAM only has two soil layers.

The FOAMPLJ Holocene transient simulation (Liu et al., 2006b; Liu et al., 2007) restarts from the end of the mid-Holocene snapshot run (see Gallimore et al., 2005 for more details), and is integrated from 6.5 ka to pre-industrial (0 ka) with varying orbital forcing (Berger, 1978) and fixed CO₂ (280 ppmv) without flux corrections. This experiment set-up allows us to focus on the insolation forcing without considering other external (solar and CO₂ variability) and internal (volcano) forcings.

2.1.1 Outline of methodology

Following the methodology in Frankignoul and Hasselmann (1977), Liu et al. (2006a) and Notaro et al. (2006), atmospheric variables (precipitation, temperature, evapotran-

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spiration etc.) can be divided into two components:

$$A(t + \delta t_a) = \lambda_V V(t) + N(t + \delta t_a) \quad (1)$$

where $A(t)$ represents atmosphere variables at time t , $V(t)$ is vegetation variables at time t , λ_V is the feedback parameter, δt_a is the atmospheric response time, and $N(t)$ is the atmospheric noise from internal atmospheric processes that are independent of vegetation variability. Following the method of Frankignoul et al. (1998), we have:

$$\lambda_V = \frac{\text{cov}[A(t), V(t - \tau)]}{\text{cov}[V(t), V(t - \tau)]} \quad (2)$$

where τ is the lag time, which is longer than the persistence time of atmospheric internal variability. The feedback parameter λ_V is calculated as the ratio of lagged covariance between A and V to the lagged covariance of V . When calculating the feedback parameter, we employed the weighted average from the first three lags (e.g., year one, two and three lags for annual timescale) with weights of 1.0, 0.5 and 0.25, respectively.

Furthermore, the statistical significance of λ_V can be assessed by the Monte Carlo bootstrap approach (Czaja and Frankignoul, 2002). λ_V is computed 1000 times, each using an atmospheric time series derived from a random permutation of the original time series A_t . The accumulative probability produced is then used to judge the significance of λ_V .

3 Results

Following the early work of Frankignoul et al. (1998), the vegetation feedback has been assessed with a simple linear statistical method (Liu et al., 2006a). Figure 1 indicates the distribution of total vegetation, grassland and the averaged feedback parameter between total vegetation cover and annual precipitation from CCSM2 and FOAMPLPJ mid-Holocene snapshot runs. In the mid-Holocene total vegetation cover, mainly perennial grassland, has extended farther north into the Sahara region in both models (figures

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not shown here for vegetation/grassland changes between mid-Holocene and pre-industrial). The negative feedback zone matches well with the grassland area, with a magnitude from 1 to about 15 mm/year/0.1 fractional coverage for CCSM2, and from 5 to about 30 mm/year/0.1 fractional coverage for FOAMLPJ. Overall, CCSM2 indicates a slightly weaker negative feedback than FOAMLPJ, although both are statistically significant (see Figs. 1d and h). To test the statistical significance, we randomly reorganize the annual precipitation, and create 1000 sets for both simulations. We recalculate the new feedback parameters with randomly-ordered annual precipitation, and compared them with those presented in Figs. 1c and g. With 80% and 90% confidence levels, we declare that the negative feedback is of statistical significance in both simulations in the North African semiarid grassland areas.

With a detailed feedback analysis, we find that the main source of negative feedback comes from bare-ground evaporation (Fig. 2). Note that the total moisture flux, namely evapotranspiration, is equal to the sum of bare-ground evaporation and transpiration from vegetated surfaces. The transpiration term is always positively related to vegetation change. However, among other factors, the total moisture flux depends strongly on the competition of bare-ground evaporation and transpiration from vegetated surfaces. In semi-dry grassland areas, if the soil is wet and dark, as in mid-Holocene condition, the first term becomes the same/more important as/than the second term, which causes the strong coincidence of grassland and negative feedback area. Charney's albedo change theory does not work out here because the albedo change from grassland to wet/dark soil is small in mid-Holocene. Hence the pre-condition of a large surface albedo change from deserted (bare-ground) and vegetated surfaces does not apply. Furthermore, a map of feedback parameters between total vegetation and evapotranspiration (Figs. 2c and f) indicates that the negative feedback mainly caused by the increase of bare-ground evaporation, overcomes the reduction of transpiration. We speculate that this may be partially related to the evaporation from a wetter and darker soil in mid-Holocene climatic conditions. When we analyze pre-industrial snapshot simulations from both CCSM2 (Levis et al., 2004) and FOAMLPJ, the negative feedback

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almost disappears (figures not shown) when the soil becomes drier and lighter.

In the 6500-year transient simulation of FOAMLPJ, we also capture a similar negative feedback and statistical significance as above (figure not shown). In this transient run, we reproduce a vegetation (mainly grassland) collapse at around 5000 years ago (Liu et al., 2006b; Liu et al., 2007), which is in good agreement with the paleoreconstruction work of deMenocal et al. (2000). Accompanying this ecosystem collapse is a gradual decline in annual precipitation (see Figs. 1b and c in Liu et al., 2006b). If the vegetation had a strong positive feedback on annual precipitation, we would expect a similar abrupt change in precipitation. This feature further confirms our finding of a negative interaction between vegetation and precipitation in North African grasslands in the mid-Holocene.

However, when analyzing monthly feedback parameters, the two climate vegetation models show slightly different features (Fig. 3). With monthly FPAR (Fraction of Photosynthetically Active Radiation, an indication of greenness for vegetation) and monthly precipitation from FOAMLPJ, we find that the feedback changes sign at different timescales. At monthly to seasonal timescales, the vegetation (FPAR) has positive feedbacks to atmospheric precipitation at the same timescale, which is indicated by the positive interaction between leaf phenology and precipitation. However, at semi-annual and annual timescales, the feedback parameter becomes negative. We speculate that this is partially caused by the interaction between top and lower layer soil water contents, their different persistent times, and effects on atmospheric precipitation (see Notaro et al., 2007¹ for more details). In early spring, a high FPAR in FOAM can induce large transpiration from deep soil water and hence greater precipitation for the following month when the top soil layer is still dry. For CCSM2, this sign change feature is not obvious, although it shows a decreasing trend of feedback with increasing timescales as in FOAMLPJ. The less positive vegetation precipitation feedback in North Africa in

¹Notaro, M., Wang, Y., Liu, Z., Gallimore, R., and Levis, S.: Statistical and dynamical assessment of a simulated negative vegetation feedback on North African precipitation during the Mid-Holocene, *Global Change Biology*, under review, 2007.

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CCSM2 than in FOAM has also been found in Liu et al. (2006a). We speculate that this is caused by the different soil components in these two climate models as mentioned before.

4 Concluding remarks

5 We have presented three important findings with two fully-coupled atmosphere-ocean-land surface-vegetation climate model simulations in the mid-Holocene. First, a negative feedback between vegetation and precipitation mainly occurs in the mid-Holocene, when the overall climate and soil are wetter and darker than pre-industrial and present-day conditions. Second, the negative feedback is partially caused by the competition
10 between ground evaporation and transpiration from vegetated surfaces. In the mid-Holocene, the first term has a stronger effect upon moisture fluxes than the second term, although we agree that this may be model dependent. Lastly, at monthly to seasonal timescales, the vegetation precipitation feedback is still positive for FOAM. The feedback changes its sign from positive to negative when moving from monthly
15 and seasonal to semi-annual and annual timescales. This sign change feature is not present in CCSM2, possibly due to different soil module components. However, both climate models have the same decreasing trend of feedback when timescales are increasing.

20 When the large-scale background climatic conditions change from wetter to drier from the mid-Holocene to pre-industrial and/or present-day, the negative feedback almost disappears. This confirms that the background climate is important when studying vegetation climate interactions. The former theory of Charney et al. (1975, 1977), based on the large difference of surface albedos between vegetated and desert areas, may only apply to present-day conditions in North Africa because this albedo change is
25 negligible in the mid-Holocene when the soil is wet and dark. Bare ground evaporation is also much weaker than transpiration in modern times due to the dry soil condition. However, in the mid-Holocene, the bare ground evaporation becomes as important as

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transpiration. Furthermore, the previous understanding of interactions between vegetation and precipitation may not change at different timescales. As shown in this paper and a recent observational study (Wang et al., 2006), when moving to different timescales, these interactions could be both positive and negative.

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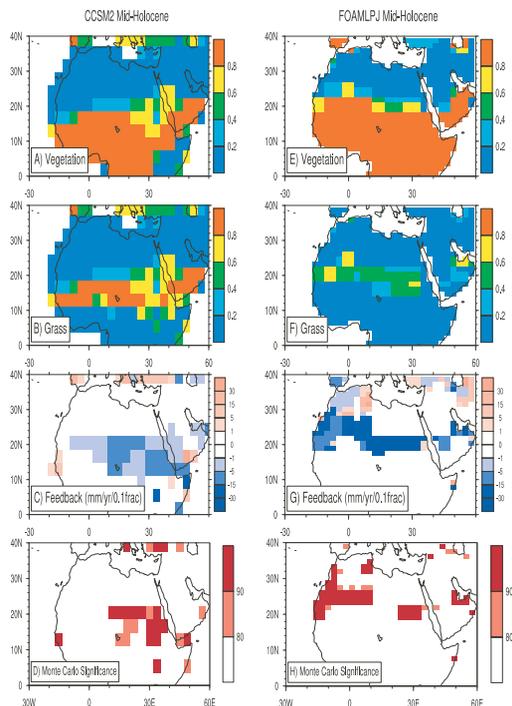


Fig. 1. Mid-Holocene total vegetation fraction for **(A)** CCSM2 and **(E)** FOAMLPJ; mid-Holocene grassland coverage for **(B)** CCSM2 and **(F)** FOAMLPJ. Estimated feedback parameters ($\text{mm}/\text{year}/0.1$ fraction) between total vegetation fraction and annual precipitation (Eq. 2) for **(C)** CCSM2 and **(G)** FOAMLPJ mid-Holocene snapshot runs. Statistical (Monte-Carlo) significance of feedback parameters for **(D)** CCSM2 and **(H)** FOAMLPJ. In calculating the feedback parameters, we constrain the range of parameter from -60 to 60 $\text{mm}/\text{year}/0.1$ fraction. We did this because in cases when the denominator of Eq. (2) becomes small (low vegetation auto-correlation), the estimated feedback parameter becomes a huge, unreliable number. We also use 9-gridcell averaging to smooth the feedback parameters here and in Fig. 2.

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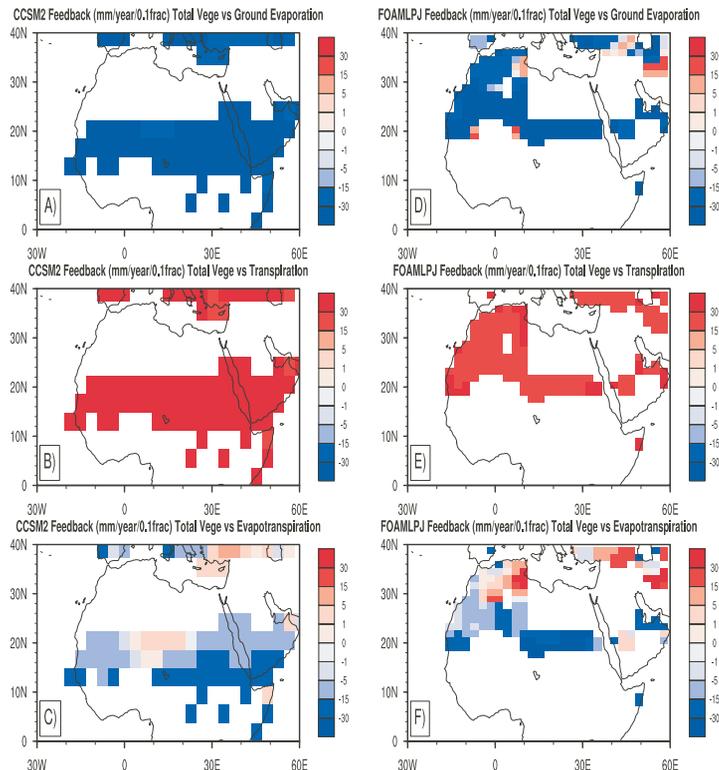


Fig. 2. Estimated feedback (Eq. 2) between total vegetation fraction and ground evaporation (mm/year/0.1 fraction) for **(A)** CCSM2 and **(D)** FOAMLPJ from mid-Holocene snapshot runs. Estimated feedback between total vegetation fraction and transpiration (mm/year/0.1 fraction) for **(B)** CCSM2 and **(E)** FOAMLPJ from mid-Holocene snapshot runs. Estimated feedback between total vegetation fraction and evapotranspiration (mm/year/0.1 fraction) for **(C)** CCSM2 and **(F)** FOAMLPJ from mid-Holocene snapshot runs. Note that, as in Fig. 1, the three leads averaging with same weights is used.

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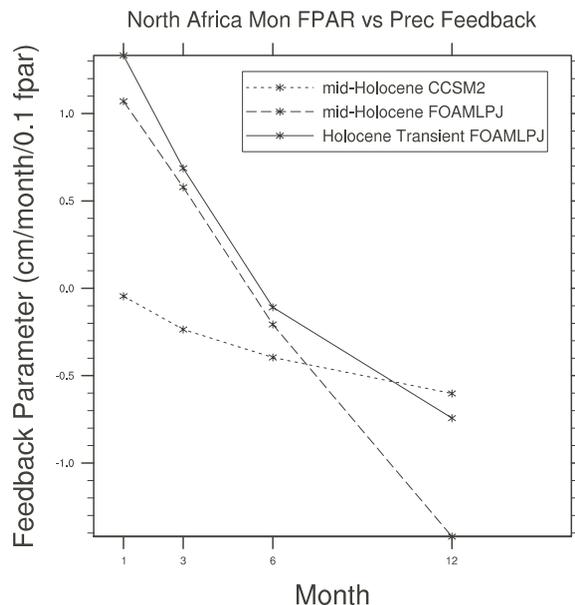


Fig. 3. Area-averaged feedback parameters (18–23 N, 11–36 E for FOAML PJ, 11–22 N, 11–36 E for CCSM2), calculated from monthly FPAR and atmospheric precipitation, when we bin individual monthly data into one-month, three-month, six-month, and twelve-month timeseries. Dashed line is for mid-Holocene snapshot run of FOAML PJ and CCSM2. Solid line is for transient Holocene run from 6000 to 5500 years BP of FOAML PJ.

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