Remote vegetation feedbacks and the mid-Holocene Green Sahara

ABIGAIL L. S. SWANN, *

Atmospheric Sciences, University of Washington

INEZ Y. FUNG,

Earth and Planetary Science, University of California, Berkeley

YUWEI LIU, AND JOHN C. H. CHIANG

Geography, University of California, Berkeley

*Corresponding author address: Abigail Swann, University of Washington, Atmospheric Sciences, Box 351640, Seattle, WA 98102-1640.

E-mail: aswann@u.washington.edu
ABSTRACT

In the mid-Holocene, the climate of Northern Africa was characterized by wetter conditions than present, as evidenced by higher paleo lake-levels and pollen assemblages of savannah vegetation suggesting a wetter, greener Sahara. Previous modeling studies have struggled to simulate sufficient amounts of precipitation when considering orbital forcing alone, with limited improvement from considering the effects of local grasslands. Here we propose that remote forcing from expanded forest cover in Eurasia relative to today is capable of shifting the Intertropical Convergence Zone northward, resulting in an enhancement in precipitation over Northern Africa ~6000 years ago greater than that resulting from orbital forcing and local vegetation alone. We demonstrate that the remote and local forcing of atmospheric circulation by vegetation can lead to different dynamical patterns with consequences for precipitation across the globe. These ecoclimate teleconnections represent the linkages between the land surface in different regions of the globe and by inference show that proxy records of plant cover represent not only the response of vegetation to local climate but also that vegetation’s influence on global climate patterns.
1. Introduction

Paleo-proxy records based on pollen assemblages are commonly used to indicate local climate conditions of the past based on the environmental constraints of the pollen producing plants. Given a sufficient network of plant cover information, a picture of climate emerges. This view is necessarily one-sided, with the assumption being that climate determines plant cover. The observed plant cover itself, while in energy balance with local climate, may be forcing climate both locally and remotely through ecoclimatic teleconnections, i.e. by changing large-scale thermal and energy gradients and hence atmospheric circulation. As the paleo-proxy records do not provide complete coverage in the spatial domain, we do not have a full picture of climate globally at any time in the past. We suggest that the influence of vegetation on atmospheric circulation patterns can be used to paint a broader view of global climate conditions. Here we show that the remote and local forcing of atmospheric circulation by vegetation leads to different dynamical circulation patterns with consequences for precipitation across the globe. Additionally, by considering ecoclimatic teleconnections, knowledge of vegetation cover in one region in the past can lead to additional, testable hypothesis about climate in other parts of the globe.

a. The ‘Green Sahara’ Problem

As an example for how vegetation cover can be used to understand climate patterns beyond the region they cover, we will consider here the “Green Sahara” problem. Paleo-proxy records indicate that North African climate was more humid during the mid-Holocene, approximately 6000 years ago, compared to today (McIntosh and McIntosh 1981; Ritchie et al. 1985; Petit-Maire and Guo 1996). Evidence for wetter conditions across what is now the Sahara desert include higher paleo lake levels (Street and Grove 1979; Street-Perrott and Perrott 1993) and, of particular interest to this study, pollen records indicate that the Sahara desert supported vegetation during the mid-Holocene (Hoelzmann et al. 1998;
Joussaume et al. 1999) with Sahel-like vegetation as far north as at least 23°N (Jolly et al. 1998b).

There are two broad categories of mechanisms that have been invoked to explain how the Sahara was capable of maintaining sufficient precipitation for vegetation in the mid-Holocene. First, the orbital forcing in the mid-Holocene was such that the earth was slightly closer to the Sun in the Northern Hemisphere summer and farther in the winter compared to present day (Berger 1978). This leads to an increase in the seasonality of temperature in the Northern Hemisphere with warmer summers and cooler winters as well as a farther northward push of the Hadley circulation during Boreal summer (Kutzbach 1981; Braconnot et al. 2007a).

Second, the Charney hypothesis (Charney et al. 1975; Charney 1975) suggests that the contrast in surface albedo between a bright desert and a dark ocean surface maintains an east-west circulation cycle with updraft over the ocean and enhanced downwelling of dry air over the desert. If the Sahara were instead vegetated, the surface would be darker, thus reducing the land-ocean albedo contrast and subsequently the zonal circulation. If the Sahara were somehow vegetated, it may maintain its own precipitation by decreasing the downwelling of dry air relative to the desert state. While Charney was not referring directly to the mid-Holocene green Sahara, his general hypothesis, that local surface albedo controls circulation and precipitation, is central to many arguments describing how what is currently the Sahara desert at one time supported green vegetation.

As we have noted, over the Sahara and present day Saudi Arabia, green vegetation was more widespread in the mid-Holocene relative to today (e.g Hoelzmann et al. 1998). In addition to a greener Sahara, vegetation distributions inferred from pollen records show that deciduous forests were widespread in the mid-latitudes, especially in Europe (Prentice et al. 1998). Relative to the present day, the distribution of grasslands in Eurasia was reduced, with deciduous forest in its place during the mid-Holocene (Tarasov et al. 1998). In this study we perform a series of experiments to test the climate impact of these two pattern
changes in vegetation cover implied by proxy record based estimates from the mid-Holocene.

A significant body of literature primarily based on modeling techniques has attempted to incorporate and evaluate the effects of orbital forcing, local vegetation changes, and changes in ocean surface temperatures to explain the difference in vegetation distribution between the mid-Holocene and today in the Sahara/Sahel region of Africa (e.g. Joussaume et al. 1995; Kutzbach et al. 1996; Claussen and Gayler 1997; Brovkin et al. 1998; Claussen et al. 1999; Braconnot et al. 2000; Bonfils et al. 2001; Levis et al. 2004; Otto-Bliesner et al. 2006). Studies have also focused on this region during the present day finding that local vegetation enhances rainfall variability through feedbacks from both evapotranspiration and surface albedo (Zeng et al. 1999).

A northward shift of the Intertropical Convergence Zone (ITCZ) is observed in model experiments of the mid-Holocene due simply to the change in orbital forcing (e.g. Kutzbach 1981). Orbital forcing is insufficient to produce precipitation comparable to estimates from proxy records in many studies, however simulation of precipitation in the mid-Holocene over North Africa is improved by the inclusion of either interactively coupled vegetation, or offline forcing from vegetation (e.g. Claussen et al. 1999). Most importantly, previous work has shown that local decreases in surface albedo properties (e.g. Claussen and Gayler 1997; Bonfils et al. 2001; Levis et al. 2004) are required to reduce the high surface albedo driven downwelling identified by Charney.

The experiments of the Paleoclimate Modelling Intercomparison Project Phase 2 and the Coupled Model Intercomparison Project Phase 5 (Braconnot et al. 2007a,b; Harrison et al. 2013) show some shift in the ITCZ with changes in orbital forcing and, in some cases, dynamic representation of vegetation distributions predicted from climate. However, all of the models from both archives, including models with both static and dynamic vegetation, underestimate the relatively increased precipitation in Afro-Asian monsoon precipitation in the mid-Holocene (Harrison et al. 2013).

In this study we investigate a new mechanism for elevated levels of precipitation over
North Africa in the mid-Holocene. We propose that an expansion of Eurasian forest relative to today would cause a northward shift in the Hadley Circulation and alter precipitation patterns in the tropics and sub-tropics. This mechanism has been identified in the present day by Swann et al. (2011); however, during the mid-Holocene, this mechanism can act in combination with both orbital forcing and local changes in vegetation to increase precipitation over North Africa.

b. Remote Forcing of Precipitation over Africa

It has long been observed that the location of tropical precipitation is highly correlated with sea surface temperatures in the tropics (e.g. Bjerknes 1969; Manabe et al. 1974; Cornejo-Garrido and Stone 1977; Liebmann and Hartmann 1982; Gill and Rasmusson 1983). At low latitudes, nearby ocean surface temperature is thus a big driver of local precipitation. There is, however, emerging evidence in the literature for a mid-latitude control on the tropical Hadley circulation (e.g. Chiang and Bitz 2005; Broccoli et al. 2006; Frierson and Hwang 2012; Chiang and Friedman 2012; Hwang et al. 2013), specifically with regards to shifting the latitudinal position of the ITCZ.

Several examples of different types of forcing in the mid-latitudes have been shown to influence the Hadley circulation and shift the ITCZ. Theoretical work with an interactive ocean indicates that this tropical response is driven by increased cross-equatorial atmospheric energy transport requirements, requiring an altered Hadley circulation (Kang et al. 2008, 2009). Consistent with this, analysis of nine future climate simulations with slab oceans found that all models shift their ITCZ towards the hemisphere with an increase in energy sources (Frierson and Hwang 2012). The relationship between interhemispheric energy difference and the location of the ITCZ has been shown in coupled models as well (e.g. Broccoli et al. 2006). This mechanism has been invoked to explain a southward ITCZ shift during the Last Glacial Maximum (Chiang and Bitz 2005), the circulation response to anthropogenic aerosol forcing of the Northern Hemisphere in recent decades (Rotstayn et al. 2000; Yoshi-
mori and Broccoli 2008; Hwang et al. 2013) and increases in mid-latitude forest cover (Swann et al. 2011). It has also been postulated that this mechanism could be responsible for an abrupt climate change observed at 14.6kya (Broecker and Putnam 2013).

Numerous studies have investigated the link between vegetation cover and local climate across the globe (i.e. Kleidon et al. 2000; Bala et al. 2007; Bathiany et al. 2010). Several studies have also investigated the influence that vegetation might have on “remote” locations through changes in atmospheric circulation (e.g. Notaro and Liu 2007; Chen et al. 2012; Ma et al. 2012) and links have been found between changes in tropical forest cover and large scale climate patterns (Kabat et al. 2004; Avissar and Werth 2005). As mentioned above, there is an extensive literature on the influence of local vegetation on the climate of the mid-Holocene over Africa (e.g. Claussen 2009). Reale and Dirmeyer 2000 also find a displacement of precipitation over Africa related to land use change in the Mediterranean region during the Roman Classical Period, a few thousand years following the time period of this study.

Swann et al. (2011) was the first to demonstrate a link between mid-latitude forest cover and the location of the ITCZ. In their experiments, an increase in mid-latitude forest cover in the Northern Hemisphere causes more solar energy to be absorbed at the surface due to the relatively lower albedo of forest versus grass. The expanded forest cover caused the Northern Hemisphere to warm as insufficient soil moisture limited the ability of the surface to shed energy through latent heat flux, instead balancing the surface energy budget through an increase in sensible heat flux and subsequent increase in surface temperature. Later studies using a different climate model have also shown links between future expected vegetation distributions and the location of the ITCZ and the South Asian Monsoon (Falloon et al. 2012; McCarthy et al. 2012). We propose here that the influence of mid-latitude forests found in Swann et al. (2011) holds in the mid-Holocene as well, and that the expansion of forests in Eurasia is able to enhance a shift in the ITCZ and cross-equatorial energy transport in addition to any changes induced by orbital forcing.
2. Methods

To investigate the role of vegetation changes over Eurasia and the Sahara, we use the National Center for Atmospheric Research (NCAR) Community Atmosphere and Land models with a carbon cycle and slab ocean (CAM 3.5-CLM 3.5-CASA’) (Gent et al. 2010; Oleson et al. 2008; Chen et al. 2010). All simulations were also tested with an earlier version of the atmospheric model (CAM 3.0-CLM3.5-CASA’) with qualitatively similar results. CAM 3.5 uses an updated convective scheme compared with CAM 3.0 as described in Chen et al. (2010).

Vegetation in the model interacts with climate through changing stomatal conductance, leaf area, and biomass and hence surface albedo, transpiration, and roughness. The leaf and stem area of vegetation is interactive with climate while the fraction of each gridcell assigned to each plant functional type is fixed for a given simulation. The interactive leaf area of plants in this model can feedback on climate and changes in productivity are explicitly calculated. The slab ocean model has interactive sea surface temperatures as other studies have shown that thermodynamic interaction between the ocean and atmosphere is necessary for allowing shifts in large-scale circulation and precipitation. The slab ocean model also has thermodynamic sea ice.

The version of the model used in this study has been evaluated against observations by Gent et al. (2010) and is found to have improvements over previous versions particularly in ENSO behavior and monsoon dynamics (Chen et al. 2010). A closely-related land model to that used for this study has been extensively tested against observations as part of the Carbon-Land Model Intercomparison Project (Randerson et al. 2009) which created observational benchmarks against which to compare the performance of land surface-carbon cycle models. CAM-CASA performs reasonably against observations with the most obvious deficiencies being too little carbon uptake during the growing season in northern biomes and NPP estimates that are overall slightly too high. The hydraulic aspects of the land model have additionally been tested against FLUXNET data (Stöckli et al. 2008).
Using this model setup we performed two control simulations (C) and three experiments. In the first experiment, all mid-latitude area in Eurasia (15°W to 165°E) between 30°N and 60°N currently occupied by either C3 grasses or agriculture is converted to broadleaf deciduous forests (EV, for Eurasian vegetation, see also Fig. 1b). This particular conversion in Eurasia (from grass and crops to forest) is used to simulate the previously forested regions of Eurasia currently occupied by grasslands and agricultural regions. In the second experiment, bare ground over the Sahara desert and Saudi Arabia is converted to grassland (SV, for Sahara vegetation, see also Fig. 1a) similar to projections of mid-Holocene vegetation cover (Hoelzmann et al. 1998). In the third experiment these two vegetation changes are imposed simultaneously (SEV, for Sahara + Eurasia vegetation). In all experiments, the remaining vegetation is left unmodified, as are glaciers and lakes. These experiments are performed for the orbital conditions of the mid-Holocene with CO$_2$ at 280 ppm (MH, for Mid-Holocene). The two control runs use present day vegetation cover and represent the orbital conditions of the mid-Holocene (CMH), and the present day orbital conditions (CPI, for Pre-Industrial). CO$_2$ levels are held fixed at pre-industrial CO$_2$ levels of 280 ppm.

The base value of optical properties for each plant type is specified in the model, but realized surface albedo values in any simulation are interactively calculated as a function of dynamic leaf area, stem area, leaf angle, plant type, snow cover, the moisture content and soil type of bare ground, and other land cover types (lakes, ice). As a general order of magnitude, the albedo of a flat leaf in visible light is 0.1 for broadleaf deciduous trees and 0.11 for both C$_3$ and C$_4$ grasses. Bare soil albedo varies between 0.08 to 0.36 depending on the soil color class and the soil moisture relative to saturation.

The model simulations are integrated for 60 years, and the results presented are averages of the last 50 years. The spin-up time of 10 years is sufficient to bring climate variables (temperature, precipitation, sea ice cover, snow cover, soil moisture, etc.) into equilibrium. CO$_2$ is held fixed at 280 ppm for the entire 60 year simulation in all simulations. The spatial resolution of the model is T42 which corresponds to approximately 2.8° by 2.8° gridcells and
there are 10 soil layers.

Resulting climate fields are then analyzed by comparing experiments with controls, and experiments with one another. Anomalies are calculated as the difference between an experiment (SV, EV, or SEV) and present day vegetation (C, for control). We focus in particular on two comparisons. The first is between the combined experiment (Saharan grass, Eurasian forests, and orbital forcing, SEVMH) and the pre-industrial control (CPI) where a change in variable $\phi$ is represented by $\Delta \phi = \phi_{\text{SEVMH}} - \phi_{\text{CPI}}$. The second isolates only the additional added effect of expanded Eurasian forests during the mid-Holocene where we compare SEVMH with SVMH so that $\Delta \phi = \phi_{\text{SEVMH}} - \phi_{\text{SVMH}}$. Statistical significance for $\Delta \phi$ is determined using a Students t-test and significance is reported as p-values where a p-value of 0.05 indicates that we reject the null hypothesis that the anomaly is zero with 95% confidence. In general we use a significance threshold of 95% but report actual p-values and indicate higher significance where possible. We estimate a lagged autocorrelation of two years or less for all variables and have used a conservative estimate of 25 degrees of freedom for each 50-year period.

The northward energy flux by the atmosphere in $W/m^2$ at each latitude $\theta$ is calculated as:

$$F_\theta = \int_{-\pi/2}^{\theta} \int_0^{2\pi} R_{\text{TOA}} a^2 \cos \theta \, d\lambda \, d\theta$$

where $\lambda$ is longitude, $a$ is the radius of Earth in m, and $R_{\text{TOA}}$ is the net radiation at the top of the atmosphere in $W/m^2$ (equation 2.21 from Hartmann (1994)). Cloud contribution to net radiation at the top of the atmosphere is measured as the difference between clear sky and all sky net radiation at the top of the atmosphere. Surface albedo contribution to radiation at the top of the atmosphere is measured as the change between two experiments in shortwave flux at the top of the atmosphere under clear sky conditions.

A global radiative kernel was used to characterize the differences in energy fluxes at the
top of the atmosphere between model experiments following the form (Soden et al. 2008):

\[ \delta R_{\text{TOA}} \approx \sum_i \frac{\partial R_{\text{TOA}}}{\partial X_i} \cdot \delta X \]  

(2)

where \( \delta R_{\text{TOA}} \) is the change in top of atmosphere energy flux, and terms inside the summation designate the change of \( R_{\text{TOA}} \) due to individual component \( X_i \), where \( X_i \) represents surface temperature, atmospheric temperature, water vapor, surface albedo, or clouds. The radiative kernel for each component represents the change in top of atmosphere energy flux due to a unit change in that component and is represented by the differential \( \partial R_{\text{TOA}} / \partial X_i \). Kernels for water vapor and clouds are further split into shortwave and longwave contributions. We use radiative kernels calculated in CAM3 (Shell et al. 2008; Soden et al. 2008) for all components except for clouds. Top of atmosphere energy flux change due to clouds is calculated as the difference between the clear sky and all sky fluxes at the top of the atmosphere, with changes in cloud radiative effects caused solely by non-cloud components removed (Shell et al. 2008). The kernels used here were developed for CAM3; however, we find it reasonable to use them for CAM3.5 as the radiative transfer algorithms in the two versions of the model are the same (Chen et al. 2010) and it has been shown that even across models the difference of kernels is small (Soden et al. 2008). Kernel calculations compare each experiment with the control simulation of the same orbital forcing, so for these calculations we compare SEVMH with CMH rather than CPI as in the rest of the paper.

a. Impact of orbital forcing, Saharan grasslands, and Eurasian forests

An expansion of forests in Eurasia and grasslands in the Sahara during the mid-Holocene relative to today has several remote impacts beyond the region with directly modified vegetation. These include impacts to temperature and precipitation patterns, changes in plant productivity, and changes in atmospheric dynamics and energy transport. We first present results showing changes in climate patterns, and second discuss changes in energy transport and dynamics which, in some cases, are the proximate cause for changes in climate patterns.
1) Temperature and Precipitation

Compared with pre-industrial climate, temperatures during the mid-Holocene were generally colder in lower latitudes and higher near the poles (Fig. 2a). This is expected from the orbital forcing differences between ~6000 years ago and present day that led to an increase in the seasonality of temperature in the Northern Hemisphere with warmer summers and cooler winters (Kutzbach 1981; Braconnot et al. 2007a). The combined experiment (SEVMH) shows some aspects of the same low latitude cooling pattern driven mostly by orbital forcing (Fig. 2a,b), but Eurasian forests have the additional effect of increasing temperatures over the Northern Hemisphere continents (Fig. 2c). Forests were added only to Eurasia in the SEVMH experiment, however temperatures over North America are also increased (Fig. 2c). The spatial pattern of annual mean temperature change driven by vegetation cover change is consistent across seasons for SEVMH relative to the mid-Holocene control, with pronounced cooling over new grasslands in the Sahara, and warming over Northern Hemisphere continental regions (Fig. 3).

Precipitation patterns change in the mid-Holocene due to orbital forcing yet are further enhanced by changes in vegetation distributions (Fig. 4). Large changes in precipitation are prominent in tropical regions associated with a northward shift of the ITCZ. The increased seasonality in temperature in the Northern Hemisphere during the mid-Holocene led to summers that were warmer than the present day. For the combined experiment (SEVMH), these warm summers lead to a shift in the precipitation weighted location of the ITCZ (Lintner et al. 2004) of 0.6° northward in August (for SEVMH-CPI, pval = 0.04). The shift in the ITCZ can also be seen visually as drying bands to the south of wetting bands (Fig. 4). The shift in ITCZ location is consistent with changes in atmospheric dynamics and energy transport as discussed in section 3 below.

The spatial pattern of precipitation change driven by vegetation cover change is relatively consistent across seasons for SEVMH relative to the mid-Holocene control (Fig. 5) with a few notable variations. The shift in the ITCZ over the Atlantic migrates north and south with
the sun, with the most pronounced drying over northern South America in June-July-August (Fig. 5c), and drying in the south of Brazil in March-April-May and September-October-November (Fig. 5b,d). This is consistent with times when the ITCZ is shifted northward due to the addition of vegetation causing drying. Over the Sahara, wetter conditions are seen in three of four seasons, with local winter showing no significant change (December - January - February, Fig. 5a).

The additional contribution of mid-latitude Eurasian forests to precipitation patterns is subtle, but most notably shows a modest, yet statistically significant, increase in precipitation over North Africa (Fig. 4c) and coincident increase in plant productivity (Fig. 8d). The precipitation increases over North Africa by an average of 26.3% (8mm/yr) in the domain 15°N-30°N and 0°-30°E (box shown in Fig. 6c) due to the addition of Eurasian forests compared to the Saharan grass only experiment (SEVMH-SVMH, Fig. 7). This suggests that additional Eurasian forest cover relative to today enhances precipitation over the green Sahara, acting in an additive manner beyond other forcing. Precipitation decreases in the storm track off of Asia in the mid-Holocene are also diminished by forests in Eurasia, resulting in little change near the coast compared to the pre-industrial (Fig. 4c). Precipitation changes little over the local areas where forests were added in Eurasia.

In the mid-Holocene, proxy records for plant available moisture and estimates of precipitation minus evaporation (P-E) from lake level data indicate that it was generally wetter over much of Africa (e.g. Street-Perrott and Perrott 1993; Hoelzmann et al. 1998; Joussaume et al. 1999). This magnitude of precipitation increase in our model simulations (SEVMH, or SVMH) when averaged across the basin is lower than predictions of the excess precipitation needed to maintain steppe vegetation observed to inhabit the region in the mid-Holocene (Jolly et al. 1998b,a; Joussaume et al. 1999), although local increases are sufficiently large (Fig. 6b). As noted above, the additional influence of forests in Eurasia is to further increase precipitation over Africa beyond the change driven by orbital forcing and local grass in the Sahara (Fig. 6c).
The net carbon uptake by plants, or net primary production (NPP), is lower in the mid-Holocene relative to present day outside of areas where plant cover was purposefully added (Fig. 8). The reduced NPP is driven by a combination of decreases in temperature in the spring and fall seasons, decreases in growing season length, and decreases in regional precipitation patterns with associated changes in soil moisture.

Productivity increases in the areas where vegetation has been directly added in each experiment including increases in NPP over Eurasia (EVMH, Fig. 8b and Fig. 1b), and the Sahara (SVMH, Fig. 8c and Fig. 1a). No change in productivity is observed over the Sahara in either CMH or EVMH as there are no plants designated over the Sahara desert in the present day vegetation map. We might expect to find that the combined experiment with both grass in the Sahara and forests in Eurasia (SEVMH) to be a near linear combination of its component experiments, particularly in locations where vegetation was modified, yet we find that Eurasian forests have the additional effect of making the grasslands in the Sahara even more productive—consistent with the increase in precipitation over North Africa (Fig. 6c and Fig. 8d). That is to say that there is an additional feedback from Eurasian forests that enhances precipitation over the Sahara, and this feedback operates through shifts in atmospheric dynamics as discussed below.

We find decreases in productivity in eastern North America in response to adding forests in Eurasia (Fig. 8b). The teleconnection to North America is also activated by adding grass in the Sahara (Fig. 8c), but the additional effect of all forcing together shows that Eurasian forests further exacerbate the decrease in NPP (Fig. 8d). Proxy records including lake levels, aeolian deposits, and estimates of precipitation minus evaporation and aridity all show drying across North America at this time (Viau and Gajewski 2001; Forman et al. 2001; Harrison and Prentice 2003) consistent with both the effects of orbital forcing alone and the enhanced decrease in productivity associated with ecoclimate teleconnections from forest cover in Eurasia or grass in the Sahara.
Expanding forests in Eurasia also decreases productivity over the cerrado regions of Brazil (Fig. 8b), while adding grass in the Sahara causes decreases in NPP primarily in southern Brazil (Fig. 8c). Estimates of precipitation in the mid-Holocene over the Amazon are sparse. Proxy observations suggest drier conditions over the southern flank of the Amazon in South America (Prado et al. 2013), with wetter conditions over the Andes (Liu et al. 2004). Charcoal records show a more mixed signal over South America (Power et al. 2008). Ecosystem reconstructions from pollen data suggest a shift to vegetation cover which is consistent with drier conditions relative to today (Mayle and Power 2008) and the results from our simulations. This decrease in NPP is enhanced in our simulations, particularly over western Brazil, by expanding forest cover in Eurasia (Fig. 8d). Orbitally driven changes in productivity over Brazil are small (Fig. 8a).

3) Atmospheric Circulation and Dynamics

An expansion of forest in Eurasia and grassland in the Sahara result in a major northward shift in the location of precipitation in the tropics during the mid-Holocene (Fig. 4b). We hypothesize that an increase in energy absorbed by a darker vegetated surface creates an energy imbalance between the two hemispheres leading to a northward shift in the Hadley circulation and decreased northward flux of energy across the equator to restore energy balance (Fig. 9, see also Chiang and Friedman 2012). A change in energy flux by the atmosphere across the equator then indicates that the shift in circulation has occurred. The anomalous energy flux could occur in the ocean as well, but heat flux by the ocean is held fixed in these simulations.

Orbital forcing alone leads to an anomalous northward energy flux across the equator in the annual mean. Adding vegetation in the Northern Hemisphere, either in Eurasia alone, or the Sahara alone leads to statistically insignificant changes in cross-equatorial energy flux. However increasing forest cover in Eurasia combined with grass cover in the Sahara, perturbs the annual mean energy balance enough to shift the Hadley circulation southward (Fig. 9).
Changes in vegetation cover increase the solar energy absorbed by the surface as the albedo decreases both directly with the addition of vegetation, and indirectly through the relative loss of sea ice at high northern latitudes due to relative increases in temperature. The surface albedo change results in an average of 4.5 W/m² decrease in net top of atmosphere energy flux north of 30°N for the SEVMH experiment (2.4% change from CPI, pval< 0.001). This energy imbalance, with a deficit in the Southern Hemisphere, then requires a northward shift in the Hadley circulation and a corresponding shift in the ITCZ which is manifested in the change in precipitation patterns (Fig. 4b). Orbital forcing alone does not lead to an annual mean shift in cross equatorial energy flux; however, the addition of forests in Eurasia on top of other forcing (SEVMH), does significantly increase the southward cross equatorial energy flux. The combination of all forcing together (SEVMH) decreases the northward cross equatorial energy flux by more than twice as much as EVMH, reducing the Northward flux from 1.8 Peta Watts (PW) in CPI by ~0.054 PW—a change of 3% (Fig. 10, Table 2). In other words, the effect of Eurasian afforestation combined with Saharan grasslands on cross-equatorial energy flux is larger than the linear combination as the combined effect includes feedbacks.

We next quantify the factors that are driving changes in the interhemispheric energy difference. Much of the additional accumulated energy in the Northern Hemisphere in our experiments is coming from a decrease in surface albedo. Calculations using a global radiative kernel allow us to separate the contribution to the top of atmosphere net radiative balance between the hemispheres from clouds, water vapor, temperature, and albedo. We find that adding Saharan grasslands leads to less than 0.5 W/m² energy difference between the hemispheres (SVMH-CMH), primarily from non-cloud feedbacks (94.5%) such as surface albedo and enhanced longwave forcing from water vapor (Fig. 11). Expanding Eurasian forests more than doubles the interhemispheric energy difference to 1.1W/m² (SEVMH-CMH) with the additional feedback coming about one third (33.2%) from cloud feedbacks and two thirds (66.8%) from non-cloud feedbacks (Fig. 11). The larger interhemispheric
energy difference in the combined experiment is consistent with SEVMH having the largest change in differential energy absorption between the hemispheres (from a decrease in surface albedo due to forest and grassland expansion) and as well as the largest change in both cross equatorial energy flux and precipitation shift (Fig. 4b, Fig. 10). The latitudinal profile of energy flux (Fig. 11) shows that grass in the Sahara leads to a locally increased energy flux from non-cloud processes the zonal mean, while Eurasian forests increase the energy flux at local latitudes primarily through cloud processes.

b. Summary

The research presented here illustrates the concept of ecoclimate teleconnections using the Green Sahara as an example. We discuss how distant vegetation changes can influence both the local climate in a given location, and our plant-derived proxy record of that local climate. We have shown three main consequences of increases in Eurasian forest area during the mid-Holocene relative to today. First, the addition of forest cover in Eurasia and grasses in the Sahara leads to a decrease in surface albedo and consequent increase in energy absorbed into the Northern Hemisphere. This additional energy leads to an imbalance between the hemispheres that persists throughout the year. Second, this energy imbalance leads to a northward shift in the Hadley circulation in order to transport more energy across the equator and a consequent shift in the location of the ITCZ (Fig. 9). This northward shift in the ITCZ gives an added boost to precipitation over North Africa on top of increases from local grass in the Sahara. Third, the shift of the Hadley circulation leads to teleconnections and an impact on plant productivity in eastern North America, and central and Southern Brazil.

Our underlying explanatory framework is consistent with the emerging hypothesis of ITCZ shifts from altering atmospheric cross-equatorial energy transports (Chiang and Friedman 2012). The results presented here show the response of a single climate model and the dependence of these results on the model itself cannot be ruled out, however this gross be-
behavior is robust across a number of modeling studies. Quantitatively however, the strength of the teleconnection may differ from model to model. The response of the carbon cycle and plant productivity through ecoclimate teleconnections has not yet been tested across models in experiments similar to those presented here and represents a new finding of this study.

We propose that an additional forcing, from the remote effects of Eurasian forest cover changes, could help shift the ITCZ northward over Africa and increase precipitation in the Sahara during the mid-Holocene. Given that the change in precipitation from Eurasian forests occurs globally, this new hypothesis is testable by additional information on climate from proxy records around the globe. The work presented here suggests that the interpretation of paleo proxy records based on plant cover should consider ecoclimate teleconnections – the fact that local vegetation reflects both local climate conditions and may imply global circulation patterns. By considering these ecoclimate teleconnections, knowledge of vegetation cover in one region in the past can lead to additional, testable hypothesis about climate in other parts of the globe.

Acknowledgments.

We would like to acknowledge the help of Gordon Bonan and Samuel Levis for assisting us with model set up. Dargan Frierson provided comments and Brian Rose provided helpful discussions. We acknowledge National Science Foundation Awards ATM-0628678 and AGS-1143329 to the University of California, Berkeley and National Science Foundation Award AGS-1321745 to the University of Washington. This work was partially conducted while A.L.S.S. was a Giorgio Ruffolo Fellow in the Sustainability Science Program at Harvard University, for which support from Italy’s Ministry for Environment, Land and Sea is gratefully acknowledged. Some of the computing resources used in this work were provided by the Climate Simulation Laboratory at NCAR’s Computational and Information Systems Laboratory (CISL), sponsored by the National Science Foundation and other agencies.
REFERENCES


Gent, P. R., S. G. Yeager, R. B. Neale, S. Levis, and D. A. Bailey, 2010: Improvements in a half degree atmosphere/land version of the CCSM. *Climate Dynamics*, 34 (6), 819–833.


Liebmann, B. and D. Hartmann, 1982: Interannual variations of outgoing IR associated


McIntosh, S. and R. McIntosh, 1981: West African Prehistory: Archaeological studies in recent decades have illuminated the prehistory of this vast region, revealing unexpected complexity in its development from 10,000 BC to AD 1000. *American Scientist*, 602–613.


Street, F. and A. Grove, 1979: Global maps of lake-level fluctuations since 30,000 yr BP. *Quaternary Research, 12 (1)*, 83–118.


Summary of Simulations: Experiments and Control runs shown in this paper are summarized here with the abbreviation, a short description, the vegetation cover imposed, orbital conditions, and CO₂ concentrations used in each simulation. The vegetation patterns imposed are shown in Figures 1a and 1b. Present day orbital conditions are set to the year 1950, and mid-Holocene orbital conditions are set to 6000 years before present.

Atmospheric Energy Transport: Change in annually averaged northward energy flux by the atmosphere at each latitude is shown in each row for an experiment compared against the pre-industrial control (CPI). The final line (SEVMH - SVMH) shows the additive effect of expanding forests in Eurasia. Columns show the total change in energy flux in PW, the change represented in percent of the pre-industrial control flux at the equator, the p-value of significance. Significance at the 99% confidence level or above is indicated by a double star (**).
<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Description</th>
<th>Vegetation</th>
<th>Orbital Conditions</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI</td>
<td>Pre-Industrial Control</td>
<td>Present Day</td>
<td>Present Day</td>
<td>280ppm</td>
</tr>
<tr>
<td>CMH</td>
<td>Mid-Holocene Control</td>
<td>Present Day</td>
<td>Mid-Holocene</td>
<td>280ppm</td>
</tr>
<tr>
<td>SVMH</td>
<td>Sahara Grassland</td>
<td>Grass in the Sahara</td>
<td>Mid-Holocene</td>
<td>280ppm</td>
</tr>
<tr>
<td>EVMH</td>
<td>European Forests</td>
<td>Forests in Europe</td>
<td>Mid-Holocene</td>
<td>280ppm</td>
</tr>
<tr>
<td>SEVMH</td>
<td>European Forests and Sahara Grassland</td>
<td>Forests in Europe and Grass in the Sahara</td>
<td>Mid-Holocene</td>
<td>280ppm</td>
</tr>
</tbody>
</table>

Table 1. **Summary of Simulations**: Experiments and Control runs shown in this paper are summarized here with the abbreviation, a short description, the vegetation cover imposed, orbital conditions, and CO₂ concentrations used in each simulation. The vegetation patterns imposed are shown in Figures 1a and 1b. Present day orbital conditions are set to the year 1950, and mid-Holocene orbital conditions are set to 6000 years before present.
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Δ EFlux (PW)</th>
<th>Δ EFlux (%)</th>
<th>pval</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMH - CPI</td>
<td>0.076</td>
<td>4.2</td>
<td>0.0003**</td>
</tr>
<tr>
<td>SVMH - CPI</td>
<td>0.020</td>
<td>1.1</td>
<td>0.2786</td>
</tr>
<tr>
<td>EVMH - CPI</td>
<td>-0.003</td>
<td>-0.1</td>
<td>0.8680</td>
</tr>
<tr>
<td>SEVMH - CPI</td>
<td>-0.054</td>
<td>-3.0</td>
<td>0.0080**</td>
</tr>
<tr>
<td>SEVMH - SVMH</td>
<td>-0.091</td>
<td></td>
<td>0.0008**</td>
</tr>
</tbody>
</table>

Table 2. **Atmospheric Energy Transport**: Change in annually averaged northward energy flux by the atmosphere at each latitude is shown in each row for an experiment compared against the pre-industrial control (CPI). The final line (SEVMH - SVMH) shows the additive effect of expanding forests in Eurasia. Columns show the total change in energy flux in PW, the change represented in percent of the pre-industrial control flux at the equator, the p-value of significance. Significance at the 99% confidence level or above is indicated by a double star (**).
List of Figures

1. ∆ Vegetation Cover: Patterns of vegetation change imposed in model experiments. (a) Map of new grasses added over the Sahara and Saudi Arabia in the local vegetation experiment (SV) in percent of grid cell converted. New grasses were added in a pattern similar to Hoelzmann et al. (1998). (b) Map of new deciduous forests added over Eurasia in the Eurasian vegetation experiment (EV) in percent of grid cell converted. New forests were added on agricultural lands and C3 grassland in Europe and Asia between 30°N and 60°N. The patterns of vegetation change from (a) and (b) are combined for a third experiment (SEV).

2. ∆ Temperature: Change in annually averaged temperature in Kelvin for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. A zonal average is shown to the right of each map. Values which do not pass a significance test at 95% confidence have been omitted.

3. ∆ Temperature for SEVMH-CMH: Change in temperature in Kelvin for each of four seasons for the SEVMH simulation compared with the mid-Holocene control (SEVMH-CMH) showing the combined effect of grassland in the Sahara and expanded forests in Europe during the mid-Holocene. The 4 seasons are (a) December-January-February (DJF), (b) March-April-May mean (MAM), (c) June-July-August (JJA), and (d) September-October-November mean (SON). Values which do not pass a significance test at 95% confidence have been omitted.
\[ \Delta \text{Precipitation:} \] Change in annually averaged precipitation in mm/day for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. A zonal average is shown to the right of each map. Values which do not pass a significance test at 95% confidence have been omitted.

\[ \Delta \text{Precipitation for SEVMH-CMH:} \] Change in precipitation in mm/day for each of four seasons for the SEVMH simulation compared with the mid-Holocene control (SEVMH-CMH) showing the combined effect of grassland in the Sahara and expanded forests in Europe during the mid-Holocene. The 4 seasons are (a) December-January-February (DJF), (b) March-April-May mean (MAM), (c) June-July-August (JJA), and (d) September-October-November mean (SON). Note that the scale on the color bar is different from that in Figure 4. Values which do not pass a significance test at 95% confidence have been omitted.
Precipitation over Africa: Change in annually averaged precipitation in $\text{mm/day}$ for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. The box drawn in panel c corresponds to the domain $0^\circ$-$30^\circ$E and $15^\circ$N-$30^\circ$N and represents the averaging region used in Fig. 7. Values which do not pass a significance test at 95% confidence have been omitted.

Precipitation over Africa: Change in precipitation in $\text{mm/day}$ averaged over the domain $0^\circ$-$30^\circ$E and $15^\circ$N-$30^\circ$N is shown for the annual mean (left group) and 4 seasons, the December-January-February mean (DJF), the March-April-May mean (MAM), the June-July-August mean (JJA), and the September-October-November mean (SON). Each time average is shown for (red) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (green) the EVMH simulation compared to the pre-industrial control showing the effect of expanded forest cover in Eurasia, (brown) the SVMH experiment compared to the pre-industrial control showing the effect of local grassland in the Sahara, (blue) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (cyan) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. The averaging domain is represented by the box in Fig. 6c.
**△ Net Primary Production:** Change in Net Primary Production \((gC/m^2/yr)\) for (a) CMH-CPI isolating the effects of orbital forcing, (b) EVMH-CMH isolating the effects of expanded forests in Eurasia, (c) SVMH-CMH isolating the effects of grass in the Sahara, and (d) SEVMH-SVMH isolating the additive effect of expanded Eurasian forests. Areas where more than 10% of each gridcell was modified as in Fig. 1 are outlined in magenta, although note that this pattern of vegetation change is fully implemented only in panel (d). Panel (b) has modifications to land cover only in Eurasia and panel (c) only in Africa and Saudi Arabia. Values which do not pass a significance test at 95% confidence have been omitted.

**Forest Expansion Shifts the Hadley Circulation:** This diagram describes the hypothesized mechanism by which the ecoclimate teleconnection acts in this study. The forest expansion case (b) has an increase mid-latitude forests relative to the control vegetation (a), with trees replacing areas occupied by grass in the present day. The relatively darker expanded forest absorbs additional solar energy \((E_{\text{absorbed}})\) leading to an imbalance in energy between the two hemispheres. To restore energy balance the Hadley circulation (represented by blue and red boxes) moves northward in order to increase the cross equatorial transport of energy from North to South \((E_{\text{flux}})\). The ITCZ (represented by vertical blue dashed lines) follows the location of convergence of air from both hemispheres and is therefore drawn northward with the expansion of tree cover in mid-latitudes (b). This mechanism is presented in Swann et al. (2011) for the present day and proposed by this study to act in the mid-Holocene in response to changes in vegetation patterns between the two time periods.
Anomalous Northward Atmospheric Energy Transport: Zonally averaged latitudinal profile of the annually averaged anomalous northward energy transport by the atmosphere comparing each experiment against present day vegetation and orbital conditions (CPI). The red dashed line represents the effects of orbital forcing (CMH - CPI), the green dashed-dot line (SVMH - CPI) represents the effects of adding grasslands in the Sahara and orbital forcing, the brown line with crosses (EVMH - CPI) represents the effects of expanding forests in Eurasia and orbital forcing, and the thick blue line (SEVMH - CPI) represents the combined effect of both vegetation changes and orbital forcing.

Top of Atmosphere Net Energy Fluxes: The change in top of atmosphere net radiative flux of energy is shown as a function of latitude for the total flux (thick solid line), contributions from clouds (thin solid line), and contributions from non-cloud factors (dashed line) including albedo, longwave and shortwave forcing from water vapor, and changes in temperature. These fluxes are shown for the combined effect of Eurasian forests and Saharan grass (blue lines, SEVMH-CMH) and the additive effect of Eurasian forests in the combined experiment (magenta lines, SEVMH-SVMH). Colored overbars show the latitudes at which grass was added to the Sahara in SEVMH and SVMH (in green), forests were added to Eurasia in SEVMH (in brown).
Fig. 1. Δ Vegetation Cover: Patterns of vegetation change imposed in model experiments. (a) Map of new grasses added over the Sahara and Saudi Arabia in the local vegetation experiment (SV) in percent of grid cell converted. New grasses were added in a pattern similar to Hoelzmann et al. (1998). (b) Map of new deciduous forests added over Eurasia in the Eurasian vegetation experiment (EV) in percent of grid cell converted. New forests were added on agricultural lands and C3 grassland in Europe and Asia between 30°N and 60°N. The patterns of vegetation change from (a) and (b) are combined for a third experiment (SEV).
Fig. 2. \( \Delta \) Temperature: Change in annually averaged temperature in Kelvin for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. A zonal average is shown to the right of each map. Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 3. Δ Temperature for SEVMH-CMH: Change in temperature in Kelvin for each of four seasons for the SEVMH simulation compared with the mid-Holocene control (SEVMH-CMH) showing the combined effect of grassland in the Sahara and expanded forests in Europe during the mid-Holocene. The 4 seasons are (a) December-January-February (DJF), (b) March-April-May mean (MAM), (c) June-July-August (JJA), and (d) September-October-November mean (SON). Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 4. Δ Precipitation: Change in annually averaged precipitation in mm/day for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. A zonal average is shown to the right of each map. Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 5. **Δ Precipitation for SEVMH-CMH**: Change in precipitation in mm/day for each of four seasons for the SEVMH simulation compared with the mid-Holocene control (SEVMH-CMH) showing the combined effect of grassland in the Sahara and expanded forests in Europe during the mid-Holocene. The 4 seasons are (a) December-January-February (DJF), (b) March-April-May mean (MAM), (c) June-July-August (JJA), and (d) September-October-November mean (SON). Note that the scale on the color bar is different from that in Figure 4. Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 6. Δ Precipitation over Africa: Change in annually averaged precipitation in mm/day for the (a) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (b) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (c) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. The box drawn in panel c corresponds to the domain 0°-30°E and 15°N-30°N and represents the averaging region used in Fig. 7. Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 7. **Δ Precipitation over Africa:** Change in precipitation in mm/day averaged over the domain 0°-30°E and 15°N-30°N is shown for the annual mean (left group) and 4 seasons, the December-January-February mean (DJF), the March-April-May mean (MAM), the June-July-August mean (JJA), and the September-October-November mean (SON). Each time average is shown for (red) the mid-Holocene control compared with the pre-industrial control (CMH-CPI) showing the effect of orbital forcing, (green) the EVMH simulation compared to the pre-industrial control showing the effect of expanded forest cover in Eurasia, (brown) the SVMH experiment compared to the pre-industrial control showing the effect of local grassland in the Sahara, (blue) the SEVMH simulation compared with pre-industrial control showing the combined effect of orbital forcing, grassland in the Sahara and expanded forests in Europe, and (cyan) the SEVMH experiment compared with the SVMH experiment (SEVMH-SVMH) showing the isolated additive effect of expanded European forests. The averaging domain is represented by the box in Fig. 6c.
Fig. 8. ∆ Net Primary Production: Change in Net Primary Production (gC/m²/yr) for (a) CMH-CPI isolating the effects of orbital forcing, (b) EVMH-CMH isolating the effects of expanded forests in Eurasia, (c) SVMH-CMH isolating the effects of grass in the Sahara, and (d) SEVMH-SVMH isolating the additive effect of expanded Eurasian forests. Areas where more than 10% of each grid cell was modified as in Fig. 1 are outlined in magenta, although note that this pattern of vegetation change is fully implemented only in panel (d). Panel (b) has modifications to land cover only in Eurasia and panel (c) only in Africa and Saudi Arabia. Values which do not pass a significance test at 95% confidence have been omitted.
Fig. 9. **Forest Expansion Shifts the Hadley Circulation:** This diagram describes the hypothesized mechanism by which the ecoclimate teleconnection acts in this study. The forest expansion case (b) has an increase mid-latitude forests relative to the control vegetation (a), with trees replacing areas occupied by grass in the present day. The relatively darker expanded forest absorbs additional solar energy ($E_{absorbed}$) leading to an imbalance in energy between the two hemispheres. To restore energy balance the Hadley circulation (represented by blue and red boxes) moves northward in order to increase the cross equatorial transport of energy from North to South ($E_{flux}$). The ITCZ (represented by vertical blue dashed lines) follows the location of convergence of air from both hemispheres and is therefore drawn northward with the expansion of tree cover in mid-latitudes (b). This mechanism is presented in Swann et al. (2011) for the present day and proposed by this study to act in the mid-Holocene in response to changes in vegetation patterns between the two time periods.
**Fig. 10. Anomalous Northward Atmospheric Energy Transport:** Zonally averaged latitudinal profile of the annually averaged anomalous northward energy transport by the atmosphere comparing each experiment against present day vegetation and orbital conditions (CPI). The red dashed line represents the effects of orbital forcing (CMH - CPI), the green dashed-dot line (SVMH - CPI) represents the effects of adding grasslands in the Sahara and orbital forcing, the brown line with crosses (EVMH - CPI) represents the effects of expanding forests in Eurasia and orbital forcing, and the thick blue line (SEVMH - CPI) represents the combined effect of both vegetation changes and orbital forcing.
Fig. 11. Δ Top of Atmosphere Net Energy Fluxes: The change in top of atmosphere net radiative flux of energy is shown as a function of latitude for the total flux (thick solid line), contributions from clouds (thin solid line), and contributions from non-cloud factors (dashed line) including albedo, longwave and shortwave forcing from water vapor, and changes in temperature. These fluxes are shown for the combined effect of Eurasian forests and Saharan grass (blue lines, SEVMH-CMH) and the additive effect of Eurasian forests in the combined experiment (magenta lines, SEVMH-SVMH). Colored overbars show the latitudes at which grass was added to the Sahara in SEVMH and SVMH (in green), forests were added to Eurasia in SEVMH (in brown).