J3.1 OBSERVED VEGETATION-CLIMATE FEEDBACKS IN THE UNITED STATES

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ABSTRACT

Observed vegetation feedbacks on temperature and precipitation are assessed across the United States using satellite-based fraction of photosynthetically active radiation (FPAR) and monthly climate data for the period of 1982-2000. This study represents the first attempt to spatially quantify the observed local impact of vegetation on temperature and precipitation over the United States, for all months and by season. Lead-lag correlations and feedback parameters are computed to determine the regions where vegetation substantially impacts the atmosphere and to quantify this forcing. Temperature imposes a significant instantaneous forcing on FPAR, while precipitation's impact on FPAR is greatest at one-month lead, particularly across the prairie. An increase in vegetation raises the surface air temperature by absorbing additional radiation and, in some cases, masking the high albedo of snow cover. Vegetation generally exhibits a positive forcing on temperature, strongest in spring and particularly across the northern states. The local impact of FPAR on precipitation appears to be spatially inhomogeneous and relatively weak, potentially due to the atmospheric transport of transpired water. The computed feedback parameters can be used to evaluate vegetation-climate interactions simulated by models with dynamic vegetation.

I. INTRODUCTION

Vegetation and climate interact through a series of complex feedbacks, which are not yet fully understood. Vegetation impacts climate directly through moisture, energy, and momentum exchanges with the atmosphere and indirectly through biogeochemical processes that alter atmospheric CO_2 concentration (Pielke et al. 1998; Bonan 2002). Most of the current understanding of these feedbacks resulted from studies using coupled vegetation-climate models (e.g. Foley et al. 1998; Levis et al. 2004; Gallimore et al. 2005; Notaro et al. 2005). Few studies have primarily applied observational data to determine the impact of vegetation feedbacks on the large-scale climate.

Using satellite-based normalized difference vegetation index (NDVI) and gridded temperature data, Kaufmann et al. (2003) applied Granger causality statistics (Granger, 1969) to quantify the effects of interannual variations in vegetation on temperature over North American and Eurasian forests. They found that increased NDVI over North America resulted in warming during winter and spring and cooling during summer and autumn. The impact on temperature was strongest during winter, when NDVI was negatively correlated with snow extent and weakly correlated with vegetation.

Liu et al. (2005) estimated the magnitude of observed global vegetation feedbacks on temperature and precipitation. They used lead-lag correlations and a statistical feedback parameter (Frankignoul and Hasselmann 1977; Frankignoul et al. 1998) to relate satellite-based fraction of photosynthetically active radiation (FPAR) to gridded temperature and precipitation data. They showed that, in the northern mid- and high-latitudes, vegetation variability is predominantly driven by temperature, while vegetation also exerts a strong positive feedback on temperature. They found that, while tropical and subtropical vegetation is mostly driven by precipitation, the influence of vegetation on precipitation is weak globally, with no evidence of a dominant positive vegetation-precipitation feedback.

Liu et al. (2005) used a statistical technique previously applied to ocean-atmosphere feedbacks to assess vegetation-climate feedbacks, thereby providing a global overview of vegetation impacts with limited attention given to underlying processes. This study applies the same statistical approach in a focused analysis of vegetation-climate feedbacks in the United States. In addition to presenting an overview of the mean and seasonality of vegetation in the United States and assessing the controls of vegetation growth, the magnitude of seasonal vegetation forcing on temperature and precipitation is quantified from observational data. The results can be applied to evaluate vegetation feedbacks in the United States as simulated by climate models.

The key difference between studies using the feedback parameter (present study; Liu et al. 2005) and the Granger causality study by Kaufmann et al. (2003) is that the former is a feedback study that quantifies the instantaneous vegetation forcing on the atmosphere, while the latter is a predictability study of the causality between vegetation and the atmosphere at a later time. The present study and that of Liu et al. (2005) are the first to quantify the observed instantaneous forcing from vegetation. This instantaneous forcing (from feedback) will be greater than the lagged causality forcing (from predictability), with the difference representing the one-month FPAR autocorrelation (shown by Liu et al. 2005).

II. DATA

Vegetation is assessed using Pathfinder Version 3 AVHRR (Advanced Very High Resolution Radiometer) FPAR data (Myneni et al. 1997) on a 0.5°x0.5° grid. FPAR is the fraction of photosynthetically active radiation absorbed by the green parts of vegetation and represents a measure of vegetation activity. All data is obtained for 1982-2000. When computing correlations and feedback parameters, the data is interpolated to a 2.5°x2.5° grid, converted to monthly anomalies by removing the annual cycle, and linearly detrended. The sources of 2.5°x2.5° monthly climate data are the NCEP-NCAR Reanalysis (Kalnay et al., 1996) for surface air temperature and CPC (Climate Prediction Center) merged analysis of precipitation dataset (Xie and Arkin 1997).

III. METHODS

The methodology of computing the feedback parameter for vegetation's forcing on the atmosphere is outlined by Liu et al. (2005). It was initially proposed by Frankignoul and Hasselmann (1977) and later applied to study SST feedback on air-sea heat flux (Frankignoul et al., 1998; Frankignoul and Kestenare, 2002) and the atmosphere's response to extratropical SSTs (Czaja and Frankignoul, 2002; Liu and Wu, 2004; Lee and Liu, 2005). As with SST, FPAR exhibits a longer memory than the atmosphere. In the present study, the impact of changes in monthly FPAR on temperature and precipitation are assessed over the United States. While feedback represents a two-way interaction, this study primarily focuses on the component of feedback with the vegetation forcing the atmosphere.

As shown by Liu et al. (2005), atmospheric variables such as temperature or precipitation can be divided into two components:

$$A(t+dt_a) = \lambda_A V(t) + N(t+dt_a)$$

A(t) is the atmospheric variable at time t, V(t) is FPAR at time t, λ_A is the feedback parameter, dt_a is the atmospheric response time (about one week), and N(t) is the climate noise generated internally by atmospheric processes that are independent of FPAR variability. The atmospheric variable is determined by $\lambda_A V(t)$, which is its feedback response to changes in FPAR, and $N(t+dt_a)$, which is atmospheric noise. As derived by Liu et al. (2005) and Frankignoul et al. (1998), the feedback parameter can be determined as:

$$\lambda_A = \frac{\mathbf{covar}[A(t), V(t-\tau)]}{\mathbf{covar}[V(t), V(t-\tau)]}$$

where τ is the time lag, which is longer than the persistence time of atmospheric internal variability. The feedback parameter is estimated as the ratio of the lagged covariance (covar) between A and V to the lagged covariance of V.

The feedback parameter quantifies the instantaneous feedback response of the atmosphere to changes in FPAR based on monthly data. For surface air temperature, λ_T is given in units of °C/0.1fpar, representing the change in observed temperature due to an increase in monthly FPAR by 0.1. For precipitation, λ_P is given in units of cm/month/0.1fpar. Positive values of λ indicate a positive forcing of FPAR on the atmospheric variable. The statistical significance of the feedback parameters is assessed using a Monte Carlo bootstrap approach with shuffled series (Czaja and Frankignoul, 2002).

IV RESULTS

This study is the first to quantify observed vegetation feedbacks over the United States. Analogous to SSTs, FPAR typically has a persistence of a few months (Fig, 1), longer than the atmosphere, and can interact with the atmosphere via several possible feedback mechanisms.

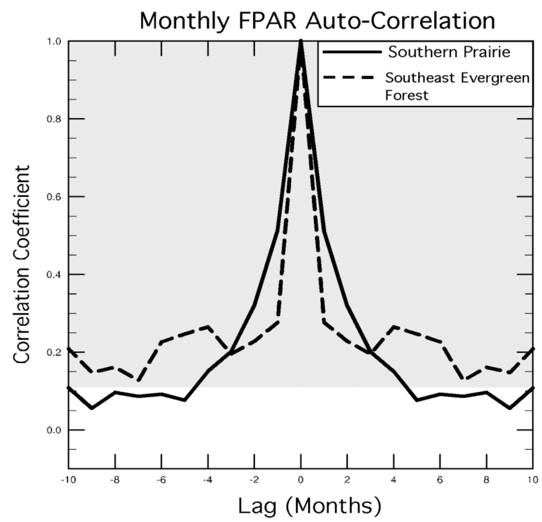

FIG. 1. Temporal autocorrelation of monthly FPAR anomalies for the southern prairie (solid) and Southeast evergreen forests (dash). Correlation coefficients are shown at different time lags, up to 10 months. Shading indicates 90% significance level.

Instantaneous correlations show that temperature is a significant control of FPAR for much of the United States (Fig. 2), particularly in MAM. Unlike temperature, correlations between FPAR and precipitation anomalies are larger when the atmospheric variable leads by one month. Much of the prairie has a statistically significant correlation between JJA FPAR anomalies and precipitation anomalies from the previous month. The largest interannual FPAR variability occurs over the central United States' prairie, where a north-south dipole is identified through EOF analysis (Fig. 3). Correlations with FPAR leading by one month suggest a positive influence of vegetation on temperature over the upper Midwest in MAM and northern Rockies in JJA. An increase in FPAR produces both decrease surface albedo and increase latent heat flux; the former increases temperature and the latter decreases temperature. This study suggests that the albedo feedback is stronger, since increases in FPAR generally lead to higher temperatures. Correlations fail to identify statistically significant feedbacks of FPAR on precipitation.

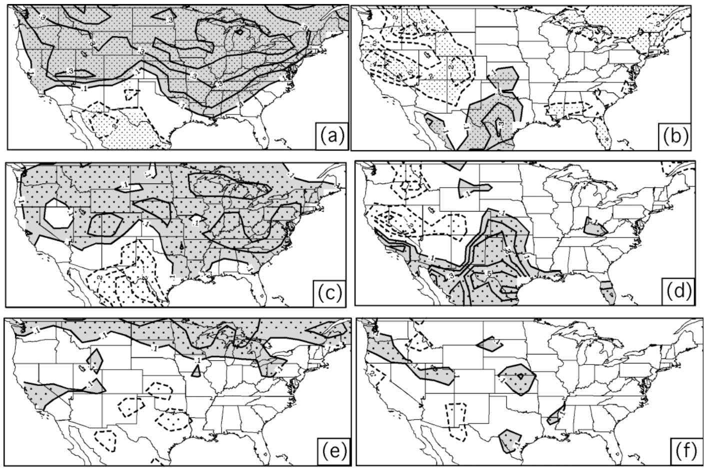

FIG. 2. Correlation between monthly anomalies of FPAR and both (a,c,e) surface air temperature and (b,d,f) precipitation. Correlations are performed (a,b) instantaneously, (c,d) with the atmosphere leading by one month, and (e,f) with FPAR leading by one month. Shading indicates positive correlations in excess of 0.1 and dotted pattern indicates 90% significance.

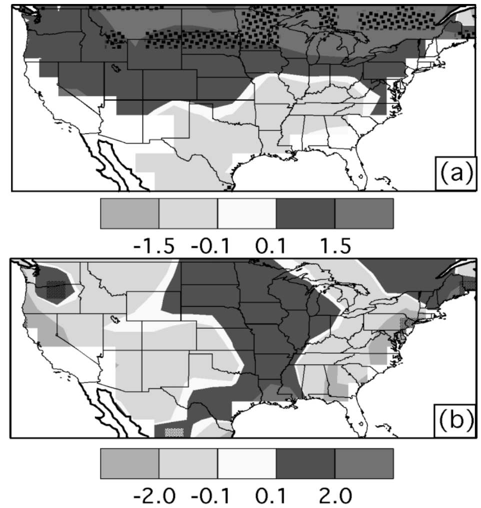

FIG. 4. (a) Vegetation feedback parameter (°C/0.1fpar) for monthly temperature anomalies. Dotted pattern indicates 90% significance. Regions with small temperature autocorrelations are masked out. (b) Vegetation feedback parameter (cm/month/0.1fpar) for monthly precipitation anomalies.

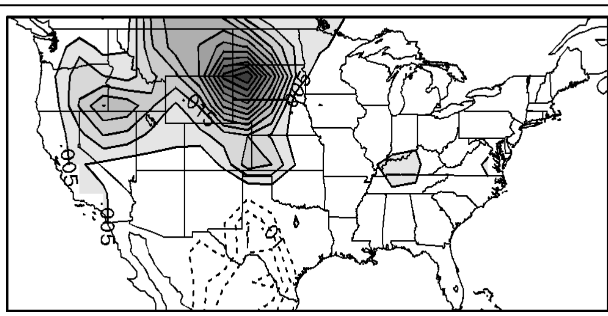

FIG. 3. Rotated EOF1 pattern for JJA FPAR anomalies. The percent explained variance is 30%. Shading indicates positive values.

In addition to lead-lag correlations, Liu et al. (2005) computed a statistical feedback parameter to relate global satellite-based FPAR and observed temperature and precipitation. The present study continues this methodology and focuses on the United States, quantifying the influence of monthly FPAR on temperature and precipitation (Fig. 4). The mean vegetation feedback parameters for temperature and precipitation average 0.9°C/0.1fpar and -0.6 cm/mon/0.1fpar, respectively, across all months.

Increases in FPAR therefore result in net warming and drying, though the effect of FPAR on precipitation is weaker than for temperature and the feedback parameter for precipitation is not generally found to be statistically significant. The mean feedback parameter for temperature is most positive during MAM and JJA, with monthly FPAR anomaly variance explaining 30% of monthly temperature variance in MAM. Maps of vegetation feedback parameters for precipitation are spatially complex, although a positive forcing over the corn and soybean belt and negative forcing over the winter wheat belt are identified when computed across all months.

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