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Reduction of spring warming over East Asia associated with vegetation feedback

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[1] Over East Asia, surface air temperature displays a significant increasing trend particularly in early months of the year for the period of 1982–2000. Warming per decade is strongest in late winter, 1.5°C in February and 1.1°C in March, but is significantly reduced in spring, 0.4°C in April and 0.1°C in May. During the analysis period, the reduced temperature increase from late winter to spring is found to be in contrast with the increased vegetation greenness derived from the satellite-measured leaf area index over the domain. We examined this inverse relationship using two climate model experiments— coupled with and without a dynamic vegetation model. In both experiments, strong warming in winter is relatively well reproduced, but weak warming in spring is observed only in the coupled experiment. Analysis of the surface energy budget indicates that weaker spring warming results from an evaporative cooling effect due to the increased vegetation greenness. Over East Asia, the vegetation-evaporation feedback, therefore, may produce seasonal asymmetry in the warming trend. **Citation:** Jeong, S.-J., C.-H. Ho, K.-Y. Kim, and J.-H. Jeong (2009), Reduction of spring warming over East Asia associated with vegetation feedback, *Geophys. Res. Lett.*, *36*, L18705, doi:10.1029/2009GL039114.

1. Introduction

[2] While surface air temperature over East Asia exhibits a significant warming trend for the last century, its magnitude is apparently different from season to season [*Trenberth et al.*, 2007]. The warming trend is more pronounced in winter, but becomes less so in spring. This seasonal asymmetry of the warming trend may be generated as a result of complex climate feedback processes involving snow, cloud, and vegetation. Decreased snow cover (and/or depth) may amplify temperature increase in winter and cloud variations also produce seasonally different warming features [*Trenberth et al.*, 2007]. While changes in vegetation may well influence temperature variations considerably over some regions, its feedback pathways are still unclear.

[3] Previous studies have documented the occurrence of earlier leaf onset and a longer growing season throughout East Asia in recent decades in association with global warming [e.g., *Ho et al.*, 2006; *Schwartz et al.*, 2006]. Changes in the seasonal vegetation activity are mainly attributed to diverse warming influences, particularly for the period from late winter to spring. The timing of leaf emergence largely responds to heat accumulation prior to leaf emergence, so that frequent warm periods in winter accelerate vegetation growth in early spring [*Ho et al.*, 2006]. Greater vegetative activity corresponding to an earlier vegetation growth means an enhancement of vegetation greenness in spring. Thus, an increase in spring vegetation greenness may, in turn, feedback to temperature by regulating surface energy fluxes.

[4] Vegetation greenness is thought to be one of major factors altering the surface energy budget. Vegetation change directly affects surface albedo, emissivity, and soil moisture content, and further alters latent and sensible heat fluxes. For example, an increase in vegetation greenness reduces albedo and thus leads to a stronger warming. Conversely, it also increases evapotranspiration thereby weakening the warming trend. Net effect of these two factors may determine the strength of warming. *Jeong et al.* [2009] showed that an increase in vegetation greenness has reduced the regional warming trend in spring over East Asia via a dominant cooling effect of vegetation-evapotranspiration feedback. It is noted that, as more leaves emerge and flourish, the amount of evapotranspiration will be increased if sufficient moisture is provided. Their results suggest that the vegetation-temperature feedback mechanism from winter to spring should be clearly detectable in the observed seasonal asymmetry of regional warming over East Asia.

[5] In the present study, we focus on the reduced warming trends from late winter to spring and examine the possible role of vegetation-temperature feedback in its seasonal asymmetry by analyzing observational data and performing two climate model experiments. Long-term simulations of a climate model coupled with a dynamic vegetation model are carried out to verify the impact of vegetation feedback on the seasonal asymmetry of warming.

2. Data and Model Experiment

[6] The leaf area index (LAI) data were obtained from the Advanced Very High Resolution Radiometer onboard National Oceanic and Atmospheric Administration polar-orbiting satellites. The LAI is constructed by substituting satellite-derived maximum normalized difference vegetation index into a three-dimensional radiative transfer model [*Myneni et al.*, 1997]. This dataset has a spatial resolution of 16 km × 16 km and a monthly temporal resolution for 1982–2000, and is currently available on-line at http://cliveg.bu.edu.

[7] The daily mean surface air temperatures for 150 Chinese stations and 4 Korean stations were obtained from the China Meteorological Administration and the Korea Meteorological Administration, respectively. Total of 154 stations are confined to the east of 100°E because

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the stations located further west are in deserts or highland areas, where LAI values are very low (virtually no vegetation) and exhibit negligible seasonal variation. In addition, urban stations (population greater than 10 million) were excluded to minimize the urbanization effect. For quality control, we have manually checked the whole data and ensured that no unreasonable bias or gaps exist in the data.

[8] To estimate the effect of vegetation-climate feedback on recent warming over East Asia, two climate model experiments were performed. We utilized the Community Atmospheric Model version 3 (CAM3) [*Collins et al.*, 2004] on a T42 horizontal resolution ($\sim 2.875^\circ \times 2.875^\circ$) with 26 hybrid-sigma vertical levels. The CAM3 uses Community Land Model version 3 (CLM3) [*Oleson et al.*, 2004] as a land-surface parameterization scheme, of which vegetation phenology is either prescribed or interactively calculated by an integrated dynamic global vegetation model (CLM–DGVM), a modified version of the Lund-Potsdam-Jena (LPJ) DGVM [*Levis et al.*, 2004].

[9] Using the present modeling system (hereafter referred to as CAM3-DGVM), we performed two hindcasting experiments, with and without interactive vegetation treatment (i.e., on and off DGVM), to quantify the vegetation-climate feedback effect. In order to obtain initial vegetation conditions for the hindcast experiments, CAM3-DGVM was spun up for 500 years resulting in the 'potential' vegetation that would be reached under the 'present' climate state without anthropogenic influences (e.g., urbanization, deforestation, or changing into crop land). Climatological mean sea surface temperatures (SSTs) and sea ice distributions (SICs) from the Hadley Centre [*Rayner et al.*, 2003] for 1950–2000 were used as boundary forcings. Greenhouse gas concentrations (GHGs) were set to climatological mean values for the same period. Then, two hindcasting experiments—on-DGVM (VegOn) and off-DGVM (VegOff) experiments—were performed with interannually varying SSTs/SICs and GHGs for 1950–2000. Simulation results for 1982–2000 were used to compare with the observational analysis. The VegOn experiment utilizes fully interactive DGVM so that vegetation in CAM3-DGVM would respond to and affect the overlying atmosphere as well. In contrast, a climatological mean seasonal cycle of vegetation calculated from the spin-up simulation results for the 451–500 model years was used for the VegOff experiment. As a result, a comparison between VegOn and VegOff experiments should provide the effect of interactive vegetation–climate feedback.

3. Seasonal Asymmetry of Linear Trends Between Temperature and Vegetation

[10] Figure 1 shows the spatial patterns of linear trends of temperature and LAI in late winter (February–March) and in spring (April–May). Linear trends were determined using the standard least-squares fitting method. The boxes in Figure 1 denote statistically significant trends ($\geq 95\%$ confidence level). Domain-averaged temperature for the 154 stations shows an obvious warming in late winter, 1.35°C 10-yr^{-1}, and a moderate warming in spring, 0.32°C 10-yr^{-1}. Seasonal asymmetry of the linear trends is clearly seen in most stations (Figures 1a and 1b). Seasonal asymmetry is most dominant over central eastern China, southern China, and South Korea. In contrast, relatively weak seasonal asymmetry is observed over northeastern China. The LAI also exhibits positive trends, but is weaker in late winter (0.06 10-yr^{-1}) and stronger in spring (0.48 10-yr^{-1}). It should be noted that the rate of change of LAI is opposite to that of temperature in late winter and spring. Namely, stronger LAI trends coincide with weaker warming trends and vice versa.

[11] To examine the physical nature of the seasonal asymmetry in warming and greening, we obtained the domain averages of temperature and LAI for the 154 stations and compared the two 5-year periods—the first five years (1982–1986) versus the last five years (1996–2000) of the analysis period. Figure 2 shows the domain-averaged temperature (solid lines) and LAI (dashed lines) from January to May. Two sets of vertical bars indicate the differences of temperature (red) and LAI (green) between the two five-year periods. Monthly temperatures for the last five years clearly exceed those for the first five years. Warming, most conspicuous in February with 2.02°C, decreases in time and is negligible in May with 0.05°C. Similarly, LAI for the last five years increased compared to that for the first five years. The LAI difference, however, is most dominant in April with 0.48, and is negligible in the winter months. Considering the asymmetry between warming and greening from late winter to spring, there is an obvious reverse relationship between the monthly trends of warming and greening. It should be noted that these monthly trends are still observed after normalizing each month by the respectively monthly standard deviation (STD) for each 5-yr period separately (figure not shown). Monthly STDs for temperatures are 0.81, 0.88, 0.65, 0.38 and 0.31 from January through May for the first 5 years and are 0.80, 0.81, 0.75, 0.39 and 0.32 for the last 5 years. On the other hand, monthly STDs of LAI are nearly the same (0.08–0.13) for both periods. Normalization was conducted to rule out that the monthly differences of warming and greening are due to monthly differences in the magnitude of variability. Thus, it is not likely that the monthly trends are due to interannual variability although it cannot be confirmed from a short record used in the present study.

[12] Warming in late winter and greening in spring are rather unexpected since enhanced greening might have been expected for enhanced warming. Given the reversed monthly trends of warming and greening over the target region, we raise a possible influence of vegetation-temperature feedback. While previous studies reported that thermal energy prior to leaf onset (late winter) is the most important factor for vegetation emergence, and earlier emergence of vegetation can induce an increase in vegetation greenness after the leaf onset period (spring) in mid-to-high latitude regions [*Ho et al.*, 2006], the present result seems to indicate that an increase in vegetation greenness can also modulate temperature change [*Jeong et al.*, 2009]. In this respect, the reduced warming and the enhanced greening trends in spring could be attributable to vegetation-temperature feedback. It should be noted that recent warming and greening trends can also be attributed to other climate factors such as snow, cloud, land-cover change, and aerosols. Thus, in order to clarify the role of vegetation-temperature feedback, we simulated tempera-

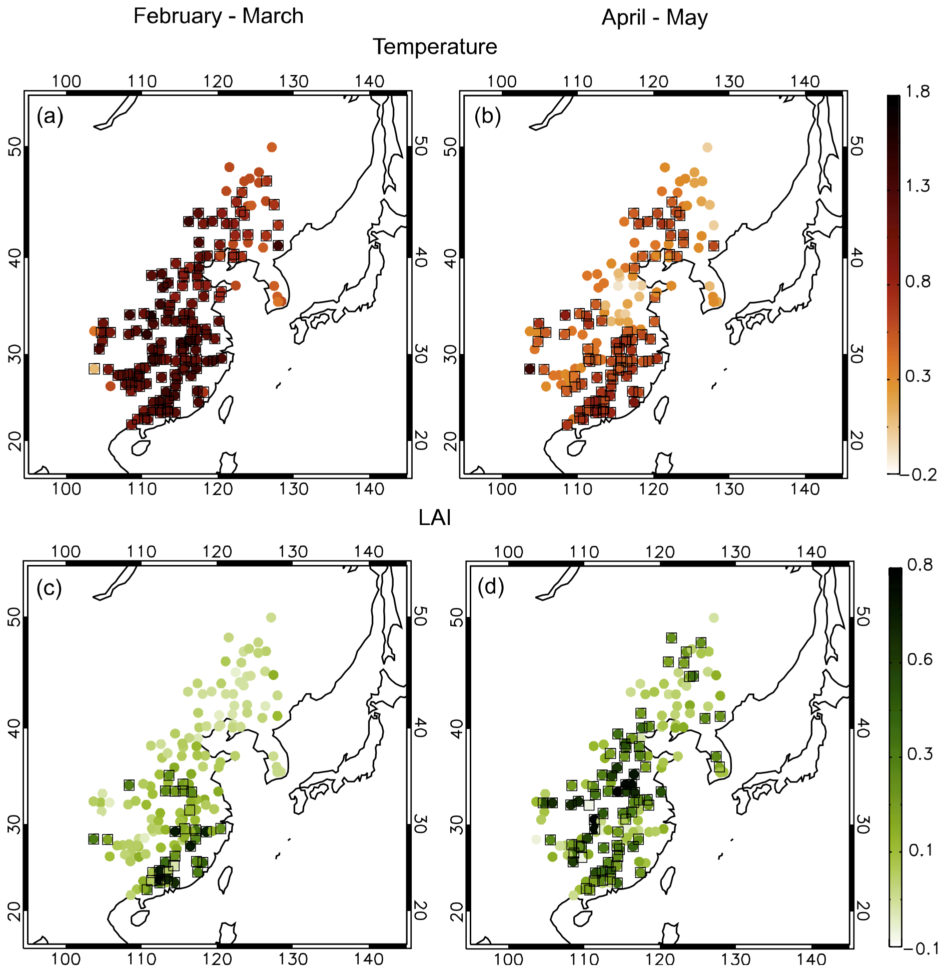


Figure 1. Linear trends of (a) February–March mean temperature, (b) April–May mean temperature, (c) February–March mean LAI, and (d) April–May mean LAI. The pixel values of LAI collected at each of the 154 stations are calculated. The units are °C/10-yr for temperature and per 10-yr for NDVI. The boxes outline the stations where trends are significant at the 95% confidence level based on the Student's *t*-tests.

ture changes from winter to spring using a climate model with dynamic vegetation.

4. Vegetation Feedbacks Simulated in the CAM3-DGVM

[13] To examine the role of vegetation-temperature feedback on the seasonal asymmetry between warming and greening, we compared the surface temperature and LAI in the VegOn and VegOff experiments. Figure 3 shows the difference in the simulated temperature and LAI between the two five-year periods, i.e., the last five years (1996–2000) minus the first five years (1982–1986) for (a) the VegOn experiment, and (b) for the VegOff experiment. All values are averaged over East Asia (105E°–135°E, 20°N–50°N) to be consistent with the observed results (Figure 2). In Figure 2, solid and dashed lines represent temperature and LAI, respectively.

[14] Comparing with observations, the simulated monthly temperatures are reasonable in both experiments (Figure 2 versus Figure 3) except that the simulated temperatures in January and February are rather high (by over 5°C); this may be due to the absence of other external factors (e.g.,

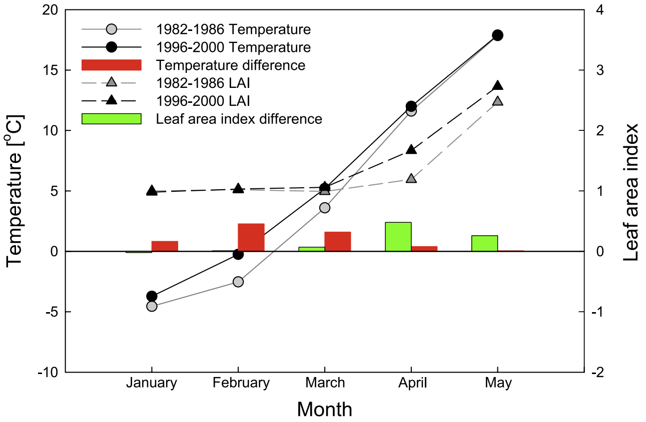
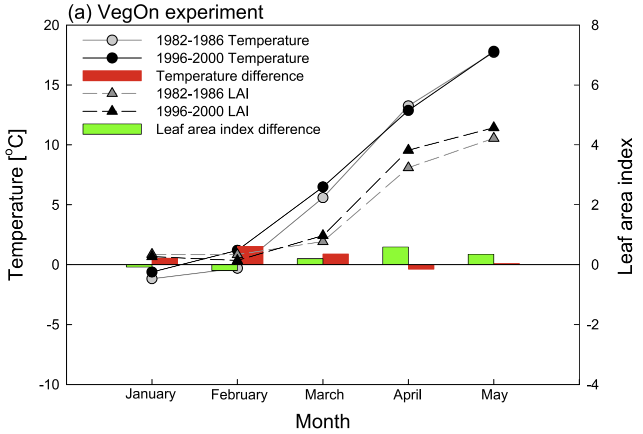


Figure 2. Observed differences in the monthly temperature and LAI from January to May between the 5-yr average for the period 1982–1986 and that for the period 1996–2000. Solid lines represent the monthly mean temperatures, and dashed lines represent the monthly mean LAI. Two sets of vertical bars indicate the temperature (red, right) and LAI (green, left) differences between the two 5-yr periods.


(a) VegOn experiment

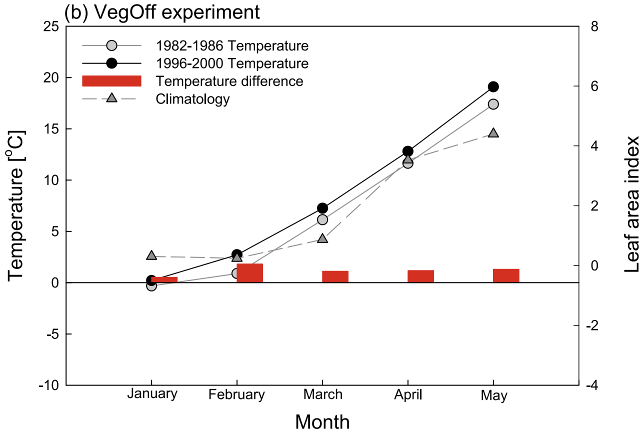

(b) VegOff experiment

Figure 3. Simulated differences in the monthly temperature and LAI from January to May between 5-yr averages for the period 1982–1986 and that for the period 1996–2000 for (a) VegOn simulation, and (b) for VegOff simulation. Solid lines represent the monthly mean temperatures, and dashed lines represent the monthly mean LAI. Two vertical bars represent the temperature (red, right) and LAI (green, left) differences between the two 5-yr periods.

land-cover change and irrigation) in the model experiments and/or model bias. Accepting that the mean monthly temperatures are slightly different between observation and model, both experiments nonetheless reasonably capture the warming trends from winter to spring. Since the purpose of our model experiments is to evaluate the potential impact of vegetation in the warming, the results of the experiments should be sufficiently applicable. In the simulated monthly temperatures, warming is clearly observed in both experiments; the most pronounced temperature increase is in February, 1.78°C in the VegOn experiment and 1.82°C in the VegOff experiment, which is consistent with observations. During the spring months, the rate of warming becomes smaller in time (1°C on March, −0.37°C April, 0.08°C May) in the VegOn experiment, but remains almost the same (1.12°C on March, 1.11°C April, 1.30°C May) in the VegOff experiment. The *t*-test using daily temperatures confirms that difference in the spring warming rates between the two experiments is significant at a 90% confidence level. This difference is still clear when monthly temperatures are normalized by the respective standard deviation for each month. Thus, internal variability of temperature is not a likely source of the difference.

[15] The monthly trend of LAI is also reasonably represented by the model. The simulated monthly mean LAI is slightly higher than the observations (Figure 2 versus Figure 3). A different prescription of vegetation types in the model seems to evoke this discrepancy; the simulated vegetation is mainly broadleaf deciduous tree, but the observed vegetation consists of broadleaf deciduous trees and abundant cropland over East Asia. Note that an increase in LAI between the two 5-year periods is seen only from March onward in the VegOn experiment. There is no year-to-year variation of LAI in the VegOff experiment, since climatological mean values of CAM3-DGVM were prescribed. The most conspicuous increase is in April (0.58) in the VegOn experiment, which is consistent with the observed LAI. Reduced warming and enhanced greening trends during the spring are found only in the VegOn experiment. This implies that vegetation-temperature feedback plays a crucial role in producing the seasonal asymmetry in the warming trend. In the model dynamic vegetation process, leaf emergence of broadleaf deciduous trees is largely regulated by accumulated temperature from winter. Thus, the enhanced warming in winter should have lead to an earlier growth and increased the vegetation greenness in spring in the VegOn experiment. The reduced warming trends related to the vegetation feedback can be confirmed through an examination of the changes in surface energy balance.

[16] Differences in selected surface energy fluxes in late winter and spring between the two five-year periods for the VegOn and the VegOff experiments are summarized in Table 1. Regardless of the season, the most substantial change between the two 5-yr periods is in SW in both experiments. Net radiation (SW minus LW) for the last five years clearly increased from that of the first five years in both experiments. Energy partitioning of net radiation, on the other hand, is quite different between the interactive and

Table 1. February–March and April–May Differences in Selected Surface Energy Fluxes Between the Period 1982–1986 and the Period 1996–2000 for the VegOn and the VegOff Experiments Over East Asia[a]

	February–March		April–May	
Variables	VegOn Difference	VegOff Difference	VegOn Difference	VegOff Difference
SW	7.1	8.0	14.2	15.4
LW	3.0	4.0	3.2	6.2
LH	1.0	2.0	8.0	4.3
SH	2.0	1.7	2.1	4.3
G	1.1	0.3	0.9	0.6

[a] In the model, net radiation (SW minus LW) at surface is divided into LH, SH, and G. The acronyms stand for SW: net shortwave flux, LW: net longwave flux, LH: latent heat flux, SH: sensible heat flux, and G: ground heat flux with the unit of W m^{-2}.

the prescribed vegetations. Examining the changes in all surface fluxes, the most dominant differences between the two experiments are in latent heat flux (LH) and sensible heat flux (SH). In the VegOn simulation for April–May, a substantial fraction of the net radiation change (11.0 W m^{-2}) is compensated by LH (8.0 W m^{-2}) but compensation by LH (4.3 W m^{-2}) is smaller in the VegOff simulation. The ratio of SH to LH (Bowen ratio) is smaller in the VegOn experiment (0.26) than in the VegOff experiment (0.99), which suggests that evaporative cooling effect by vegetation is larger in the VegOn simulation. Besides, an increased absorption of shortwave radiation in the VegOn simulation due to reduced albedo as a result of increased LAI (i.e., positive feedback between vegetation and albedo), was not found in our result. It appears that the dominant impact of LAI changes is in the modification of energy partition between latent and sensible heat fluxes, but not in the surface albedo. These results are also consistent with the surface energy budget in association with vegetation [*Cowling et al.*, 2009].

5. Concluding Remarks

[17] Long-term trends in temperature and in LAI over East Asia have been analyzed in late winter and spring for 1982–2000. The strongest warming is observed in late winter (February), while warming is significantly reduced in spring (April–May). In contrast, LAI change is negligible in late winter, but it increases significantly in spring. This reversed trend between the two variables was confirmed by two sets of climate model experiments with interactive and prescribed vegetation processes. The interactive vegetation experiment (VegOn) produces a weakening of spring warming, but fairly constant warming is simulated in late winter and spring in the experiment without interactive vegetation (VegOff). The difference is due to the increased LAI leading to a greater contribution of LH than SH in the surface energy budget in the model simulation. This result clearly implies that the observed reduced warming in spring can be attributed to the vegetation feedback process.

[18] Although the interactive vegetation experiment qualitatively well simulated changes in temperature and LAI, simulated model vegetation types are somewhat different from those in observations. Abundant crop distribution over the target region might have induced discrepancy of model results from observation (i.e., slightly weaker warming in model). CAM3-DGVM system does not resolve the effect of cropland and urbanization during this period, which might have been of considerable influence on regional climate over East Asia. This study does not attempt to improve climate models, but only evaluates the impact of a potential vegetation feedback between temperature and vegetation. Unfortunately, this study was performed using a climate model with a coarse resolution. For more accurate confirmation of the vegetation feedback, it is necessary to carry out ensemble simulations (possibly using coupled ocean-atmospheric GCMs) on a fine resolution and investigate the different impacts of natural vegetations (i.e., deciduous forest, evergreen forest) and human-induced vegetation (i.e., crop, wheat) on climate.

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