Comprehensive Study on the Influence of Evapotranspiration and Albedo on Surface Temperature Related to Changes in the Leaf Area Index

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ABSTRACT

Many studies have investigated the influence of evapotranspiration and albedo and emphasize their separate effects but ignore their interactive influences by changing vegetation status in large amplitudes. This paper focuses on the comprehensive influence of evapotranspiration and albedo on surface temperature by changing the leaf area index (LAI) between 30°–90°N. Two LAI datasets with seasonally different amplitudes of vegetation change between 30°–90°N were used in the simulations. Seasonal differences between the results of the simulations are compared, and the major findings are as follows. (1) The interactive effects of evapotranspiration and albedo on surface temperature were different over different regions during three seasons [March–April–May (MAM), June–July–August (JJA), and September–October–November (SON)], i.e., they were always the same over the southeastern United States during these three seasons but were opposite over most regions between 30°–90°N during JJA. (2) Either evapotranspiration or albedo tended to be dominant over different areas and during different seasons. For example, evapotranspiration dominated almost all regions between 30°–90°N during JJA, whereas albedo played a dominant role over northwestern Eurasia during MAM and over central Eurasia during SON. (3) The response of evapotranspiration and albedo to an increase in LAI with different ranges showed different paces and signals. With relatively small amplitudes of increased LAI, the rate of the relative increase in evapotranspiration was quick, and positive changes happened in albedo. But both relative changes in evapotranspiration and albedo tended to be gentle, and the ratio of negative changes of albedo increased with relatively large increased amplitudes of LAI.

Key words: surface temperature, evapotranspiration, albedo, leaf area index, comprehensive influence


1. Introduction

As the interface between the land surface and the atmosphere, vegetation plays a significant role in regulating the land–atmosphere interaction, thereby affecting regional and global climates. Its variations influence the exchange of heat, mass, and momentum between the land surface and the lower atmosphere (Dickinson et al., 1992; Bonan, 1994; Guillevic et al., 2002; Kang et al., 2007; Li and Xue, 2010). Pielke et al. (1998) suggested that vegetation dynamics might be as important for climate as other forcings, such as atmospheric dynamics and composition, ocean circulation, ice sheet extent, and orbit perturbations.

In recent decades, many studies have been conducted to detect the effects of vegetation on albedo (Charney et al., 1975; Sud and Fennessy, 1982; Bonan et al., 1992; Claussen et al., 2001), evapotranspiration (ET; Shukla and Mintz, 1982; Chen and Zeng, 2012; Zhu and Zeng, 2014), and surface roughness length (Sud et al., 1988). Generally speaking, increased vegetation over the Northern Hemisphere is expected to reduce surface albedo because of an increase in the amount of solar radiation absorbed by vegetation, which may result in further regional or even global climate warming. For example, Levis et al. (2000) showed that this process could increase global warming during the 21st century when considering the northward expansion of the boreal forests as a result of climatic warming. Bonfils et al. (2012) also determined that an invasion of the tundra by tall shrubs tended to systematically warm the soil. However, increased vegetation also accompanies intensified evapotranspiration, which is favorable for cloud development and causes surface cool-
ing (Bounoua et al., 2000; Buermann et al., 2001). These opposing biophysical effects of vegetation—warming through increased energy absorption (relatively low albedo) and cooling through increased evaporation—tend to dominate at different latitudes, depending on the regional climate characteristics and geographical features (Meir et al., 2006; Xue et al., 2010). Many studies emphasize one aspect of the effects of increased vegetation, but ignore its interactive influences. Therefore, the goal of this paper is to discuss the comprehensive impacts of evapotranspiration and albedo on surface temperature. Throughout this entire paper, we will always maintain the concept that the importance of evapotranspiration and albedo for surface temperature is on the same level.

Many previous studies used relatively large amplitude changes to investigate the influence of vegetation on temperature. For instance, Dickinson and Henderson-Sellers (1988) and Shukla et al. (1990) replaced tropical forests with grass, which led to warmer and drier conditions. Over the mid–high latitudes, simulations with boreal forest result in warmer conditions than those with bare ground or tundra (Bonan et al., 1992). More recently, both Bounoua et al. (2000) and Buermann et al. (2001) applied maximum and minimum leaf area index (LAI) values from yearly satellite records to investigate the impact of extreme variability in the amount of vegetation on temperature. These experiments provide valuable references for understanding the influence of vegetation on climate but also may bracket these influences with relatively large changes in the amount of vegetation. However, in this paper, the results are discussed with different ranges of LAI changes. Furthermore, changes in climate are expected to be larger over the mid–high latitudes relative to the tropics. The entire poleward shift of the boreal ecosystem that arises from regional warming and increasing CO₂ levels may have significant impacts on climate, including changes in precipitation patterns, carbon levels, and the energy balance (Lucht et al., 2006; Schaphoff et al., 2006; Alo and Wang, 2008; O’Ishi and Abe-Ouchi, 2009). Thus, the region over 30°–90°N was selected as the research focus.

In the next section, the model and LAI datasets that were applied in this study, as well as the experimental design, are described. Section 3 presents the results and discussion, emphasizing the comprehensive effects of evapotranspiration and albedo on surface temperature. Finally, concluding remarks are given in section 4.

2. Model, data, and experimental design

2.1. Model description

In this study, we employed the coupled model of the Community Earth System Model (CESM), including the atmosphere and land components of the Community Atmosphere Model version 4 (CAM4; Neale et al., 2013) and the Community Land Model version 4 (CLM4; Oleson et al., 2010; Lawrence et al., 2011), respectively. CLM4 represents the fundamental physical, chemical, and biological processes of the terrestrial ecosystem and describes the water, energy, and carbon–nitrogen processes by coupling with the carbon–nitrogen model (CN) and the dynamic vegetation model (CNDV, Castillo et al., 2012). When the CN or CNDV model is inactive, the prescribed LAI data is used as the boundary condition.

2.2. Leaf area index

Two sets of LAI data were applied in this study. One was the LAI used in CLM4 (the default LAI), which is the climatological mean with monthly variability at a 0.9° lat × 1.25° lon horizontal resolution. Figure 1 shows its spatial differences between March–April–May (MAM) and December–January–February (DJF), June–July–August (JJA) and DJF, as well as September–October–November (SON) and DJF over 30°–90°N. It is in line with expectations that the average LAI in MAM, JJA and SON should be larger than that in DJF. By and large, the amplitudes of the differences between JJA and DJF are largest, followed by those between SON and DJF, and then MAM and DJF. Therefore, for the purposes of investigating the influence of a change in the LAI in different and reasonable ranges, we constructed another dataset, the idealized LAI data, from the default LAI dataset. For the idealized LAI, each monthly value over 30°–90°N was the averaged value of DJF of the default LAI, whereas over other regions, it was the same as the default LAI. Consequently, by analyzing the seasonal results of the simulations using the two LAI datasets, the influence of a change in the seasonal amplitudes of the LAI could be investigated.

2.3. Experimental design

Two simulations, CTL and IDL, utilizing the default LAI and the idealized LAI, respectively, were performed. Beyond this, the two simulations were totally identical. For example, the atmosphere and land components were active in both simulations, and they were both driven by historical sea surface temperatures for 1979–2003 (Hurrell et al., 2008). Both simulations were run at a 0.9° lat × 1.25° lon horizontal resolution with the carbon and nitrogen cycles turned off.

3. Results and discussion

In this section we discuss the seasonal changes to evapotranspiration and albedo, which were directly influenced by the changes to the LAI, and emphasize their comprehensive influences in determining surface temperature. When referring to differences in the following sections, we mean CTL minus IDL averaged over the last 23 years of the simulations (1981–2003).

3.1. MAM

Generally, the CTL’s surface temperature increased over high latitudes and decreased over mid latitudes when compared to IDL (Fig. 2). The main statistically significant regions, indicated by the three boxes in the figure, were selected as the objective areas. Over the southeastern United States (area 1), the increased LAI led to an increase in both