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The role of surface roughness, albedo, and Bowen ratio on ecosystem energy balance in the Eastern United States

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ABSTRACT

Land cover and land use influence surface climate through differences in biophysical surface properties, including partitioning of sensible and latent heat (e.g., Bowen ratio), surface roughness, and albedo. Clusters of closely spaced eddy covariance towers (e.g., < 10 km) over a variety of land cover and land use types provide a unique opportunity to study the local effects of land cover and land use on surface temperature. We assess contributions albedo, energy redistribution due to differences in surface roughness and energy redistribution due to differences in the Bowen ratio using two eddy covariance tower clusters and the coupled (land-atmosphere) Variable-Resolution Community Earth System Model. Results suggest that surface roughness is the dominant biophysical factor contributing to differences in surface temperature between forested and deforested lands. Surface temperature of open land is cooler (−4.8 °C to −0.05 °C) than forest at night and warmer (+0.16 °C to +8.2 °C) during the day at northern and southern tower clusters throughout the year, consistent with modeled calculations. At annual timescales, the biophysical contributions of albedo and Bowen ratio have a negligible impact on surface temperature, however the higher albedo of snow-covered open land compared to forest leads to cooler winter surface temperatures over open lands (−0.4 °C to −0.8 °C). In both the models and observation, the difference in mid-day surface temperature calculated from the sum of the individual biophysical factors is greater than the difference in surface temperature calculated from radiative temperature and potential temperature. Differences in measured and modeled air temperature at the blending height, assumptions about independence of biophysical factors, and model biases in surface energy fluxes may contribute to daytime biases.

1. Introduction

Land cover influences surface climate through radiative (i.e. albedo) and non-radiative (i.e. surface roughness and Bowen ratio) biophysical surface properties (Bonan, 2008). Non-forested land generally has a higher albedo than forested land (Betts and Ball, 1997; Moody et al., 2007; Jin et al.,2002), which leads to daytime cooling in deforested areas. The surface roughness warms forest relative to open land by drawing warmer air from aloft via increased turbulence at night; during the day, deforested lands experience suppressed mixing while forests cool through more efficient dissipation of sensible heat (Rotenberg and Yakir, 2010). At night, surface roughness cools open land relative to forests, which are hypothesized to draw warmer air from aloft through increased turbulent mixing and release a greater amount of stored heat compared to open lands (Lee et al., 2011; Schultz et al., 2017). During the growing season, forests often have cooler surface temperatures than open fields due to greater evaporative cooling (i.e. higher Bowen ratio; Juang et al., 2007). However, irrigation of cropland can increase the Bowen ratio and cool surface temperatures over open lands compared to forests (Adegoke et al., 2003; Kueppers et al., 2007).

In addition to the general biophysical responses across land cover types, the relative contributions of albedo, Bowen ratio, and roughness to differences in surface temperature can vary by biome and latitude. In the high latitudes, albedo has been recognized as the dominant biophysical forcing factor of land cover on surface climate, primarily due to snow cover (Feddema et al., 2005; Betts et al., 2007; Davin et al., 2007; Burakowski et al., 2016). In the tropics, forests cool surface temperatures through enhanced evapotranspiration compared to

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grassland and cropland (Li et al., 2015). In the mid-latitudes, however, the contribution of LULCC-driven differences in albedo, evapotranspiration, and surface roughness to biophysical forcing of surface climate remains unclear (Bonan 2008).

Multiple global climate model studies have concluded that historical mid-latitude deforestation cooled the Northern Hemisphere, primarily through an increase in surface albedo when agricultural lands replaced forest (Brovkin et al., 2006; Betts, 2001; Betts et al., 2007; Davin and de Noblet-Ducoudré, 2010; Kvalevåg et al., 2010). The presence of seasonal snow cover in the mid-latitudes strengthens cooling over open lands relative to forest due to the increased surface albedo over open lands resulting from snow burial of the short canopy.

Non-radiative processes such as evaporative efficiency and surface roughness have recently been acknowledged as having an effect on surface temperature comparable in magnitude and opposite in sign to radiative processes. Davin and de Noblet-Ducoudré (2010) conducted a series of idealized global deforestation experiments with the Institut Pierre-Simon Laplace (IPSL) model to evaluate the relative contributions of albedo, surface roughness, and evapotranspiration efficiency on surface temperature differences between forest and grassland. Between 40°N and 50°N, radiative cooling of grasslands compared to forests from albedo (−2.2 K) was mitigated by warming from non-radiative surface roughness (+1.1 K) and evapotranspiration efficiency (+0.75 K) effects. Nonlinear effects were calculated as the residual between the reconstructed signal and overall net biogeophysical effect, however the mechanisms explaining possible nonlinear interactions were not explored. Using the Community Climate System Model (CCSM), Lawrence and Chase (2010) report that reductions in evapotranspiration and latent heat are the primary drivers of surface temperature changes resulting from land cover change, with radiative forcing playing a secondary role. A similar finding was reported in the 'Land-Use and Climate, Identification of robust impacts' (LUCID) multi-model ensemble of global climate models (de Noblet-Ducoudré et al., 2012). A multi-variate analysis demonstrated that surface cooling from historical deforestation is significantly dampened by non-radiative processes (Boisier et al., 2012).

Studies that used remote sensing approaches also highlight the importance of non-radiative processes on surface temperature. For example, using satellite-derived albedo, land surface temperature (LST), and evapotranspiration (ET), Zhao and Jackson (2014) evaluated the biophysical effects of LULCC on LST. They found that longwave radiative forcing induced by changes in LST and ET were comparable or exceeded the shortwave radiative forcing from changes in albedo (Zhao and Jackson, 2014). Li et al. (2015) suggest that between 35°N and 45°N, the biophysical effects of albedo (i.e., cooling) and evapotranspiration (i.e., warming) are equivalent and opposite in sign, leading to weak differences in land surface temperature between forested and deforested lands. An analysis that combined ground observations and remote sensing demonstrated that surface cooling from increased albedo of deforested lands is offset by warming from decreased sensible heat fluxes, resulting in a net warming at the surface (Luyssaert et al., 2014). Most recently, Bright et al. (2017) combined remote sensing and in situ observations to demonstrate that non-radiative processes dominate local responses to land cover and land management changes.

Observations from eddy covariance towers suggest that the overall cooling effect from deforestation is strongly influenced by non-radiative processes. In the southeastern United States, the effects of eco-physiological and aerodynamic attributes cooled hardwood and pine forests relative to grassland by 2.9 °C and 2.1 °C, respectively, compared to albedo, which warmed forests by 0.7 °C to 0.9 °C (Juang et al., 2007). In California, an oak savanna daily-averaged potential air temperature was 0.5 °C warmer than an adjacent annual grassland due to the lower albedo and aerodynamic roughness (Baldocchi and Ma, 2013). Lee et al. (2011) formulated the intrinsic biophysical mechanism to decompose the factors contributing to surface temperature differences between forested and open lands. Specifically, an observed surface temperature difference can be separated into the energy exchange due to differences in albedo, surface roughness, and Bowen ratio. In temperate regions, the low surface roughness of non-irrigated grasslands contributes 1 K of annual surface temperature warming relative to forests. In contrast, higher surface albedo of grasslands cools surface temperature by −0.5 K and increased Bowen ratio also cools grasslands by −0.25 K (Lee et al., 2011). However, a diurnal asymmetry leads to a stronger surface roughness effect during the day (+2 K warming over grasslands) than at night (−0.5 K cooling over grasslands). During the daytime, the increased surface roughness of forest canopies contributes to greater dissipation of heat compared to aerodynamically smooth grasslands, whereas the mixing at night above forests canopies draws warmer air from aloft (Schultz et al., 2017). A similar paired FLUXNET site study confirmed surface roughness as the dominant biogeophysical feedback from land cover and land use change, however coupled climate model deforestation experiments indicated that large scale atmospheric changes, or indirect feedbacks, tend to mitigate the direct effect of surface roughness (Chen and Dirmeyer, 2016).

Here, we build upon previous modeling and observational eddy covariance studies to evaluate how well a coupled land-atmosphere model simulates biophysical contributions of albedo, surface roughness, and evapotranspiration to surface temperature in a mid-latitude temperate region of the Eastern United States. We compare sub-grid simulations performed using the Variable-Resolution Community Earth System Model (VR-CESM) to two eddy covariance tower clusters in the Eastern United States. The eastern United States was chosen because of the availability of two closely spaced tower clusters that represent dominate forest and deforested land cover types in the region. Observational towers located within close proximity receive more similar atmospheric forcing conditions than towers located tens or hundreds of kilometers apart. The close proximity thus more closely resembles conditions simulated for sub-grid model output, in which plant functional types receive the same atmospheric forcing conditions for a given grid cell. First, we evaluate tower-derived and modeled contributions of albedo, roughness, and evaporative cooling using the Lee et al. (2011) approach at the site level. We then use sub-grid, PTF-level regional simulations to explore spatial differences in biophysical factors over the entire eastern US.

2. Datasets and methods

2.1. Eddy covariance tower clusters

2.1.1. University of New Hampshire, Durham, New Hampshire (NH)

The tower cluster in Durham, New Hampshire was installed in 2014 and includes three Eddy covariance towers that collect data over a cornfield (UNH-corn), a hayfield consisting of C3 non-arctic grass (UNH-grass), and a broadleaf deciduous temperate forest (UNH-hardwood) (Fig. 1). The sampling period included uninterrupted snow cover from January 2015 through late March 2015 at all three sites, with snow cover persisting through early April 2015 at the UNH-hardwood site.

The towers sampled meteorological and near-surface eddy covariance fluxes at half-hourly intervals (Table 1). Turbulent sensible and latent heat fluxes were measured using a LI-COR® LI-7200 enclosed path CO_2/H_2O analyzer and Gill® Windmaster sonic anemometer at 1 m above the cornfield and hayfield canopies, and 5 m above the forest canopy. Turbulent fluxes were calculated using the EddyPro® open source software (EddyPro®, 2014). Radiative fluxes were measured using Kipp & Zonen CNR4 net radiometers that measure incoming and outgoing longwave and shortwave radiation at each tower.

Gap filling for missing meteorological data (air temperature, incoming shortwave, precipitation, relative humidity, and wind speed) in the flux tower cluster was performed using two United States Climate Reference Network (USCRN) stations that provide sub-hourly