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Interannual and seasonal variations in energy and carbon exchanges over the larch forests on the permafrost in northeastern Mongolia

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Abstract

The larch forests on the permafrost in northeastern Mongolia are located at the southern limit of the Siberian taiga forest, which is one of the key regions for evaluating climate change effects and responses of the forest to climate change. We conducted long-term monitoring of seasonal and interannual variations in hydrometeorological elements, energy, and carbon exchange in a larch forest (48°15′24″N, 106°51′3″E, altitude: 1338 m) in northeastern Mongolia from 2010 to 2012. The annual air temperature and precipitation ranged from −0.13 °C to −1.2 °C and from 230 mm to 317 mm. The permafrost was found at a depth of 3 m. The dominant component of the energy budget was the sensible heat flux (H) from October to May (H/available energy [R_a] = 0.46; latent heat flux [LE]/R_a = 0.15), while it was the LE from June to September (H/R_a = 0.28, LE/R_a = 0.52). The annual net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (RE) were −131 to −257 gC m^{-2} y^{-1}, 681–703 gC m^{-2} y^{-1}, and 423–571 gC m^{-2} y^{-1}, respectively. There was a remarkable response of LE and NEE to both vapor pressure deficit and surface soil water content.

Keywords: Energy and carbon flux; Larch; Permafrost; Mongolia; Vapor pressure deficit; Soil water content

1. Introduction

The concentration of atmospheric CO_2 has increased from a pre-industrial value of about 280–379 ppm in 2005 (Solomon et al., 2007). Forests cover 30% of the land surface and store 45% of terrestrial carbon, and can sequester large amounts of carbon annually (Bonan, 2008). Luyssaert et al. (2007) have made a comprehensive analysis of the carbon budget using data from 513 forest sites from all over the world. They showed that the gross primary production (GPP) of forests, which is the gross uptake of CO_2 that is used for photosynthesis, benefited from higher temperatures and precipitation. On the other hand, the net ecosystem production (NEP), which is

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the balance of net primary production (NPP), that is, the balance of photosynthesis and autotrophic respiration and heterotrophic respiration, was found to be independent of annual temperatures and precipitation (Luyssaert et al., 2007). They suggested that the carbon budgets of semiarid forests (boreal, temperate, and tropical) would benefit most from additional data inputs due to small sample sizes and high variability among sampled sites. Boreal forests had a consistent average sink of 0.5 ± 0.1 PgC y^{-1} for 1990–2007 and Asian Russia had the largest carbon sink in boreal forests (Pan et al., 2011). Schulze et al. (1999) argued that European forests have a higher total net primary productivity than Siberia (1.2–1.6 vs. 0.6–0.9 $\times$ 10^{15} gC per region per year), despite a smaller area, because of differences in growing season length, climate, and nutrition. In East Asian forests, there is a clear linear relationship between annual GPP and annual mean air temperature (Hirata et al., 2008). Hirata et al. (2008) also found a strong exponential relationship between annual ecosystem respiration (RE) and annual mean air temperature. In their analysis, the photosynthetic photon flux density influenced the seasonal and interannual variation of GPP of subarctic and temperate forests while GPP was not influenced at the other sites. Kato and Tang (2008) estimated that the net ecosystem exchange (NEE: negative NEE indicates sequestration of carbon from the atmosphere into the terrestrial ecosystem) at forests in boreal Asia was -132.6 ± 73.7 gC m^{-2} y^{-1}, which correlated linearly with mean annual temperature and logarithmically with precipitation. They suggested that additional information should be obtained in the future from arid areas of Asia to evaluate the effect of drought on the NEE. In addition, they pointed out that the shorter period of measurement may cause significant bias in some ecosystems due to the failure to account for the effect of disturbances. There have been limited studies regarding the long-term carbon budget of subarctic forests.

Surface climate is determined by the balance of fluxes, which can be changed by radiative (e.g., albedo) or non-radiative (e.g., water-cycle-related processes) terms. Both radiative and non-radiative terms are controlled by details of vegetation (Denman et al., 2007). The atmosphere both controls and responds to the partitioning of solar energy into sensible and latent heat (evaporation) fluxes at vegetated surfaces, largely because of stomatal regulation. Evaporation is also a major component in the water balance, influencing water availability and so on, and influences ecosystem dynamics including carbon sequestration and storage (Kelliher et al., 1997). Forests have low surface albedo and can mask the high albedo of snow, which contributes to planetary warming through increased solar heating of the land. The ratio of evapotranspiration to available energy is generally low in forests compared with some crops and lower in conifer forests than deciduous broadleaf forests (Bonan, 2008). The boreal forest, one of the world's larger biomes, is distinct from other biomes because it experiences a short growing season and extremely cold winter temperatures (Baldocchi et al., 2000). In boreal forests in Canada, the evapotranspiration rate was less than 2 mm d^{-1} over the growing season for coniferous species according to the observations of the Boreal Ecosystem Atmospheric Study (BOREAS; Sellers et al., 1995). The coniferous sites of BOREAS were observed to have the lowest growing season albedos for any vegetated surface that we know of, about 0.08, and the winter albedo was around 0.25 (Sellers et al., 1997). Despite the potential importance of the Siberian taiga in the Asian boreal region's surface–atmosphere energy exchange for regulating the Northern Hemisphere climate, there was little study of surface fluxes in this region (Kelliher et al., 1997). They showed that the average daily evaporation was 1.9 mm d^{-1} in a 130-year-old stand of larch trees (*Larix gmelinii*) located 160 km south of Yakutsk in eastern Siberia, which is relatively low. Although their observation was for only 2 weeks in July, the mean evapotranspiration rate was 1.16 mm d^{-1} from April 21 to September 7, 1998, while it was 1.5 mm d^{-1} for the growing season from June 1 to August 31 in a larch forest near Yakutsk in eastern Siberia (Ohta et al., 2001). Ohta et al. (2008) found that the annual evapotranspiration, including interception loss, was relatively steady at 169–220 mm y^{-1} compared with the wide range in annual precipitation (111–347 mm y^{-1}) for 7 years from 1998 to 2006 in a larch forest in eastern Siberia at the same site as Ohta et al. (2001). Dolman et al. (2004) revealed that the average evapotranspiration rate of the forest approached 1.46 mm y^{-1} during the growing season, with peak values of 3 mm y^{-1}. Most studies were based on a single year of measurement except for Ohta et al. (2008). They pointed out that the interannual variation of evapotranspiration was small, but the yearly evapotranspiration coefficient (the ratio of evapotranspiration to potential evaporation) ranged from 0.30 to 0.45, which suggests that the interannual variation of evapotranspiration was controlled by the regulation of the land surface rather than by atmospheric demand. They also suggested that the soil