GAME-Siberia findings on one-dimensional land-surface processes in forested areas and follow-up research

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Abstract

Global Energy and Water-cycle Experiment (GEWEX) Asian Monsoon Experiment-Siberia (GAME-Siberia) field research extended from 1996 to 2002 and included two intensive observation periods in 1998 and 2000. This paper summarizes four major findings on one-dimensional (1-D) land-surface processes related to water and energy cycles. First, plant phenology strongly affects the energy balance above larch forest canopy in the middle reaches of the Lena River, and the Bowen ratio dramatically decreases owing to leaf foliation. Second, no significant inter-annual variation of evapotranspiration was found, although precipitation varied widely by year. Steady evapotranspiration resulted from trees' use of permafrost meltwater. Third, energy budget differences above larch and pine forests were remarkable in early spring, but Bowen ratios were similar in summer. Finally, parameters indicating canopy-conductance response were similar in larch and pine forests in the middle reaches of the Lena River, but differed in larch forests located between the Lena's middle reaches and headwaters.

Keyword: Siberian forest, water balance, energy balance, one-dimensional scale, inter-annual andseasonalvariations

1. Introduction

Boreal forests stretch from 45° N to 70° N, occupying an area of 13.7 million km^2 and comprising one third of the world's forests. Forty percent of boreal forests are found in Siberia. Siberian forests may play an important role in the climate system, but water and energy balance characteristics in this region are still unclear.

Intensive investigations of water and energy exchanges began in the early 1900s in Scandinavia (NOPEX; Halldin *et al*., 1999) and North America (BOREAS; Sellers *et al*., 1995, 1997). However, little is known of water and energy cycles in Siberia, especially in eastern Siberia. Previous research focused on short-term observations from central and eastern Siberia (Kelliher *et al*., 1997, 1998). The GAME-Siberia project examined three ecological regions (tundra, plain taiga, and mountain taiga) of the Lena River watershed from 1998–2002 and included two intensive observation periods.

GAME research revealed important aspects of water and energy cycles in eastern Siberian forests. This paper summarizes those findings and introduces follow-up research. Additional results obtained from tundra and glassland sites have been reported by Kodama *et al*. (2004) and Yabuki *et al.* (2004).

2. Outline of the forest sites

2.1. Mature larch forest site on the left bank of the middle reaches of the Lena River (LL)

This site is located on the left bank of the Lena River, 62° 15'N, 129° 37'E, about 20 km north of Yakutsk City. *Larix cajanderi* dominates. Stand density is 840 trees ha^{-1} with an average height of 18 m; the leaf area index (LAI) is 3.71 in the foliated season and 1.71 in the leaf-less season. Annual mean temperature is -10 C, and the annual precipitation is 188 mm (IIASA). The maximum depth of the permafrost thaw layer is 1.2–1.4 m.

2.2. Mature pine forest site on the left bank of the middle reaches of the Lena River (LP)

This site is also located on the left bank of the Lena River, 62° 14'N, 129° 39'E. The main tree species is *Pinus sylvestris*. Stand density is 2660 trees ha^{-1} with an average height of 10 m. The LAI is 2.5. Climate conditions resemble those at LL. The maximum thawing depth is 2.5 m.

2.3. Young larch forest site on the right bank of the middle reaches of the Lena River (RL)

The young larch site is located on the right bank of the Lena River. *Larix cajanderi* dominates at this site. The mean stand height is 7.6 m, and the stand density is 4200 trees ha^{-1}. Annual mean temperature is -10 C, and annual precipitation is 210 mm (IIASA).

2.4. Young larch forest site in a mountainous area (ML)

This site is located in the headwaters of the Amur River in the Stanovoi Mountains (55° N, 124° E) about 50 km north of Tynda City. *Larix cajanderi* dominates. The stand density is 4100 trees ha^{-1} with an average height of 4.3 m, although some trees exceed 15 m. The annual mean temperature is -6 C, and the site receives 425 mm of precipitation annually (IIASA).

3. Seasonal energy balance variations

Seasonal energy balance variations above the canopy were successfully measured at LL from the snowmelt season to the leaf-fall season in 1998 (Ohta *et al.*, 2001). Figure 1 indicates the time series of each energy-balance component and land-surface conditions. As shown in the figure, the latent heat flux suddenly increased as trees started to foliate in early June. Although snow melt occurred in mid-May, latent heat flux kept values low in this period.

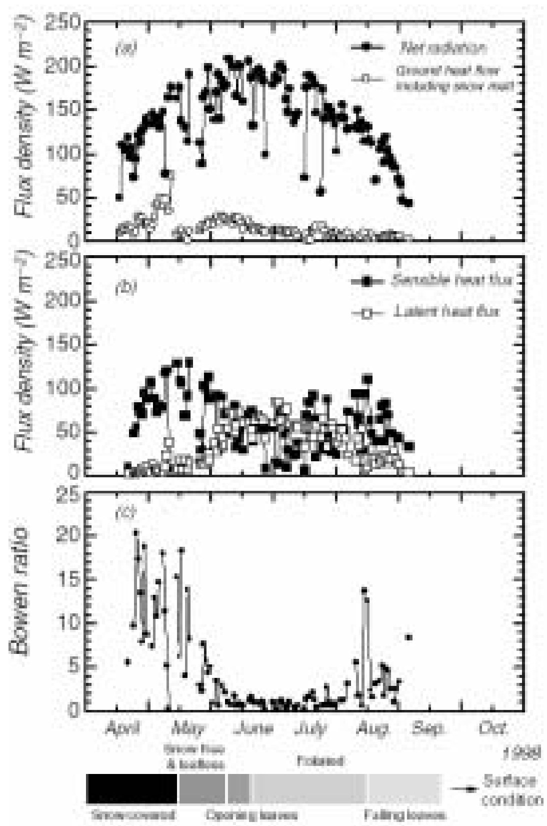

Figure 1 Time series of the energy balance components (a) and (b), Bowen ratio (c), and land-surface conditions (bottom bar) at LL in 1998. (Ohta *et al*., 1998)

In contrast, sensible heat flux dropped at the end of May, though net all-wave radiation increased until mid-June. Consequently, the Bowen ratio time series shows a clear "U" shape and has a value of 1.0 even in the vegetation growing season. At site RL, the Bowen ratio was 0.5 – 3.5 in early spring and 0.1 – 1.5 in summer of 2000; the seasonal trend indicated a U shape, similar to that at LL (Tanaka *et al*., 2001). Plant phenology strongly affects the energy balance above larch canopies, and the energy budget was dramatically changed by tree activity.

Seasonal variation of the Bowen ratio at LP differed from that at RL and LL (Hamada *et al.*, 2004), especially in spring. Site LP showed high latent heat flux values even in spring 2000, in contrast to values at RL. All sites showed magnitudes of latent heat flux almost equal to those of sensible heat flux at MP. Consequently, MP showed a Bowen ratio of about 1.0 from spring to summer and did not display a U shape.

There are two possible reasons for the differences in seasonal variations between LP and LL/RL. First, permafrost thawing conditions differ between the two forest types: the larch forests (LL and RL) have a lower thaw rate than the pine forest. Thus, pine trees can use water in the soil layer earlier in spring. Additionally, pine trees are evergreen and do not spend time unfolding leaves. Pine trees, consequently, can transpire as soon as suitable environmental conditions occur, whereas larch trees require two to three weeks to acquire leaves before the onset of transpiration. A large part of the effective radiation is shared as sensible heat flux during this period. These energy balance differences between deciduous and evergreen forests are most apparent in spring.

4. Water balances in eastern Siberian forests in the 1-D scale

One-dimensional water balances based on flux measurements were calculated at LL, LP, and RL. Table 1 summarizes the water balances obtained at each site. Inter-annual variation in precipitation was wide, as shown in the results obtained at LL. Consequently, soil moisture contents also displayed wide annual variation (not shown in this paper), but the amount of evapotranspiration remained steady. Almost all precipitation was transpired or evaporated during the warm seasons (except at LL in 1999), regardless of tree species.

Table 1 Annual water balance at ML, MP, and YL from spring to summer

	LL 1998	1999	2000	LP *1 2000	RL *2 2000
Input	211(100)	360(100)	222(100)	228(100)	309(100)
rain	106	257	132	143	191
snowmelt	105	103	90	85	118
Output	151(72)	143(40)	145(65)	208(91)	274(87)
transpiration	124	108 *3	112 *3	162	-
evaporation	16	35*	30	46	-
sublimation	11	-	3	-	-

*1: Hamada *et al*., (2004), *2: Tanaka *et al*., (2001), *3: These values were calculated by a big-leaf model with parameters determined by data collected in 1998 (Tanaka *et al*., 2000)

It is important to understand how evapotranspiration remains steady despite wide inter-annual variation in precipitation and/or soil moisture contents. Permafrost plays an important role in keeping evapotranspiration steady in this region (Sugimoto *et al.*, 2002). Figure 2 shows the values of δO^{18} in summer precipitation, tree water, and soil water. Annual δO^{18} ranges in trees were obtained in August. The frozen zone showed a δO^{18} value of -24 ‰. In 1998, a drought year, only surface soil above 15-cm deep had a value higher than δO^{18}; water in the melting soil below 15-cm deep also showed low δO^{18} values, about -24 ‰. This tendency implies that meltwater from the permafrost percolated from a deeper layer to a surface layer according to the hydraulic gradient (not shown in this paper). Trees could uptake this permafrost meltwater in 1998 owing to their δO^{18} values, which were lower than those of summer precipitation and equal to those of the surface soil. However, during the rainy years of 1997 and 1999, δO^{18} values for the surface soil and trees were similar to those of summer precipitation. These results suggest that trees use precipitated water for photosynthesis in usual and/or rainy years. Trees will use the permafrost meltwater in drought years and precipitated water in rainy years. Consequently, evapotranspiration remains steady.

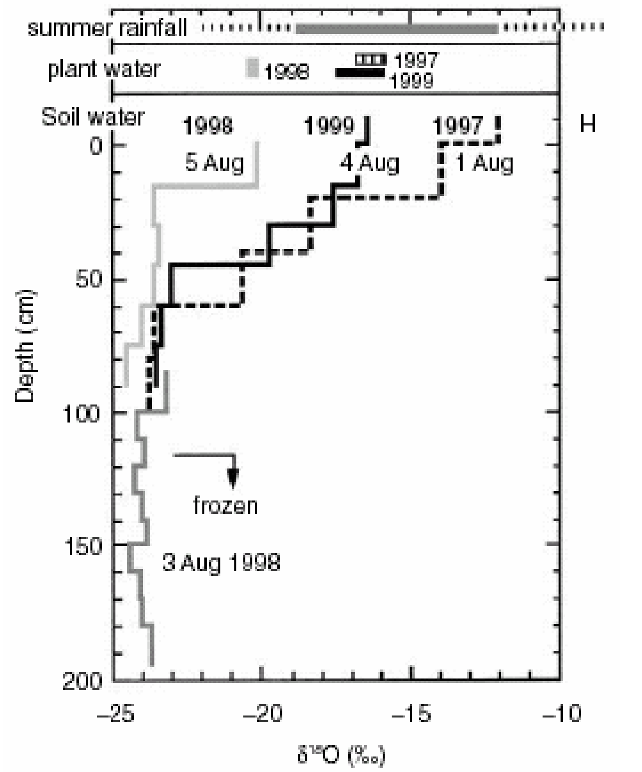

Figure 2 The δ O18 values for summer precipitation, trees, and the soil layer. The δ O18 values in trees were observed annually in August. (Sugimoto *et al*., 2002)

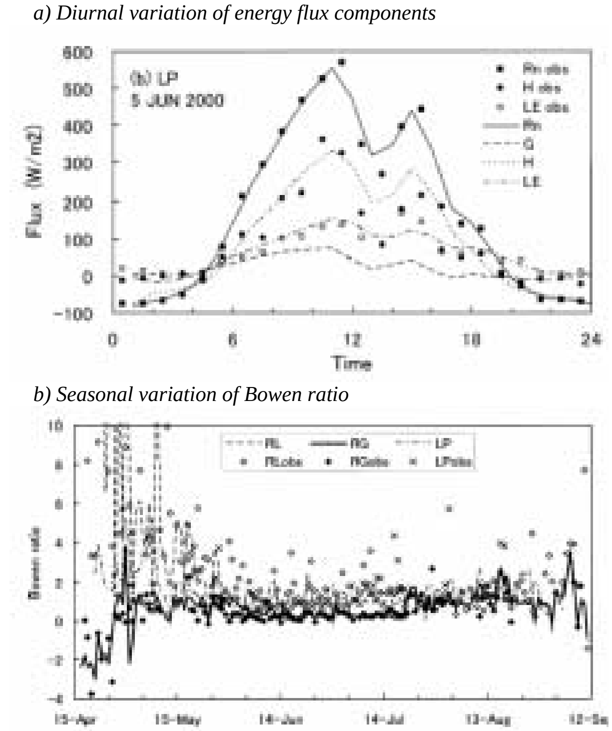

Figure 3 Time series of (a) the observed and simulated components of energy balance at LL in the 2000 summer, and b) the Bowen ratio at the RL and LP in the 2000 snowmelt-summer-autumn seasons.

5. Evaluation of water and energy cycle characteristics in eastern Siberian forests using one-dimensional models

Characteristics of water and energy exchanges above forests were evaluated using a one-dimensional land-surface model (2LM) at LL, LP, and RL (Yamazaki *et al.*, 2004). Figure 3 shows the simulated and observed diurnal variation of the energy balance components at LP (a) and the simulated and observed seasonal Bowen ratio time series at RL and LP (b). Both results simulated by the 2LM agreed well with observed values. Forest physiological response is represented by the three parameters: minimum stomatal resistance (r_m), stomatal parameter of solar radiation (S_{abm}), and air dryness (B). There were no significant differences among the three parameters, and the values of r_m and S_{abm} showed particular similarity at the three forest sites. The B value was slightly larger at LP than at the other sites. These results suggest that physiological responses to transpiration were similar at the three forest sites in the middle reaches of the Lena River despite differences in tree species and ages.

In contrast, the conductance model parameters showed differences between LL and ML. The Jarvis-type conductance model was applied to the results at these two sites (Tanaka *et al.*, 2000; Kimoto *et al.*, 2001). The optimal temperature for transpiration was estimated as approximately 9 C and 7–20 C at LL and RL, respectively. In addition, the atmospheric-saturation-deficit parameter was 1.5 times larger at LL than at ML. These results imply that trees become more active under cooler conditions and respond little to air dryness at LL, although both LL and RL feature the same dominant tree species.

6. Concluding remarks and follow-up projects

The GAME-Siberia project clarified basic characteristics of water and energy exchanges in Siberian forests. Plant phenology is an important factor in water and energy cycles in Siberian forests, especially deciduous forests. The partition of effective energy into sensible heat flux is larger in Siberian forests than in temperate and tropical forests, and latent heat is strongly limited by air dryness. Moreover, the Bowen ratio is higher in Siberia, especially in spring and autumn, even compared to that in North American boreal forests.

A large part of precipitation is transpired and evaporated from the entire eastern Siberian ecosystem. Thus, major runoff may be limited to the snow-melt season. Inter-annual evaptranspiration is steady despite the wide variation in annual precipitation, and trees will use permafrost meltwater in times of drought.

Land-surface model parameters show similar characteristics for the water and energy exchanges at each site in the middle reaches of the Lena River. However, model parameters show variances in optimal temperatures and atmospheric saturation deficits at sites with the same tree species. These results imply a spatial distribution of transpiration responses in Siberia, despite the region's relatively simple vegetative composition and structure.

GAME-Siberia research intensively examined seasonal and inter-annual variation of water and energy cycles, but the temporal and spatial distribution of plant activities related to these cycles is still not well known. To develop land-surface process models, it is critical to understand the distribution of forest eco-physiological parameters. One follow-up project supported by the Japan Science and Technology Agency (JST) is setting parameters for forest eco-physiological effects on water/energy/carbon cycles in temperate to boreal forests. Preliminary results suggest that the parameters in the Jarvis-type conductance model are affected by not only forest functional types but also climate conditions, temperature, radiation, and air dryness.

Another major research avenue will be to examine how snow and ice affect water/energy/carbon cycles in Siberian forests. Snowmelt is particularly important for the water cycle in the boreal zone, but interactions among forests, snowmelt, and permafrost thawing have not yet been analyzed well in Siberia. The Institute of Observational Research for Global Change is monitoring climate conditions from the tundra to Mongolia, an area that includes the eastern Siberian taiga. Snow and ice influences will be investigated in this long-term monitoring.

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