Effects of Wind Speed and Direction on Eddy Fluxes over a Larch Plantation

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Abstract

The closure of energy balance is a useful measure for evaluating the quality of eddy flux measurements. However, it was reported that eddy energy flux became imbalanced by available energy at many study sites. The energy imbalance is of a great interest to the flux community, whereas the problem remains unsolved. In this paper, we investigate the effects of wind speed, wind direction and phenology on eddy energy fluxes measured over a larch plantation to understand the mechanism of the energy imbalance. Flow distortion by the tower affected energy balance closure. If wind directions through the tower were excluded, energy balance was lower than the average of FLUXNET sites (Wilson *et al.*, 2002). Energy balance was more closed in the summer than in the defoliate season. The larger imbalance of energy balance closure through defoliation was partly due to the increasing spatial variability of net radiation. Energy balance closure became worse under the conditions of low wind speed. Both sensible and latent heat fluxes increased with friction velocity.

Key words: Eddy energy fluxes, Energy balance closure, Friction velocity

1. Introduction

The closure of energy balance is a useful measure for evaluating the quality of eddy flux measurements (Aubinet *et al.*, 2000). However, it was reported that eddy energy flux became imbalanced by available energy at many study sites (Wilson *et al.*, 2002). The energy imbalance is of a great interest in the flux community, whereas the problem remains unsolved. Tomakomai Flux Research Site (FRS), a larch plantation, has an ideal terrain for measuring eddy fluxes (Fujinuma *et al.*, 2001), in which energy balance is almost closed (Miura *et al.*, 2003). In this paper, we investigate the effects of wind speed, wind direction and phenology on eddy fluxes measured over the larch plantation to understand the mechanism of the energy imbalance using data from July to December 2002.

2. Materials and Methods

2.1 Site description

The study site is Tomakomai FRS, a Japanese larch plantation (*Larix kaempferi* Sarg.) in Tomakomai, Hokkaido, Japan (42°44'N, 141°31'E). The terrain is almost flat, with a slope between 1° and 2°. The area of the larch forest is about 100 ha, and the canopy height is 15–16 m. Canopy LAI reached 2.5 m² m⁻² at the maximum in summer. There were scattered deciduous broadleaf trees (*Betula ermanii*, *Betula platyphylla*, and *Ulmus japonica*) and sparsely

distributed spruce (*Picea jezoensis*). A 42-m tower was built near the forest center for measurements of fluxes and meteorology. Fetch was between 300 m for the north and 800 m for the west; it was 350 m for the south, which was the dominant wind direction. The forest floor was thickly covered with understory species, which mainly consist of fern (*Dryopteris crassirhizoma*) and *Pachysandra terminalis* with the maximum height of 0.9–1.4 m and maximum LAI of 3.6 m² m⁻² in July. In 2002, larch leaves turned completely yellow by 3 November, and larch trees defoliated by 18 November in 2002. Continuous snow cover began on 17 December (Tanaka *et al.*, 2003). Hirano *et al.* (2003) described site characteristics in detail.

Figure 1 shows the relative frequency of wind direction, which was divided into the north, east, south and western directions. The southern wind, 67%, is the dominant wind direction in summer (July and August). From autumn to winter, western wind frequency increased instead of there being a decrease in southern wind frequency.

2.2 Measurement of eddy fluxes

Sensible heat flux (H) and latent heat flux (LE) have been measured over the canopy by the eddy covariance technique since 2000 (Hirano *et al.*, 2003). The fluctuations of wind speed and virtual temperature were measured with a 3D sonic anemometer-thermometer (DA600, Kaijo), and CO₂ and water vapor fluctuations were measured with an open-path CO₂/H₂O analyzer (LI7500, Licor) at a height of 27 m.

Fig. 1. Relative frequency of half-hourly wind direction for each month in 2002.

Data were sampled at 10 Hz through a low-pass filter with a cut-off frequency of 5 Hz, and half-hourly averages of fluxes were calculated without trend removal; double rotation and WPL corrections were applied, and sensor span and separation between sensors were corrected. To minimize flow distortion by the tower, the flux sensors were mounted on a 2-m long boom projecting to the west. Data with an eastern wind blowing from the tower were excluded to remove the influence of the tower. We also excluded data when tilt angles of wind were out of $\pm 10^\circ$. Details of flux and meteorological measurements were described in a study by Hirano *et al.* (2003). A flux footprint analysis using the model of Korman and Mexiner (2001) showed that 80% of eddy fluxes measured at 27 m in the daytime typically originated within about 200 m, whereas they originated within about 500 m in the nighttime.

Net radiation (R_n) was measured at 42 m with a radiometer (MR40, Eko, Japan), which was mounted on a 2-m long boom projecting to the south. Soil heat flux at ground surface (G) was calculated by adding heat storage change in the topsoil layer above heat plates (MF-81, Eko, Japan), which were installed at depth of 0.05 m, to measure conductive heat flux. Total heat storage flux (S) in a column standing on a ground surface up to the flux measuring height of 27 m was calculated as the sum of heat storage changes in boles, leaves and air in the column. Miura *et al.* (2003) described the measurement and calculation of S in detail.

2.3 Analysis of energy balance closure

We evaluated energy balance closure by two methods using data measured from July to December 2002. The first one used a slope of linear regression between eddy energy fluxes ($H + LE$) and available energy ($R_n - G - S$) on a basis of half-hourly mean. Ideal closure is represented by a slope of one and an intercept of zero. The second method used energy balance ratio (EBR) derived from sum of eddy energy fluxes and available energy.

$$EBR = \frac{\sum(H + LE)}{\sum(R_n - G - S)} \quad (1)$$

The EBR method produces an overall evaluation of energy balance closure at longer time scales by averaging over random errors in the half-hour measurements. We primarily used the regression method to discuss energy balance closure in this study.

3. Results and Discussion

3.1 Effect of wind direction

The effects of wind direction were examined to assess data quality. Figure 2 shows the wind-directional distribution of EBR when available energy was above 200 W m^{-2} . If we exclude wind directions of 19° and 63° through the tower, and 30° on either side following the suggestion of Kaimal and Finnigan (1994), EBR was between 0.75 and 1.20. Consequently, we excluded data for wind direction between 10° and 90° to avoid the small EBR, which was probably caused by the flow distortion; excluded data account for 9.8% of all data.

Fig. 2. Wind-directional distribution of EBR. Data were divided into direction classes of 10° from July through the first half of November under the condition of available energy being above 200 W m^{-2} . Vertical bars denote standard variation.

3.2 Seasonal variation in energy balance closure

The slope and intercept were 0.94 and 6.3 W m^{-2} , respectively for all available data from July to December 2002; r^2 was 0.93. The slope and intercept during the daytime ($R_n - G - S > 50 \text{ W m}^{-2}$) and nighttime ($R_n - G - S < -20 \text{ W m}^{-2}$) were 0.98 and -6.6 W m^{-2} , and 0.97 and 14.2 W m^{-2} , respectively. The mean slope at FLUXNET forest sites was 0.79 ± 0.01 with a range between 0.53 and 0.99, and the mean intercept was $3.7 \pm 2.0 \text{ W m}^{-2}$ with a range between -32.9 and 36.9 W m^{-2} (Wilson *et al.*, 2002). On the other hand, EBR calculated using whole day data was 0.62, which was smaller than the mean EBR of 0.84 at FLUXNET forest sites, ranging from 0.34 to 1.69 (Wilson *et al.*, 2002). EBR during the daytime and nighttime was 0.93 and 0.57, respectively. Consequently, energy balance was almost closed in this forest during the daytime.

Figure 3 shows seasonal variation in the slope obtained by forcing the intercept to be zero, which represents energy balance closure for each month. During summer (July and August), the balance was almost closed. In contrast, from November to December, the energy balance closure became lower with defoliation. This energy balance closure in the defoliate period was partly due to difference in the source area between eddy fluxes and R_n . During defoliation, the forest canopy became more spatially heterogeneous because of scattered leaves. In addition, the forest floor contributed much more to energy exchange. The radiational characteristic of the forest floor was more spatially variable than that of the canopy. These facts suggest that the spatial variation of R_n is larger in the defoliate period.

We neglected the latent heat of snow melt and freeze, although snow covered the forest floor in late December. This neglect is one of the reasons for the lowest energy balance closure in December.

3.3 Effect of wind speed

The effects of wind speed on energy balance closure were investigated using data in July and August, when the energy balance was almost closed (Fig. 3). Figure

Fig. 3. Seasonal variation in the slope of the linear regression between eddy energy fluxes and available energy with zero intercept.

Fig. 4. Relationships between the half-hourly eddy energy flux and available energy during summer (July and August 2002).

4 (a) shows the relationship between eddy energy fluxes ($H + IE$) and available energy ($R_n - G - S$) categorized into friction velocity (u^*) classes of 0.2 m s^{-1} . Both the slope and intercept increased with u^* . The ratios of H and IE to available energy also depended on u^* , respectively. The slope of the former relationship increased with u^* , and the intercept conversely decreased (Fig. 4 (b)). On the other hand, the slope of the later relationship decreased when u^* was above 0.2 m s^{-1} , although the intercept increased with u^* (Fig. 4 (c)).

The effect of u^* on energy balance closure was further analyzed using the EBR method by classifying available energy into three categories (Fig. 5 (a)). EBR increased with u^* in the same manner as the regression slopes. EBR was close to one when u^* was between 0.4 and 0.6 m s^{-1} . Eddy energy fluxes were underestimated and overestimated at u^* below 0.2 m s^{-1} and above 0.6 m s^{-1} , respectively. EBR was more dependent on u^* when available energy was below 200 W m^{-2} . The dependence became weak with available energy. The ratio of IE to available energy was larger than that of H . The H ratio increased with available energy (Fig. 5 (b)), whereas the IE ratio decreased (Fig. 5 (c)). When available energy was below 200 W m^{-2} , the dependence of both the ratios on u^* was strong. The dependence of the IE ratio became very weak when available energy was larger than 400 W m^{-2} . Consequently, the dependence of EBR on u^* was more affected by H than IE when available energy was large. One of the reasons of the weak dependence of IE was stomata closure caused by water stress under high light conditions.

In the nighttime, EBR decreased under a strong turbulent condition with high u^* , although it increased up to 0.93 with u^* to 0.4 m s^{-1} (Fig. 6). The H ratio increased with u^* and the IE ratio of became more negative. Under a strong turbulent condition, positive IE was often larger than negative H , which produced negative EBR. This fact is the reason why EBR decreased at high u^* .

Fig. 5. Relationships between half-hourly (a) EBR, (b) $H / (R_n - G - S)$ or (c) $IE / (R_n - G - S)$ and u^* during summer (July and August 2002). Data were divided into three available energy classes and u^* classes of 0.2 m s^{-1} . Vertical bars denote standard variation.

Fig. 6. Relationship between half-hourly EBR, $H / (R_n - G - S)$ or $IE / (R_n - G - S)$ and u^* in the nighttime (available energy $(R_n - G - S) < -20 \text{ W m}^{-2}$) during summer (July to August 2002). Half-hourly mean data were divided into u^* classes with the same number of data. Vertical bars denote standard variation.

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