Water balance for a Mongolian steppe and its environmental constraints

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I Introduction

Apart from precipitation, water vapor exchange (also called latent heat flux, LE or evapotranspiration, ET) between the atmosphere and terrestrial ecosystems is the major component of the terrestrial hydrological budget. At the given site, ET largely depends on the availability of water and energy. ET is also controlled by and thus represents the complicated interplays between canopy architecture and development, soil characteristics, and a variety of environmental variables. Steppe covers 83% of territory in Mongolia (-1.3 × 10^6 km^2) (World Resources Institute, 2003). For the semiarid and arid ecosystems like Mongolian steppe, water stress is a limiting factor for plant growth, and vegetation productivity is tightly associated with the multi-year precipitation variations. Therefore, information about water vapor exchange above the steppe ecosystem is crucial for an improved understanding of the coupling among water and carbon cycling, steppe management, and climate change in Mongolia. The eddy covariance (EC) technique is now widely used for long-term continuous flux measurements across the world (Baldocchi, 2003). In this study, we used the EC technique to quantify water vapor and energy fluxes above a steppe in Mongolia.

II Materials and methods

The study site is located at Kherlenbayan-Ulaan (KBU), the Hentiy province of Mongolia (lat. 47° 12.838' N, long. 108° 44.240' E, 1235 m a.m.s.l.) (Fig. 1). It was built in March 2003 as a component of the RAISE project for long-term measurements of microclimatic variables, water vapor, CO_2 and energy fluxes. The climate is continental in the temperate zone. Average annual air temperature is 1.2 °C and average annual precipitation is 196 mm. The soil is the typical Chestnut soil. The vegetation is dominated by temperate C3 plants.

We used the eddy covariance (EC) technique to measure water vapor and energy fluxes above the steppe. The EC system was set up and instrumented in March 2003. The system included a 3-D ultrasonic anemometer/thermometer (SAT-550, Kaijo Sonic Co., Tokyo, Japan, 15-cm path length) and an open path infrared gas (CO_2/H_2O) analyzer (IRGA) (Li7500, LICOR Inc., Lincoln, NE USA, 15-cm path length). The former measured instantaneous fluctuations of the vertical (w), horizontal (u), lateral (v) winds and the virtual temperature (T_v), and the latter measured instantaneous fluctuations of water vapor (q) and carbon dioxide (c) concentrations. They were mounted on a 1 m booming arm placed on the top of a 2.5 m downward U-shape tower (*i.e.* 3.5 m above the ground) and oriented to the prevalent wind direction (east). We also measured net radiation (CNR1, Kipp and Zonen BV, Delft, the Netherlands) at 2.5 m, and air temperature and humidity (HMP-45D, Vaisala Inc., Helsinki, Finland) at 2.5 m above the ground. Output signals of wind speed and gas concentration were sampled at 10 Hz while output signals of radiation, temperature and humidity were scanned at 0.2 Hz. The half-hourly mean scalar fluxes were computed online and recorded continuously by a CR23X datalogger (Campbell Scientific, Logan, UT, USA). This data logger also recorded half-hourly means of air temperature/humidity, net radiation and air pressure.

We also measured soil temperature profile at depths of 5, 10, 20, 30, 50, 70, 100 and 150 cm by platinum resistance thermometers (C-PT, CLIMATEC Inc., Tokyo, Japan), soil heat flux at depths of 2 and 10 cm by soil heat plates (PHF-1.1, REBS, Inc., Seattle, WA, USA), soil moisture profile at depths of 10, 20, 30, 50, 70, 100 and 150 cm by time domain reflectometry probes (CS616, Campbell Scientific, Logan, UT, USA), and precipitation by a tipping bucket rain gauge (CYG-52202, RM Young Company, Traverse City, MI, USA). They were sampled at 0.1 Hz and the 30-min mean data were logged on a CR10X datalogger (Campbell Scientific, Logan, UT,

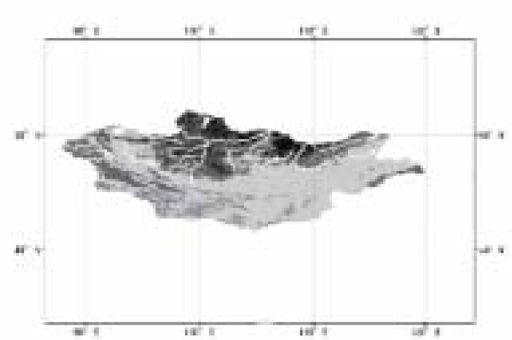

Fig. 1 Location of the site.

USA). In addition, leaf area index was measured monthly by the clipping method during the 2003 growing season.

At a homogenous terrestrial surface, the net radiation (R_n) is partitioned between sensible heat flux (H), latent heat flux (LE), soil heat flux (G), and the energy storage within the canopy (ΔS):

$$R_{\mathrm{n}} = \mathrm{LE} + H + G + \Delta S \qquad (1)$$

All the energy fluxes are expressed in W m^{-2}. The storage term is omitted in this study. G was directly measured by the soil heat plate, and LE and H were quantified by the EC technique (Baldocchi, 2003):

$$H = \rho c_{\mathrm{P}} \overline{w'T'} \qquad (2)$$

$$\mathrm{LE} = \rho L \overline{w'q'} \qquad (3)$$

where ρ is the air density (kg m^{-3}) at a given air temperature; c_P is the specific heat capacity of air at constant pressure (J kg^{-1} °C^{-1}); w', T' and q' denote fluctuations of vertical wind speed, air temperature and specific humidity, respectively; and over bars indicate average of the product over the sampling interval (30 min in this study). Positive scalar fluxes denote mass and energy transfer from the canopy surface to the atmosphere while negative fluxes signify the reverse.

Data post-processing included 1) the correction of the scalar fluxes for the density flux effect following the algorithm described by Webb *et al*. (1980), and 2) the cospectral correction for the CO_2, water vapor, and sensible heat fluxes using the algorithm proposed by Eugster and Senn (1995).

We assessed the closure of the energy balance using the following linear regression relationship:

$$LE + H = a_1 + a_2(R_{\mathrm{n}} - G) \qquad (4)$$

where a_1 and a_2 are intercept and slope, respectively. Since the storage term was not measured, the cumulative values of 24-h periods were used to minimize the possible effect of the energy storage upon the closure. During the measurement period from 25 March 2003 to 24 March 2004 (366 days), a_1, a_2 and the coefficient of determination (r^2) were 7.41 W m^{-2}, 0.714 and 0.909, respectively (Fig. 2).

We used the methods proposed by Falge *et al.* (2001) to fill the data gaps caused by sensor malfunction, rain events, sensor maintenance, IRGA calibration, power failure, *etc*.

III Results and discussion

Fig. 3 presents mean diurnal cycles of R_n, LE, H and G over May through September, which represents most of the growing period. Diurnal trends exhibit the similar pattern in shape, *i.e.* LE, H and G varied approximately the same way as R_n did. The R_n at the site was mainly partitioned into H and G (Fig. 3), suggesting the available energy was primarily used for heating the air and the soil. Relative to their daytime counterparts, the nighttime energy fluxes were small in magnitude. At night, G was the major contributor to R_n; and by contrast, H and LE were near zero.

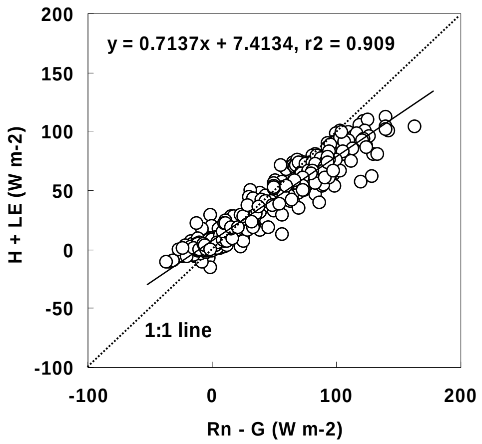

Fig. 2 Energy balance check.

Fig. 4 shows annual variation of the energy fluxes in the monthly scale. Relatively most of large H values were observed from April to June. In the growing season, although the R_n increased, H decreased due to the influence of both active plant ecophysiological activities and rain events, which relatively increased the LE fraction in R_n. The H showed lower values in winter snow-cover season. At the site, water vapor exchange between the steppe and the atmosphere occurred mainly in the growing season with the maximum in July (121.1 MJ m^{-2} month^{-1}, equivalent to 48.5 mm of ET) (Fig. 4). It was observed that LE was highly associated with the rain events in this period. Daily maximum LE was 6.93 MJ m^{-2} per day (day 198) (2.8 mm per day). The annual total of LE was 407 MJ m^{-2} (163 mm). G was usually positive from March to September. G achieved its maximal value in July and afterwards began to decline. From October to February, the G was generally negative.

A linear relationship between ET and leaf area index

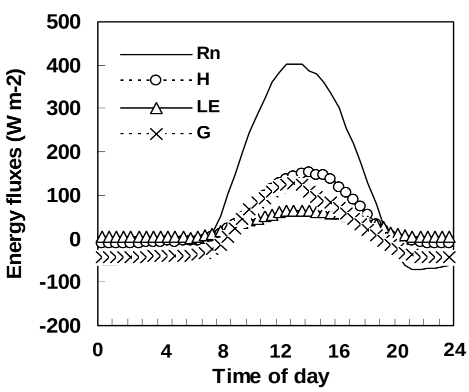

Fig. 3 Diurnal trends of energy fluxes.

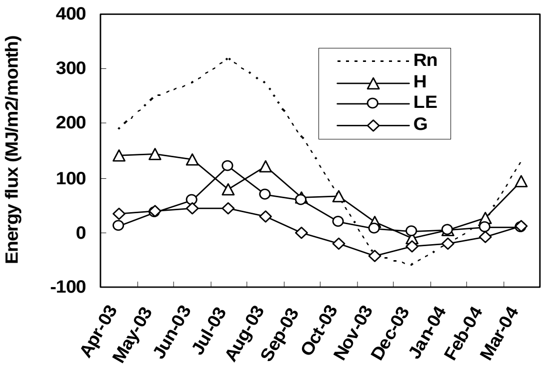

Fig. 4 Annual variation in energy fluxes.

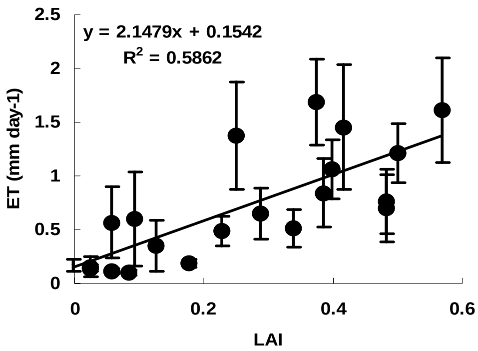

Fig. 5 LAI affecting ET in a linear fashion.

(LAI) was built as shown in Fig. 5, implying that water vapor exchange at the site was closely associated with canopy development at the site. ET was found to be highly linked with soil water conditions or precipitation events during the growing season (data not shown here).

Annually cumulative ET rate (from 25 March 2003 to 24 March 2004) was estimated to be about 163 mm with the EC technique. This value is considerably lower than the equilibrium ET rate (571 mm). In an annual scale, the EC may underestimate convective energy fluxes of *H* and LE about 19%. Assuming the Bowen ratio is correctly determined by the EC method, we used the Bowen ratio to distribute the fraction of underestimate between *H* and LE. This correction to ET yielded a value of 203 mm. During the measurement period, the KBU Weather Station recorded 249 mm of precipitation (but note our eddy tower rain gauge recorded 268 mm precipitation, which was corrected with the KBU station data when the rain gauge failed). These estimates of ET imply that about 65% to 80% of the annual precipitation was returned to the atmosphere and the rest was used for charging ground water or as storage in the soil.

IV Conclusions

One full year measurements of water vapor and energy fluxes were conducted over a typical steppe in central Mongolia. The patterns for water vapor and energy patterns were examined in daily and seasonal scales. Annual water budget for the steppe was estimated from the measurements.

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