Surface Heat Flux Analysis in Gobi Desert Steppe, Mongolia
– An Observation Study

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Abstract

41% of Earth’s land area is drylands, including the arid region of China and Mongolia. Evaporation per unit area of arid region is relatively low, but the surface area of the dryland region gives it a regional significance in the context of climate variability. We used the eddy covariance method to estimate heat fluxes in the Gobi Desert steppe of Mongolia from May to October 2014. Observation period averaged net radiation, sensible heat flux, and latent heat flux were 85 W m⁻², 58 W m⁻², and 11 W m⁻², respectively. The sensible heat flux was larger than the latent heat flux throughout most of the study period, but the latent heat flux exceed the sensible heat flux for a couple of days after rainfall events. Total evaporation estimated by the eddy covariance method almost equaled total rainfall and decreased the soil water content. Discussion is extended to the imbalance problem, especially the latent-heat heat flux compared with precipitation and the soil moisture change.

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1. Introduction

Drylands occupy 41% of Earth’s land area and are home to more than 2 billion people (Millennium Ecosystem Assessment 2005). Deserts account for about 17% of dryland area, and about 23% of global desert area is temperate desert, more than 80% of which is found in central and east Asia, including the arid lands of northwestern China, southwestern Mongolia, and the five central Asian states of the former Soviet Union—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Cowan 2007; Zhang et al. 2016). Evaporation per unit area of dryland is relatively low, but the surface area of the Asian dryland causes its impact on the regional climate variability (Xue 1996; Sato and Kimura 2006). Whereas these areas are sensitive and vulnerable to the climatic change and human activities, and should be monitored carefully to prevent the disasters like drought, dust occurrences, and desertification.

Part of drylands is in eastern Asia including China and Mongolia, and the problems of desertification, drought, and dust event are frequent. Since 2012 we have been making observations of dust in the northern Gobi Desert steppe of Mongolia to clarify wind erosion processes (Ishizuka et al. 2012; Abulaiti et al. 2014). Wind erosion depends on soil water content (SWC) (Shao 2000). Dust events are rare when the surface SWC exceeds a threshold value. Because evaporation has a profound effect on SWC, there is a need to quantify the components of the energy balance in dust source regions with the goal of developing an early warning and monitoring system based on dust modeling.

We used eddy covariance observations and change of soil water content to quantify the heat and water balances in the Gobi Desert steppe of Mongolia in 2014 during the season of no snow cover, from May to October. Discussion is extended to the imbalance problem to apply eddy covariance method in arid regions. Most of Gobi Desert’s land surface was covered with gravel. Conditions in this region are also unusual in that gravel-sized particles (> 2 mm) cover 29% of the ground surface. Results of observations in such places are rare and will contribute to the accumulation of knowledge in heat and water balances over arid regions of East Asia for developing an early warning and monitoring system based on numerical model against the drought, dust occurrence, and desertification.

2. Observational and analytical methods

2.1 Observational methods

The observation station at Tsogt-Ovoo is in the northern desert steppe of Mongolia (44°23'04"N, 105°16'59"E, 1232 m). An extensive, uniformly flat desert surrounds the station site, except for a low mountain (about 1300 m) 4 km toward the west (Fig. 1). Rainfall data were collected from May to October 2014. According to Ishizuka et al. (2012) and Abulaiti et al. (2014), the average annual temperature was 3.8°C in 2011, with a range from –31.3°C in January to 37.1°C in August. The annual precipitation was 62.5 mm in 2011 and was concentrated in the spring and summer; the precipitation was 49.3 mm from May to September. The season of snow cover lasts from mid-October to the end of April. At the observation site, the soil consisted of 77% sand, 12% silt, and 11% clay. Vegetation at the site covered much less than 5% of the surface; the landscape was therefore very much like a desert.

The meteorological parameters measured were solar radiation, reflected solar radiation, upward long-wave radiation, downward long-wave radiation (model CNR4 radiometer, Kipp and Zonen, The Netherlands; 1.54 m above the ground), air temperature and humidity with ventilation (model HMP-155D-10 humidity and temperature probe, Vaisala, Finland; 1.96 m above the ground), precipitation (model CTFK-1 tipping-bucket rain gauge, OTA, Japan; 0.65 m above the ground), wind speed and direction (model YG-5103 windmill anemometer with wind vane, Young, USA; 3 m above the ground), and air pressure (model PTB210, Vaisala, Finland; 1.5 m above the ground). The dome of radiometer were wiped out once per week by the local people. Volumetric soil water content and soil temperature were measured with amplitude domain reflectometry probes (model ML2x ADR soil moisture sensor, Delta-T, UK) and a platinum resistance thermometer (model C-PTG-10, Climatec, Japan) at 8 depths: 1, 2, 5, 10, 15, 20, 30, and 50 cm. A sonic anemometer (model Wind Master Pro, Gill Instruments, UK; 3.06 m above the ground) and open-path CO₂/H₂O gas analyzer (model LI-7500A, LI-COR, USA: 3.06 m above the ground) were installed for observations of sensible and latent heat fluxes. Rainfall data were not recorded accurately because the water-receiving inlet filled with dust. We therefore used rainfall data from the Tsogt-Ovoo meteorological observatory, which is maintained by the Institute of Meteorology, Hydrology and Environment 5 km from our site. Instrumentation for rainfall was reserving observation based on the surface synoptic observations. Instantaneous measurements were taken at intervals of 0.1-s for wind velocities and sonic temperature, water vapour to calculate sensible and latent heat...
fluxes: 1 s for wind speed and direction by windmill anemometer with wind vane; at intervals of 5 s for air temperature, humidity, and air pressure; at intervals of 10 s for radiation components; and at intervals of 1 min for volumetric soil water content and soil temperature. The data were recorded by a data logger (model CR1000, Campbell Scientific, USA); all data were averaged over 60-min intervals. Regarding the data treatment to calculate sensible and latent heat fluxes was explained at the next 2.2.

2.2 Analytical methods for sensible, latent, and ground soil heat fluxes

We wrote a Fortran program to process the data collected at 0.1-s intervals and to make flux calculations based on the 30-min runs. The 0.1-s data were checked for obviously erroneous data (i.e., spikes) that were either outside a physically acceptable range or were more than five standard deviations from the 5-min moving average. In the former case, the spike(s) was simply removed from the time series since it may be caused by the instruments and/or data logger malfunction. In the latter case, if less than four consecutive data were detected as spike(s) the data were replaced by a linear interpolation because we speculated those were caused by random electronic spikes, while if four or more consecutive data were detected as spikes the data were not replaced since those were unusual but could be occurred. (Vickers and Mahrt 1997; Mano et al. 2007). The wind velocity components were rotated to nullify the average horizontal and vertical velocity components (i.e., the double rotation method, McMillen 1988). We used a block average method to calculate the 30-min covariances between the vertical wind and (1) sonic temperature and (2) H₂O. The covariances were corrected for frequency response losses (Massman 2000, 2001; Rannik 2001). We applied the necessary corrections to determine the fluxes: the water vapor correction for the sensible heat flux (Hignett 1992) and the density fluctuation correction for the latent heat flux (i.e., the WPL correction, Webb et al. 1980). Storage terms were equated to the differences between the beginning and end of a run of the 0.1-s (1) sonic temperature and (2) H₂O data and were added to the sensible and latent heat fluxes, respectively.

To ensure the accuracy of the fluxes, we performed tests to identify and remove erroneous values caused by electronic, meteorological, and statistical problems. The basic tests for the 0.1-s data proposed by Vickers and Mahrt (1997) were applied, and runs were rejected when a quality flag with erroneous was raised more than twice. The integral turbulence characteristic of the horizontal and vertical velocity components (Foken et al. 2004) was calculated for each run, and a turbulence that differed by more than 250% from modeled values was considered unacceptable (Foken et al. 2004). In the case of the steady-state test of Foken and Wichura (1996), runs were removed as non-steady state if the means of covariances over 5 min deviated by more than 250% from the original covariance (Foken et al. 2004). Since wind speed was usually relatively high and rainfall amount was small at the study site (c.f. Section 3.1), removed runs were few in number; 0.7% for the sensible heat flux and 6% for the latent heat flux of the total 8,449 runs. Data gaps were filled using the daily average values of the same day.

Soil heat fluxes were calculated by the soil temperature integral method (Kimura et al. 2013) using the vertical profile of soil temperature and soil water content.

3. Results and discussion

3.1 Time series of the heat balance component

Figure 2 shows the time series of the daily mean solar radiation, reflected solar radiation, upward long-wave radiation, downward long-wave radiation, air temperature, vapor pressure, wind speed, and air pressure from 1 May to 31 October 2014. Values averaged over this period were 249 W m⁻², 61 W m⁻², 420 W m⁻², 318 W m⁻², 16.8°C, 6.4 hPa, 4.2 m s⁻¹, and 874 hPa, respectively. Period-averaged albedo was 0.24. On many days, the upward long-wave radiation exceeded 400 W m⁻². Downward long-wave radiation ranged from 200 to 400 W m⁻² during the study. Daily average temperature was between 0 and 30°C. Daily mean water vapor pressure exceeded 10 hPa on rainy days, but on many dry days it was less than 5 hPa. Daily mean wind speed almost always exceeded 4 m s⁻¹. The period-averaged air pressure was 874 hPa. Air pressure tended to decrease with increasing temperature.

Figure 3 depicts the time series of daily precipitation and volumetric soil water content at different soil depths. Total precip-
The soil water content was sensitive to rainfall events from the surface to a depth of 10 cm but was insensitive at depths below 15 cm. Comparatively strong rainfall (> 8 mm) around 23 May, 29 June, and 24 September affected the soil water content.

Figure 4 illustrates the time series of net radiation ($R_n$), sensible heat flux ($H$), latent heat flux ($E$), and soil heat flux ($G$) (downward is positive). Period-averaged fluxes were 85 W m$^{-2}$, 58 W m$^{-2}$, 11 W m$^{-2}$, and -0.2 W m$^{-2}$, respectively. The sensible heat flux was larger than the latent heat flux throughout most of the study period, but the latent heat flux exceeded the sensible heat flux on a couple of days after rainfall events. A value other than zero of $R_n - G - H - E$ is known as an imbalance. The imbalance was 16 W m$^{-2}$ during the study period. This imbalance will be discussed in Section 3.2.

Figure 5 depicts the time series of evaporation (mm day$^{-1}$). Total evaporation was 68 mm during the study period and was identical to the total rainfall. For verification purposes, we examined the evaporation inferred from the change of the soil water content. The soil water content during the study period decreased by 70 mm down to a depth of 15 cm, within which depth the
change in soil moisture was very close to the amount of evaporation estimated by the eddy covariance method. Evaporation rates reached a maximum of 2 mm day$^{-1}$ when the daily rainfall exceeded 8 mm. However, during most periods the evaporation rates were approximately 0–0.5 mm day$^{-1}$. As an example, Fig. 6 shows daily variations of evaporation rates and soil water content at a depth of 1 cm starting on 23 May, when the daily rainfall was 8.9 mm. The evaporation rate decreased with decreasing soil water content. The total evaporation following the rainfall reached 8.9 mm within a timespan of 8 days. Figure 7 shows the temporal variation of the heat balance components from 24 May to 1 June. Net radiation, latent heat flux, and soil water content down to a depth of 5 cm decreased from one day to the next, whereas soil surface temperature and soil water content at depths greater than 10 cm increased.

### 3.2 Energy imbalance

Many past studies have addressed the energy imbalance issue (Liu and Foken 2001; Foken 2008; Leuning et al. 2012; Wohlfahrt and Widmoser 2013). In this study, the metric of energy imbalance, $(R_n - G - H - E)/R_n$, was 0.20. This value is within the range of past results (Liu and Foken 2001).

According to Kondo (2016), there are two causes of an energy imbalance. The first is observational errors. The second is a phenomenon that becomes apparent in observations at higher heights (e.g., above a forest canopy). Kondo (2016) indicated that most of the energy imbalance was due to observational errors. Observational errors include uncertainties in eddy covariance measurements and measurements of available energy, that is, errors in the estimation of net radiation (Leuning et al. 2012).

Matsushima and Kimura (2015) have argued that the sensible heat flux estimated with a heat budget model is comparable to estimates of sensible heat flux based on observations made by the eddy covariance method at our study site. Furthermore, total evaporation estimated with the eddy covariance method was almost identical to total rainfall and caused soil water content to decrease, as described in Section 3.1. It is therefore unlikely that the energy imbalance was due to errors in the eddy covariance measurements. Leuning et al. (2012) have shown that some radiometers used by the flux measurement community may overestimate net radiation. For example, Michel et al. (2008) have reported that use of factory-default calibration coefficients with a Kipp and Zonen model CNR1 net radiometer results in overestimates of hourly averaged net radiation by 15 W m$^{-2}$ compared to the net radiation measured with high-quality reference instruments. Brotzge and Duchon (2000) compared some net radiometers and reported differences of $±20$ W m$^{-2}$ for average daily net radiation. Because the instruction manual for the CNR4 radiometer indicates that the errors of the pyranometer and pyrgeometer are 5% and 10%, respectively, of the daily integrated values, the net radiometer used in this study may have also contributed to the observational errors.
the Japan Meteorological Agency (JMA) and found that the solar radiation estimated with the model CRN1 radiometer overestimated the JMA value by 10%. After reducing the daily average solar radiation by 10%, the calculated imbalance became 17 W m$^{-2}$, very similar to the value of 16 W m$^{-2}$ in this study (Section 3.1). Kondo (2016) indicated that 17 W m$^{-2}$ could be regarded as an observational error. These previous studies have clearly indicated that quality control of radiation data is an important issue (Mauder et al. 2006).

At the present time, values of the diurnal average latent heat flux estimated by various observational heat balance methods may have an error of about 20 W m$^{-2}$ (Kimura and Kondo 1998). Even if the estimated imbalance of 16 W m$^{-2}$ was entirely related to the latent heat flux, this imbalance is within the range of observational errors. In addition, Aubinet et al. (2012) have shown that the surface energy balance can be closed over homogeneous surfaces such as deserts and bushland (Heusinkveld et al. 2004; Mauder et al. 2007). However, 16 W m$^{-2}$ latent heat flux error is significantly large for water budget in arid regions although this value is small enough as observational error. On agricultural fields in arid regions, gravel mulch is used to restrict evaporation and to collect dew for irrigation. Li (2002) has shown that in the semiarid region of China daily condensation can be as high as 0.2 mm day$^{-1}$ (= 6 W m$^{-2}$) as a result of the decrease of temperature by radiative cooling during the night. We hypothesized that the gravel that covered the soil surface caused water vapor in the air to condense at night and that the condensate immediately evaporated near sunrise when the air near the ground was still stable. Therefore, the eddy covariance instruments did not record the effect of the evaporation. If this hypothesis is correct, evaporation of the condensate would have affected the energy imbalance. In other words, the gravel that covers the surface of the land may promote evaporation in the Gobi area. This will reduce the imbalance or even close it. However, this scenario is no more than a hypothesis, because we have not ever experienced morning dew during the stay in Mongolia. The effect of water vapor condensing on the gravel should therefore be included in estimates of the net energy budget for this site.

4. Conclusion

To quantify the sensible and latent heat fluxes and water budget in the Gobi Desert steppe of Mongolia during the rainy season, we used eddy covariance observations and change of soil moisture in 2014 from May to October. Most of Gobi Desert’s land surface was covered with gravel, and results of observations in such places are rare. As a result, the following conclusions were obtained.

- Averaged net radiation, sensible heat flux, and latent heat flux were 85 W m$^{-2}$, 58 W m$^{-2}$, and 11 W m$^{-2}$. The latent heat flux was smaller than the sensible heat flux throughout most of the study period, but the sensible heat flux fell below the latent heat flux after rainfall events. The imbalance was 16 W m$^{-2}$ during the study period.
- Total evaporation was 68 mm during the study period and was identical to the total rainfall. The soil water content decreased by 70 mm down, and the change in soil moisture was close to the total evaporation.
- The metric of energy imbalance in this study was within the range of past results. Even if the estimated imbalance (16 W m$^{-2}$) was related to the latent heat flux, this value was considered to be within the range of observational errors. However, 16 W m$^{-2}$ latent heat flux error was significantly large for water balance in arid regions although this 16 W m$^{-2}$ was small enough as observational error. We hypothesized that the evaporation of the condensate on the gravel near sunrise would have affected the energy imbalance, because the eddy covariance instruments did not record the effect of the evaporation when the air stability was stable. If this hypothesis is correct, this will reduce the imbalance or even close it.

Atmosphere-land surface interaction is complex in arid regions of East Asia, and many observation results have to be accumulated to develop an early warning and monitoring system based on numerical model against the drought, dust occurrence, and desertification. Results of this study will contribute the accumulation of knowledge in heat and water balances over arid regions of East Asia.

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