Effects of atmospheric conditions and soil moisture on surface energy heat/water fluxes at a grassland site in Mongolia

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1. Introduction

The exchange of sensible and latent heat fluxes at the surface is one of the most important aspects of the land-atmosphere interaction. These energy fluxes, which draw from the partitioning of net radiation absorbed by the surface, are the direct fuel for atmospheric dynamics. For a given amount of available energy at the surface, change in the relative proportions of sensible heat and latent heat fluxes critically influences boundary layer structures, cloud development, rainfall, and ultimately contributes to how strong the land and atmosphere are coupled together. Therefore it is crucial to understand the variability of land surface energy flux and the mechanism behind that variability.

The mechanism controlling surface energy flux has to be examined interacting atmospheric and ground surface processes and feedback loops. An opportunity to gain some insight into this work at Nalaikh site where we have been conducting continuous measurements of fluxes of radiative energy, sensible heat, latent heat, as well as complementary vegetation and soil water status since summer of 2002. Wide ranges of atmospheric humidity and radiation variations were observed during the drought period (Zhang et al, 2004). With careful stratification, we were able to analyze how soil moisture, atmospheric humidity, and net radiation interactively influence surface energy flux. We observed that the effects of one factor on surface energy flux depend on the other factors, reflecting dynamic controls of atmospheric, and soil processes on land-atmosphere energy exchanges. Specifically, with this study, we are going to answered the following of questions:

1. How does soil moisture affect surface energy flux for a given set of values of atmospheric vapor pressure deficit (VPD) and net radiation?
2. How does VPD affect surface energy flux for a given soil moisture condition and a given value of net radiation?
3. How does net radiation affect surface energy flux for a given soil moisture condition and a given value of VPD?
4. How does soil moisture affect the relationship between VPD and surface energy flux and that between net radiation and surface energy flux?
5. How does VPD affect the relationship between soil moisture and surface energy flux and that between net radiation and surface energy flux?
6. How does net radiation affect the relationship between soil moisture and surface energy flux and that between VPD and surface energy flux?

2. Study Site, Measurements, and Method of Analysis

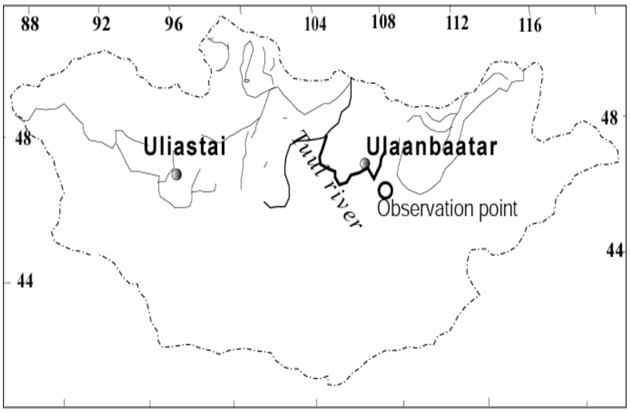

Figure 1: Location of the study site

2.1. Study Site

An observation site was established on sparse grassland at Nalaikh in northeastern Mongolia (47°45'N, 107°20'E) 40 km southeast of Ulaanbaatar. The site is located on a sediment plain in the broad Tuul River valley (Figure 1). The nearest mountains, with relative heights of less than 500 m, were at least 10 km away, and the topography at and around this site was very smooth. The observation site is in a semi-arid region characterized by warm, dry summers. The summer air temperature (June to August) was higher than average at 0.7°C in 2003 and 2.3°C in 2004. Precipitation in the growing season (May to September) averaged 224.9 mm from 1980 to 2004 was and 246.9 mm and 190.4 mm in 2003 and 2004, implying an moister summer than usual in 2003 and an drier summer than usual in 2004.

The surface soil in the study region is sandy, contains little organic matter, and is less than 10 cm thick. Large sand grains occur beneath the organic layer with a bulk density of 1.1–1.7 gcm^{-3} and porosity of 32–59%. The observation site was located at the periphery of the sub-Arctic permafrost region. Characterized by thick active layer and higher ground temperatures. Observations of ground temperature from the surface to a depth of 3 m showed that the surface temperature was continuously below 0°C at the beginning of October.

Vegetation was uniformly sparse grass covering 38–60% of the land surface during the maximum growing period. Plant type and species showed little variation; Artemisia frigita was dominant (~60%) with other species including Arenaria and Leymus chinensis. The maximum grass height in mid-July was less than 20 cm.

2.2. Measurements

An automatic climate observation system (ACOS) recorded air temperature, humidity, and wind speed at heights of 0.5, 1.0, 2.0, and 4.0 m. Short-wave radiation and long-wave radiation were measured in both upward and downward directions. In addition, sensors measuring air pressure and an infrared radiation thermometer recording grass leaf temperature and net radiation were installed 1.5 m above the ground surface. The eddy covariance method was used to measure latent heat (Q_E), sensible heat (Q_H), and friction wind speed ($u*$) at 2 m above the ground. We used an open-path hygrometer/H_2O sensor (KH20, Campbell, USA) and a three-dimensional supersonic anemometer (81000, YOUNG, USA). The data presented below were collected during the two study years (2003 to 2005), however, the eddy covariance measurement was conducted just during the grass growth period of 2004. Therefore, aero-dynamics is main method to present full seasonal variation of heat/vapor fluxes at the study site. The parameters estimation in aero-dynamics formulas were achieved from result of eddy covariance measurement as show in following section.

Precipitation gauges often underestimate true precipitation amounts. The downward bias of gauge-measured annual precipitation estimated to be between 17 and 42% in Mongolia (Zhang et al, 2004). Soil moisture was observed both automatically and manually. Seven time-domain reflectometry (TDR) probes and seven Pt thermometers were installed at depths of 0, 0.2, 0.4, 0.8, 1.2, 2.4, and 3.0 m; two sets of heat flux meters were also inserted at 0.02 and 0.2 m. Along with a data logger, these sensors comprised the soil monitoring system (SMS). Soil moisture in the surface layer (0–60 cm) was also manually sampled to calibrate the TDR data.

Phenology observations included the grass coverage and biomass and the water content of grass leaves. These observations were conducted at 10-day intervals from May to Sep. of 2003 to June 2005 and were conducted at four 50 x 50 cm plots. The results shown are averages from the four plots.

2.3. Method of Analysis

We used a combinatorial stratification method to analyzing the direct and indirect effects of multiple factors on surface energy flux. In this method, the relationship between one factor and surface energy flux is examined successively at different, narrow intervals of other factors. The surface energy flux was characterized with the Bowen ratio as a function of (1) soil water status, (2) VPD, and (3) net radiation. A combinatorial stratification method was needed because we wanted to avoid potential complication which may arise from correlation among VPD, net radiation, and soil moisture in explaining the effects of these factors on the Bowen ratio. Initially, we included wind speed in the analysis but did not find a significant dependence of the Bowen ratio on wind speed; therefore we dropped it from further analysis. Temperature can also affect the Bowen ratio but it would be extremely difficult to separate its effect from that of VPD. Therefore we did not include temperature in this analysis.

To stratify, we divided soil water status, VPD, and net radiation into two, three, and four levels, respectively: Soil water status was categorized into drought and non-drought conditions based on observations of soil moisture. The four levels of VPD were <10, 10–20, and >20 hPa while the four levels of net radiation were <50, 50–100, 100–150, and >150 Wm^{-2}. Similar to the separation of soil water status into drought and non-drought conditions by extractable soil water, these levels of VPD and net radiation represented a tradeoff between the desire to have a fine-grained stratification and the requirement of adequate number of data for statistical analysis.

3. Summary of Results

With stratification scheme on atmospheric condition, we proceeded with the analysis of the direct and indirect effects of soil moisture, VPD, and net radiation on surface energy flux. The effects of soil moisture were examined combining of VPD and net radiation levels.

Analysis on for heat flux for different soil moisture status reveal that Bowen ratio decreases rapidly with increasing soil moisture when the soil is dry but becomes insensitive to variations in soil moisture when the soil is wet. However, the rate of decrease and the level of soil moisture above which Bowen ratio is invariant depend on atmospheric conditions. The reduced soil moisture weakens the influence of VPD but enhances the influence of net radiation on surface energy partitioning. Soil moisture also controls how net radiation influences the relationship between surface energy flux and VPD. When the soil is wet, increased net radiation enhances the positive effect of VPD on latent heat flux; however, when the soil is dry, increased net radiation enhances the negative effect of VPD on latent heat flux. Furthermore, how VPD affects the relationship between surface energy flux and net radiation depends on soil moisture. When the soil is wet, the increase in VPD dampens the increase of Bowen ratio with net radiation; when the soil is dry, the increase in VPD enhances the increase of Bowen ratio with net radiation at high levels of VPD.

The effect of VPD on surface energy fluxes is strongly nonlinear because VPD can both positively and negatively affects latent heat flux. At low VPD, an increase in VPD enhances latent heat flux and decreases Bowen ratio; at high VPD, an increase in VPD decreases latent heat flux and increases Bowen ratio. However, this overall relationship is sensitively affected by net radiation and soil moisture conditions. Bowen ratio increases with net radiation. Increasing VPD enhances the sensitivity of Bowen ratio to changes in soil moisture. Low VPD coupled with low net radiation may cause Bowen ratio to change very little with soil moisture even when the soil is dry. As VPD increases, however, Bowen ratio decreases faster with increasing soil moisture and the level of soil moisture above which Bowen ratio is insensitive to soil moisture becomes higher. Consequently, at high VPD, the effect of drought on the surface energy flux is much stronger.

The investigation on heat flux vs radiation budget imply that increasing net radiation enhances the sensitivity of Bowen ratio to changes in soil moisture. Low net radiation coupled with low VPD may cause Bowen ratio to change very little with soil moisture even when the soil is dry. As net radiation increases, however, Bowen ratio decreases faster with increasing soil moisture and the level of soil moisture above which Bowen ratio is insensitive to soil moisture becomes higher. Furthermore, increased net radiation enhances the effect of drought on the surface energy flux.

This work have been conducted on the basis of data from a single vegetation type (a was uniformly sparse grass). Therefore it is legitimate to ask how general these answers are with respect to different vegetation types and canopy structures. In developing the answers to these questions, we did not have to invoke species-specific properties; general micrometeorological principles appear to be sufficient for interpreting the observed patterns. Thus we expect that our answers will be at least qualitatively applicable to other vegetation types. These idiosyncrasies may well mean that the answers we developed here will have to be revised quantitatively for different vegetation types and land surface characteristics. For example, as vegetation structure varies from dense to sparse, one can expect VPD plays increasingly more a role of a measure of atmospheric evaporative power than that of a factor regulating stomatal conductance, thus changing the direct and indirect effects of VPD on surface energy flux. Only through analyses of actual data from different sites can we know definitively how general our answers to the six questions are.

Our finding that multiple soil and atmospheric factors have both direct and indirect effects on land surface energy flux has important implication for understanding many boundary layer phenomena. The apparent discrepancies between these observations may result from the complicated direct and indirect effects of soil and atmospheric conditions on land surface energy flux.

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