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Autumn Daily Characteristics of Land Surface Heat and Water Exchange over the Loess Plateau Mesa in China

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ABSTRACT

The Loess Plateau, located in northern China, has a significant impact on the climate and ecosystem evolvement over the East Asian continent. In this paper, the preliminary autumn daily characteristics of land surface energy and water exchange over the Chinese Loess Plateau mesa region are evaluated by using data collected during the Loess Plateau land–atmosphere interaction pilot experiment (LOPEX04), which was conducted from 25 August to 12 September 2004 near Pingliang city, Gansu Province of China. The experiment was carried out in a region with a typical landscape of the Chinese Loess Plateau, known as "loess mesa". The experiment's field land utilizations were cornfield and fallow farmland, with the fallow field later used for rotating winter wheat. The autumn daily characteristics of heat and water exchange evidently differed between the mesa cornfield and fallow, and the imbalance term of the surface energy was large. This is discussed in terms of sampling errors in the flux observations–footprint; energy storage terms of soil and vegetation layers; contribution from air advections; and low and high frequency loss of turbulent fluxes and instruments bias. Comparison of energy components between the mesa cornfield and the lowland cornfield did not reveal any obvious difference. Inadequacies of the field observation equipment and experimental design emerged during the study, and some new research topics have emerged from this pilot experiment for future investigation.

Key words: Chinese Loess Plateau, mesa region, energy exchange, corn, fallow soil

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1. Introduction

The Chinese Loess Plateau along the middle reaches of the Yellow River has complex geomorphic features. At an elevation ranging from 1000 m to 1800 m, it consists of diverse landscapes including the loess mesa, lowlands, gullies, hills, the loess ridge, continuous knolls, dry gulches, flat ground, loess terraces, and other land surface types (?). The loess deposition, which is the main component of the Chinese Loess Plateau, is loose and easily washed away by runoff. The Yellow River, with the highest levels of silt anywhere in its reaches, flows through this region and carries away more than 1.4 billion tons of silt annually. Around 430,000 km^2 of land is suffering from soil erosion (?). Therefore, the policy of the Chinese government—"Abandoning Sterile Mountainous Farming Lands for Growing Trees or Grass"—is a necessary and strategic measure to meliorate the environment over these kinds of land surfaces.

Among the various Loess Plateau landscapes, the loess mesa is characterized by a large flat mountain top area, where agriculture is well developed and supports one-twelfth of the Chinese population (?). Few land–atmosphere interaction studies have been conducted on the Loess Plateau because of its complex underlying surface. However, a land–atmosphere interaction study in this loess mesa region would provide a significant contribution toward understanding the characteristics of land surface energy balance, land surface parameterization, and water and soil conservation over the Chinese Loess Plateau.

Regional distributions of land surface energy components have been derived from a combination of satel-

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lite remote sensing and ground measurement data in some other regions of the world (?; ?; ?; ?; ?; ?; ?). ? suggested that vegetation and soil parameters have large impacts on simulations of surface energy and water balance in the semiarid Sahel; soil properties, including thermal diffusivity, played an important role in the surface water and energy budgets. Land or sea surface process field experiments have also been conducted all over the world in various heterogeneous and semiarid regions (?; ?). A number of studies have been conducted on regional actual evaporation or evapotranspiration estimation with the aid of satellite remote sensing data in recent years (?; ?; ?; ?; ?; ?). The models for calculating sensible and latent heat fluxes over the Tibetan Plateau were developed as well (?). A process-based model was established to simulate the spatial and temporal patterns of evapotranspiration and its components over the Lushi basin of the Loess Plateau. ? determined the zero flux plane (ZFP) by soil moisture observation and calculated evapotranspiration from the change of soil water content above the ZFP over the Loess Plateau Liudaogou Basin, located in Shenmu county, Shaanxi Province. A three-layer soil model was used to estimate the heat and water balances of the bare soil surface (?). However, all these studies were based on using the routine meteorology observation data; few eddy covariance flux measurement systems were fully conducted over the Chinese Loess Plateau. Based on these motivations, and on improving the understanding of the loess mesa region land surface process, we organized a pilot field experiment prior to the formal investigation, the Loess Plateau land–atmosphere interaction pilot Experiment, from 25 August to 12 September 2004 (LOPEX04), in a loess mesa region, the Baimiao mesa cornfield, fallow field, and its adjacent lowland cornfield, near Pingliang city, Gansu Province of China. The key observations of the pilot field campaign focused on measurements of land surface energy components, soil temperature and soil moisture.

In this paper, we attempt to analyze the data collected from the pilot experiment (LOPEX04) and the characteristics of the land–atmosphere interaction, and examine the land surface energy closure in the Chinese Loess Plateau mesa region. Description of the observation sites, data analyzing methodology, results and discussions are presented over the next two sections. Concluding remarks are drawn in the final section of this paper.

2. Observation sites and instruments

The geographic locations of sampling fields are illustrated in Fig. 1; coordinates of the central point are 35.35°N, 106.42°E, and the height above sea level is 1592 m. The experimental area was located in a semiarid climate zone, with an average mean temperature of 6°C, a maximum recorded temperature of 34°C, a lowest recorded temperature of −24°C, average annual precipitation of 510 mm, 2425 hours of sunshine per year, and 170 days free of frost [obtained from local meteorological data (?)]. Representative soil types in the Loess Plateau include heavy loam, medium loam, light loam, and sandy loam. The soil texture of the pilot experimental sampling fields is typical medium loam with a high proportion of silt; this type of soil has a large heat and water capacity (?; ?). The loess mesa and the level areas at its base were agricultural lands, planted primarily with corn and winter wheat. The winter wheat field laid fallow and the corn was in the silking stage during the experimental period. Prior to the experiment, a disastrous hailstorm occurred over the cornfield at the base of the mesa, shredding and nearly destroying the corn leaves. This might have a significant effect on canopy heat storage and photosynthesis; it also might influence the degree of surface reflectance measured at the top of the canopy.

Two sets of triaxial sonic anemometer (CSAT3, Campbell Scientific Inc., USA), KH2O Krypton Hygrometer sensor, HFT3 soil heat sensors (Campbell Scientific Inc., USA), soil volumetric water content reflectivity sensors (CS616, Campbell Scientific Inc., USA), soil temperature sensors (TCAV, Campbell Scientific Inc., USA), a Portable Automated Mesonet (PAM) radiation measurement system (Mitsubishi Corporation, Japan), and a CRN-1 radiometer system (Kipp & Zonen, Holland, Campbell Scientific Inc., USA) were deployed during the experimental period. The triaxial sonic anemometers and KH2O Krypton Hygrometer sensor were mounted at a height of 2.5 m above the bare soil surface and 1.0 m above the top of the corn canopy. The soil heat flux sensor was buried 0.05 m below the soil surface. The soil volumetric water content and soil temperature sensors were measured at 0.05 m, 0.10 m, 0.20 m, and 0.40 m below the soil surface. The radiation sensors were mounted at a height of 1.5 m above the bare soil surface and 1.0 m above the top of the corn canopy. The sensible and latent heat fluxes were computed from the turbulence observation data of the triaxial sonic anemometer and KH2O Krypton Hygrometer sensor. The four radiation components from which net radiation flux was derived were incoming and outgoing shortwave and longwave radiation fluxes, which were measured sep-

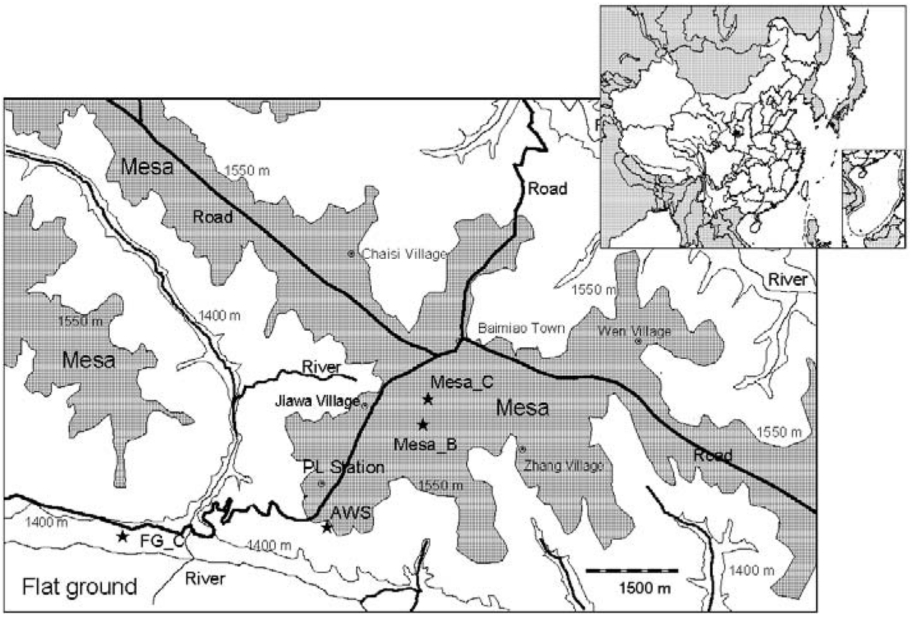

Fig. 1. Geographic location and landscape of the LOess Plateau land–atmosphere interaction pilot EXperiment 2004 (LOPEX04) study area. Mesa_C (★) represents the eddy covariance flux station at the mesa corn field; Mesa_B (★) represents the eddy covariance flux station at the Mesa bare soil surface; FG_C (★) represents the eddy covariance flux station at the lowland corn field; AWS (★) represents the Automatic Weather Station installed at the edge of the mesa; and (⊙) is a town or village.

arately using four radiometers. All these instruments consisted of two sets of eddy covariance measurement systems. One eddy covariance unit with a PAM radiation measurement system was permanently installed at the mesa cornfield after a short periodic of intercomparison observations (26 August–10 September 2004); while another eddy covariance flux measurement unit with a CRN-1 radiometer system was installed on the mesa fallow at the start of the first experimental period (26–31 August 2004) and then transferred to the lowland cornfield site at the base of the loess mesa in the later period (1–10 September 2004).

In order to ensure that the eddy covariance measurement systems had sufficient fetch, or footprint, the sonic anemometer sensors were placed to maximize their contact with the local prevailing wind direction. The sampling frequency of the triaxial sonic anemometer and KH2O Krypton Hygrometer sensor was 10 Hz, and the fluxes were derived at 10 minute intervals. The soil heat flux, soil temperature and water content were also outputted at 10 minute intervals. In addition, an Automatic Weather Station (AWS) was installed at the edge of the mesa for monitoring mountain valley winds; the measurements included wind velocity and direction at a height of 2.0 m, as well as temperature and humidity at a height of 1.5 m during the experimental period.

The experimental period was characterized by partly cloudy weather–principally cumulus cloud occurring over the observation fields. This might cause significant fluctuations in the observed global radiation flux. A 3.0 mm precipitation event took place on 1–2 September 2004, during which time the measurement systems failed to function.

3. Observation data and analyses

In order to ensure the experimental measurement data was comparable and reliable, two eddy covariance flux measuring systems were set up in the same field for one to two days' of intercomparison observation prior to 26 August 2004 and after 10 September 2004. The detailed results are presented in Fig. 2. The net radiation was calculated using four radiation components, namely incoming and outgoing shortwave and longwave radiation fluxes. The EC-A system used the CRN-1 radiometer, while the EC-B used the PAM measurement. The results show that the two sets of four radiation components were consistent with each other except for the downward longwave radiation, which produced a small difference of the net radiation. After a simple correction to the EC-B long-downward wave radiation, the consistencies between the two sets of observation data became much better; the consis-

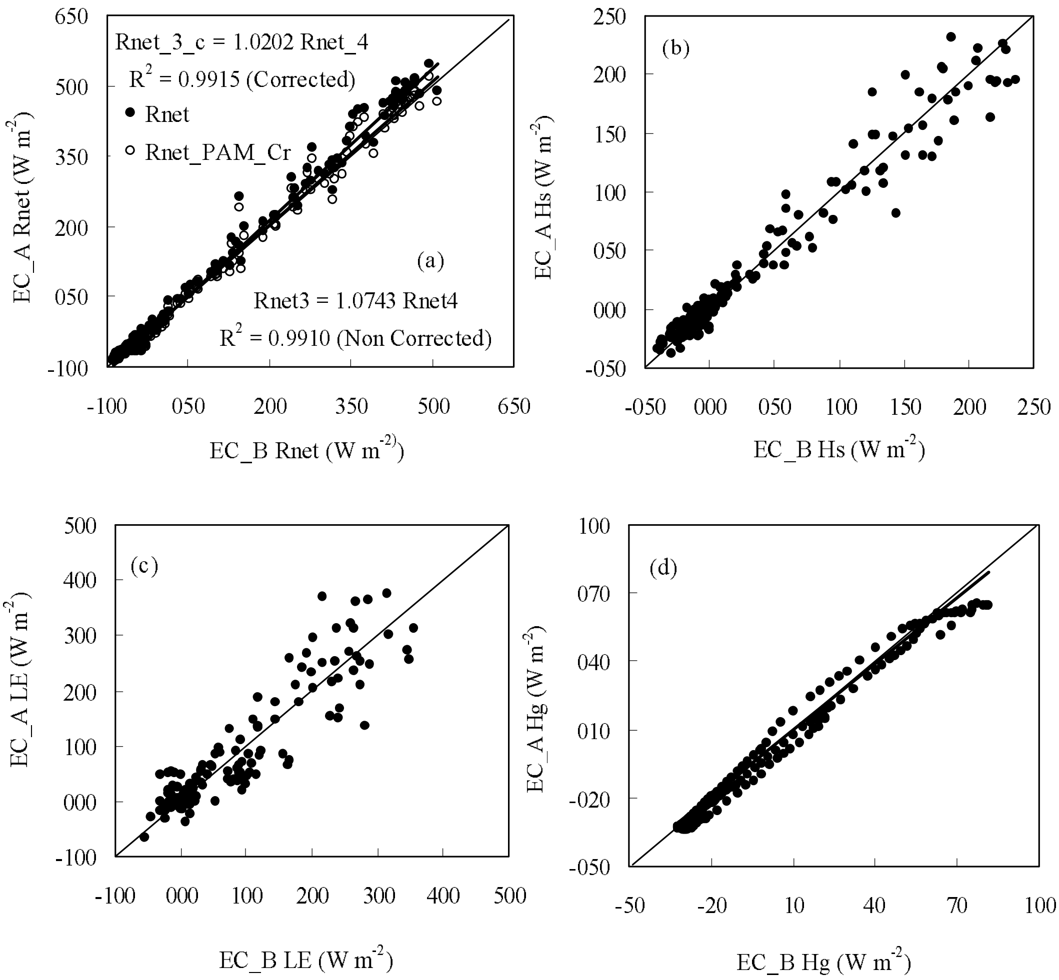

Fig. 2. Intercomparisons of the energy components measured by two sets of instruments deployed during the experiment: (a) Net radiation; (b) Sensible heat flux; (c) Latent heat flux; and (d) Soil heat flux.

tency of the net radiation (described by slope of the regression line) measured by the two systems improved from 1.0743 to 1.0202 (1.0 for the ideal case). The sensible and latent heat fluxes were calculated from anemometer measurements. These instruments were new and manufactured by the same company. Although the plotted results were scattered, their level of consistency was very good. Gao et al. (2003) indicated that approximately 90% of the measured flux at the measurement height (3 m) was expected to come from the area within 600 m upwind for neutral stability; the Loess Plateau mesa region of the experiment field was much larger than this size in the present study. Thus the measurements of the eddy covariance systems could characterize the properties of the observational sites.

The soil heat fluxes at a depth of 5 cm were in good agreement each other, as the soil temperature above and below the heat flux panel controlled the magnitude of the soil heat flux, and the vertical temperature grade was the same for a specific site. We also conducted measurements in the laboratory and confirmed that the same difference between the upper and lower temperature causes the same soil heat flux.

The EC-A measuring system was installed in the mesa cornfield after the intercomparison measurements. The EC-B measuring system was installed on the mesa fallow exposed soil surface during 26–31 August 2004 and in the flat lowland cornfield at the mesa base during 1–10 September 2004. Figure 3 shows that the degree of energy imbalance is considerable in the Loess Plateau Soil–Plant–Atmosphere Continuum (SPAC) system, especially during the daytime. This implied that the magnitudes of heat storage terms for the soil, vegetation canopy, and air were also considerable in the loess mesa SPAC system. Detailed measurements of soil temperature, soil moisture, canopy temperature, and air temperature are necessary for estimating these storage terms in a land surface energy balance study (**?**). We also found a typical situation

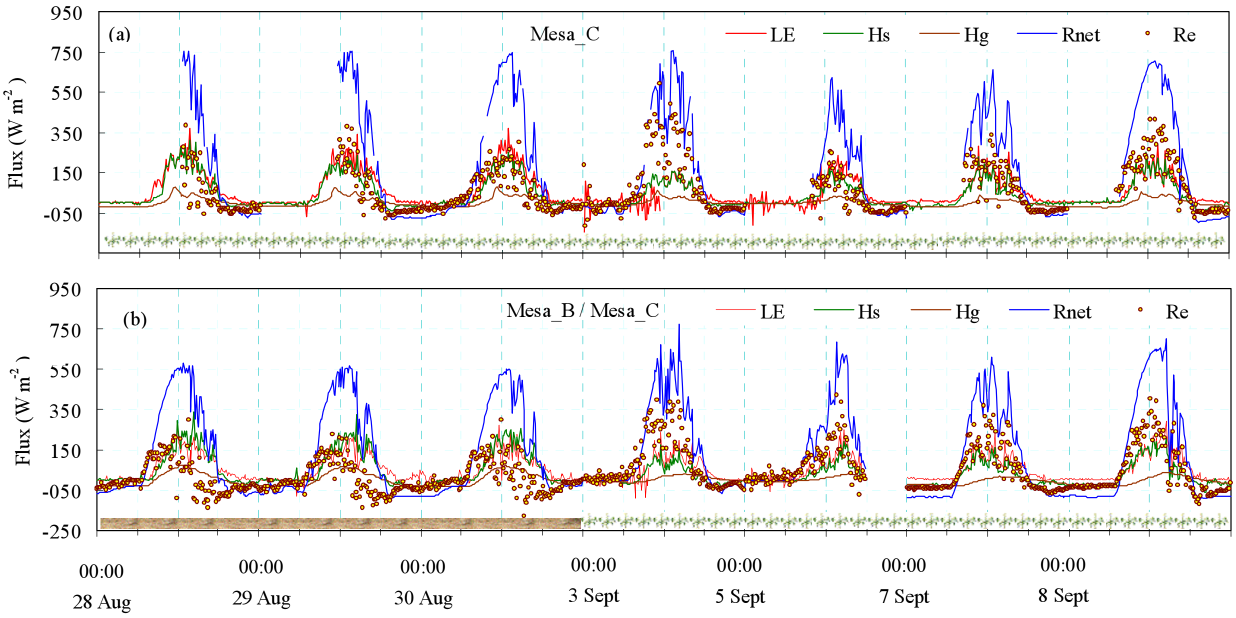

Fig. 3. Time series of the EC system measured energy components at two eddy covariance flux stations: (a) Cornfield on the mesa area (Mesa_C) during 28–31 August 2004 and 3–10 September 2004; (b) Bare soil surface on the mesa (Mesa_B) during 28–31 August 2004; cornfield on the lowland at the foot of the mesa (FG_C) during 3–8 September 2004.

under the bare soil surface: In the afternoon, the net radiation is less than the total of soil heat flux, sensible flux, and latent heat flux. A peak in the soil heat flux was observed around 1110 LST in the cornfield. This might have been caused by the influence of the incidental angle of solar radiation and orientation of the corn leaves on the radiative transfer process.

The comparison of energy flux observations in the mesa cornfield and the exposed bare soil surface are presented in Figs. 4a–d. The net radiation fluxes were larger in the cornfield than those in the exposed bare soil surface; the discrepancy was less than 150 W m^{-2}, and this was a reasonable result considering the radiative properties of the bare soil as opposed to those of the vegetation canopy. Two sets of net radiation datasets taken from the mesa cornfield and the mesa fallow surface were closely correlated. This was determined by the difference of surface reflectance and temperature variation at the two sites. The latent heat fluxes are the energy consumed by evaporation from the soil surface and evapotranspiration from the canopy. Therefore, the latent heat flux in the cornfield was greater than that in the fallow field. In the early morning or late afternoon, the soil heat flux was also larger in the cornfield than in the fallow field. At midday clear sky, the soil heat flux was larger in the fallow field than in the cornfield because the exposed soil received more solar radiation than the cornfield.

In some exceptional cases, such as windless weather combined with high air temperature, the topsoil temperature in the cornfield might be higher than that in the bare soil surface, because the crop layer of corn trapped more heat than the bare soil surface; this caused a larger soil heat flux in the cornfield than in the fallow field.

The comparison of energy components measured in the mesa cornfield and the adjacent lowland cornfield are illustrated in Figs. 4a–d. The differences between these fluxes were much smaller in this case. Net radiation was a little less in the mesa cornfield; the canopy reflectance of the nearby lowland cornfield was smaller than that from the mesa cornfield because of the hail damage to the corn leaves in the lowland cornfield. There was no evident difference between the sensible and latent heat fluxes at the mesa and lowland cornfield sites. The soil heat flux showed temporal variation during the daytime; the soil heat flux was greater in the morning at the mesa cornfield, and greater in the afternoon in the lowland cornfield. The reason was that the cornfield on top of the mesa received less net radiation because of the denser corn in the field below. The soil surface of the lowland cornfield was warmer in the afternoon than that of the mesa top because of its lower elevation. So, the soil heat flux in the lowland cornfield was greater in the afternoon than that in the cornfield on the mesa.

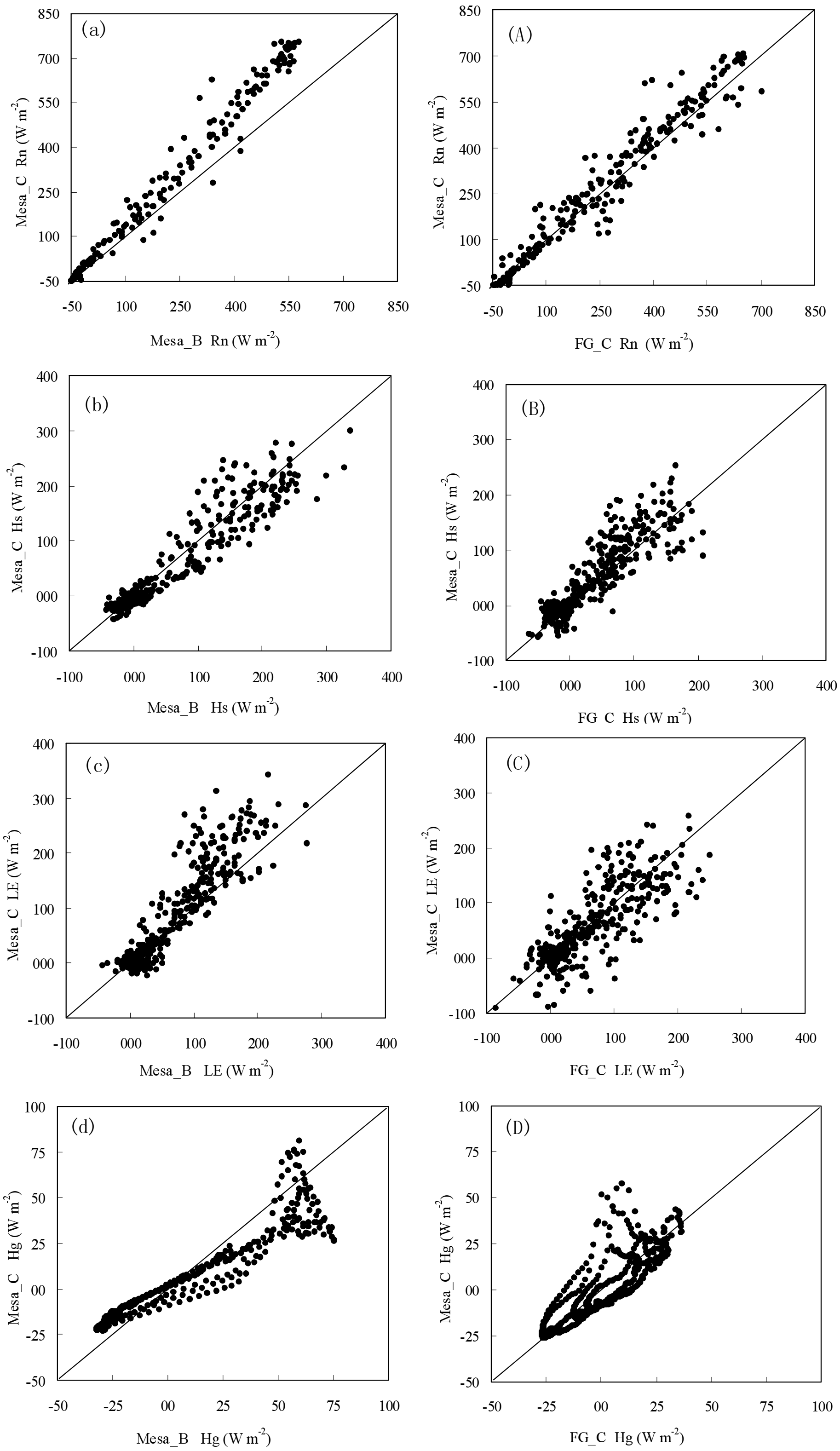

Fig. 4. Comparison of the energy complements measured in the mesa corn field and bare soil surface (top row): (a) Net radiation; (b) Sensible heat flux; (c) Latent heat flux; (d) Soil heat flux. Bottom row: The mesa cornfield and the lowland cornfield adjacent to the mesa: (A) Net radiation; (B) Sensible heat flux; (C) Latent heat flux; (D) Soil heat flux.

4. Results and discussion

The ratio of the sum of sensible and latent fluxes to the total available energy sum of net radiation and soil heat fluxes is defined as the energy budget closure deficit (CD). Theoretically, the CD should be equal or almost equal to 1.0 for a level and homogeneous observation field having sufficient fetches, or footprint. However, we observed evidence that the net radiation could not be balanced by the sum of measured latent, sensible and soil heat flux over the Chinese Loess Plateau mesa region. When the near surface net radiation increased, the value of the energy imbalance term also increased for the observation data measured at the bare soil surface; the CD was larger there than in the cornfield. As for the measurements in the mesa cornfield, the mesa fallow field and the lowland cornfield, the average CD values were 0.5707, 0.7334, and 0.5020, respectively. As the temporal fluctuation of observed net radiation was large, the land surface energy closure deficit was anomalous. In general, the degree of closure deficit was better in daytime than at night. This result was consistent with the results from ChinaFLUX and the International Network of Eddy Covariance Sites (FLUXNET) (?; ??).

In light of the results derived from other major field campaigns, the energy imbalance problems were widespread. For instance, a degree of uncertainty of around 10% to 20% of the total energy in locally measured sensible and latent surface heat fluxes was observed during the First International Satellite Land Surface Climatologic Projects (ISLSCP) Field Experiment (FIFE) by many investigators (?; ??; ?; ?). Kustas et al. (1999) pointed out that the measured sum of sensible and latent heat flux was generally less than the sum of net radiation and soil heat flux. Thus, CD was about 0.7–0.9 (daytime average: 0.77) during the Washita'94 Experiment conducted in the Little Washita Experimental Watershed near Chickasha, Oklahoma, USA. At forest sites, the seasonal mean CD was 0.81–0.98 from April to September, and at the fen site the monthly mean CD was 0.5–0.8 (?). ? and ? indicated that land surface energy closure problems also occurred in field experiments conducted on the Tibetan Plateau, and a rice paddy on the central plain of China; further refinements in measuring soil heat fluxes may be necessary. There were evident discrepancies for the soil heat fluxes at different depths; the maximum difference between soil heat fluxes could reach 50–100 W m^{-2} between a depth of 1 mm and 46 mm below the soil surface (?). ? pointed out that soil and canopy heat storage are each roughly 15% and 7% of the total net radiation respectively, which was about 80 W m^{-2} for maize and 40 W m^{-2} for soybeans during morning hours. The closure failure might have been due to not obtaining a sampling long enough in duration to accurately reflect the actual case of low frequency,

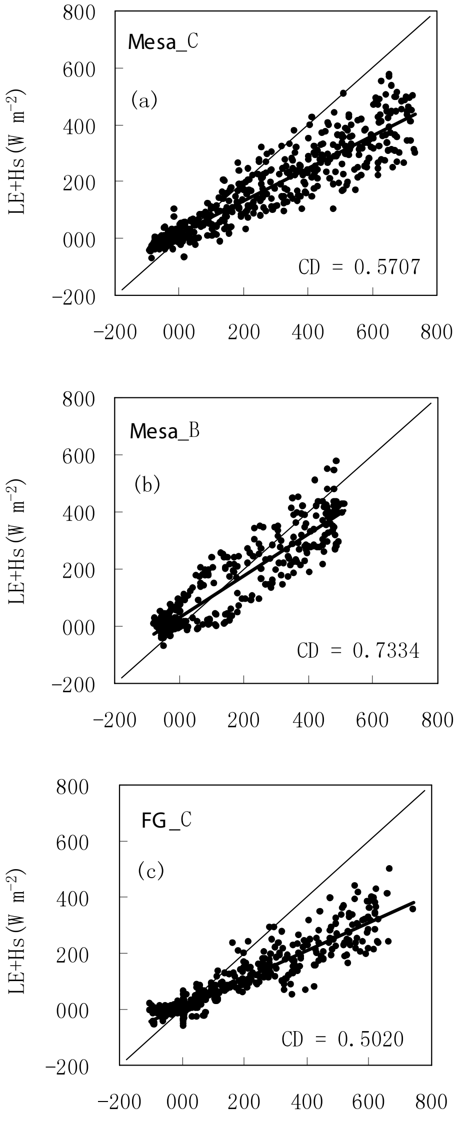

Fig. 5. Energy balance closure tested during the LOPEX04 experimental period: the measured sensible and latent heat flux (LE+Hs) against available energy (Rnet-Hg). (a) Cornfield on the mesa (Mesa_C). (b) Fallow field on the mesa (Mesa_B). (c) Cornfield in the flatted lowland (FG_C).

large-scale turbulent motions onto the turbulent fluxes (?).

Due to the special landscape of the Loess Plateau mesa region, the observed energy imbalance and its temporal variation were evident, which can be explained from the following aspects:

(1) The different source areas of the eddy covariance measurement sensors–the fluxes' footprint can cause the energy imbalance. The source area of a net radiometer is a radius determined by the net radiation sensor's height that is centered below the instrument; it is fairly constant and independent of time and wind. On the other hand, the spatial dimensions of the triaxial sonic anemometer and KH2O Krypton Hygrometer flux footprint are not fixed in space and are dependent on atmospheric stability conditions and the mean upwind direction; the source areas of a net radiometer and eddy covariance flux footprint are never matched (**?**). **?** developed a three-dimensional Lagrangian footprint model with the ability to predict the area of influence of a measurement within a wide range of boundary layer stratifications and receptor heights. For a 50 m receptor height, the size of the upwind 50%-level source area was 200 m for the strongly convective atmosphere; it could reach 2000 m for the stable atmosphere. For the strip-sown corn distributed at the Loess Plateau mesa area, the footprint effect needs to be carefully considered in future studies.

(2) The turbulent mixing has effects on energy balance closure, the energy closure deficit increase with friction velocity. If the mean friction velocity exceeds a threshold value, it is only slightly increased, and gradually becomes constant, but the trend is weak at night compared to daytime (**?**). Future experimental data should be analyzed using this scheme.

(3) The soil heat storage above the soil heat flux sensor, the vegetation heat storage, and the biochemical energy storage transformed by photosynthesis, might cause errors in available energy calculation. Therefore, all these terms in the energy balance over the Chinese Loess Plateau need to be taken into account for the energy closure, and the detail in observations for soil temperature, vegetation temperature, vegetation water content and other relevant parameters need to be collected in future experiments.

(4) Non-neglected advection has effects on the energy closure; even slight elevation gradients over a range of spatial scales can induce nocturnal drainage flows and advection near the surface during periods of strong static stability. So, the determination of the observation site location where the eddy covariance measurement system will be set up is very important.

(5) The eddy covariance technique underestimates the total mean turbulent flux to some extent because of low pass filters (high frequency loss) and high pass filters (low frequency loss). We do not currently know how to correct these errors. The instruments themselves might cause observation errors; calibrations are necessary for the instruments every two years.

5. Concluding remarks

LOPEX04 was successful in its collection of measurement data for the surface energy component fluxes, soil temperature and moisture, and near surface layer meteorological variables over the Chinese Loess Plateau mesa region. By analyzing the collected data, the preliminary autumn daily characteristics of land–atmosphere energy and water exchange over the Chinese Loess Plateau mesa region were obtained. Our conclusions are:

(1) The land surface energy imbalance terms over the Chinese Loess Plateau mesa region cornfield were large, which implied that the magnitudes of the storage terms were considerable in the Loess Plateau Soil–Plant–Atmosphere Continuum (SPAC) system.

(2) The characteristics of the cornfield on the mesa and the bare soil surface of the fallow field on the mesa were different, but there was no evident difference in daily energy exchange characteristics between measurements at the mesa and in the adjacent lowland cornfields.

With the feasibility demonstrated for conducting land surface process field experiments over the Chinese Loess Plateau mesa region, based on the autumn daily land surface energy exchange characteristics presented in this investigation and the new research interests found during the experimental period, the following salient points should be addressed and studied in future experiments over the Chinese Loess Plateau mesa region:

(1) Detailed measurements of soil heat flux, soil temperature, soil moisture for the determination of soil heat storage, water and heat transfer within the loess soil are necessary in order to improve the degree of land surface energy balance closure.

(2) Detailed measurements of vegetation parameters, including vegetation biomass, vegetation water content and temperature are essential. These parameters are very important in studies of the energy storage term of the canopy, and for microwave remote sensing of soil moisture retrieval over the Chinese Loess Plateau mesa and neighboring regions.

(3) The determination of regional evaporation or evapotranspiration over the loess mesa region are important in studies of energy exchange, the loess mesa hydrology, and agricultural development over the Chinese Loess Plateau.

(4) The loess mesa land surface characteristics assessed via satellite remote sensing; the combination of satellite remote sensing and land surface meteorology data are essential in the research of Chinese Loess Plateau land surface processes.

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