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Variability of Soil Moisture and Its Relationship with Surface Albedo and Soil Thermal Parameters over the Loess Plateau

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ABSTRACT

Data from July 2006 to June 2008 observed at SACOL (Semi-Arid Climate and Environment Observatory of Lanzhou University, 35.946°N, 104.137°E, elev. 1961 m), a semi-arid site in Northwest China, are used to study seasonal variability of soil moisture, along with surface albedo and other soil thermal parameters, such as heat capacity, thermal conductivity and thermal diffusivity, and their relationships to soil moisture content. The results indicate that surface albedo decreases with increases in soil moisture content, showing a typical exponential relation between the surface albedo and the soil moisture. The heat capacity, the soil thermal diffusivity, and soil thermal conductivity show large variations between Julian day 90–212 and 450–578. The soil thermal conductivity is found to increase as a power function of soil moisture. Soil heat capacity and soil thermal diffusivity increase with increases in soil moisture. The SACOL observed soil moisture are also used to validate the AMSR-E/AQUA retrieved soil moisture and there is good agreement between them. The analysis of the relationship between satellite retrieved soil moisture and precipitation suggests that the variability of soil moisture depends on the variation of precipitation over the Loess Plateau.

Key words: soil moisture, surface albedo, soil heat capacity, soil thermal conductivity, soil thermal diffusivity, AMSR-E soil moisture product, Loess Plateau

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1. Introduction

It has long been recognized that soil moisture plays an important role in the regional climate system through its effect on surface albedo and on the partitioning between sensible and latent heat fluxes. Over the continental regions, soil moisture is the most important component of the meteorological memory, along with snow cover (Delworth and Manabe, 1988, 1993). In this context, studies of the arid and semi-arid regions, which cover more than one-third of China's land surface, constitute an important part of overall global climate change research (Fu and An, 2002). The soil moisture can greatly affect albedo and evaporation. Near-surface soil moisture controls the partitioning of available energy at the ground surface into sensible and latent heat exchanges with the atmosphere (Wei, 1995) and influences regional climate change further. Gao et al. (2008) found a new algorithm, which gives a realistic estimate of soil temperature; their contribution is providing an analytic insight into the role of heterogeneity and gives some simple formulae as tools for interpretation of the role of heterogeneity in observed diurnal temperature variations. Liu et al. (2008) analyzed seasonal variations of the surface albedo in the semi-arid area of Tongyu, over northeastern China, as well as the relationship between the surface albedo and soil moisture, using Tongyu station observation data. Soil parameters have relationships with soil components, terrain, and geographic location.

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Table 1. The measurement instruments and quantities measured.

Parameter/variable name description	Range	Units	Measurement height	Instrument
Downward and upward shortwave radiation	0–1200	W m^{-2}	1.5 m	Kipp and Zonen, CM21
Soil heat flux	−300–300	W m^{-2}	5, 10 cm	Hukseflux, HFP01SC-L
Soil moisture content	0–70	m^3 m^{-3}	5, 10, 20, 40, 80 cm	CAMPELL, CS616_L
Soil temperature	−50–70	°C	2, 5, 10, 20, 50, 80 cm	Hukseflux, STP01-L
Precipitation intensity	0–15	mm	0.3 m	TE525MM-L, Texas Elect

The Loess Plateau is the largest arid and semi-arid zone in China and one of the regional dust aerosol sources. Information related to Loess Plateau is very important but not very much exists in the literature. Water is a crucial factor restricting vegetation restoration and conservation in the Loess Plateau (Zhang and Shangguan, 2002). Annual rainfall is relatively low over this region, and its distribution is uneven in both space and time. Water can be redistributed in the soil, as the soil layer is very deep (Hu and Shao, 2002). The characteristics of the soil water distribution make it difficult to conserve environmentally in the Loess Plateau. Because of the uniqueness of soil, geography, and climate regimes associated with the Loess Plateau, it is very important and necessary to study soil moisture content on the Loess Plateau.

In past years, the government and people have realized more and more the importance of research in semi-arid regions, and as a result some important experiments have been conducted in such regions of China with some important results; for example, Heihe River basin Field Experiment (Hu and Gao, 1994; Wang and Mitsuta, 1991), Inner Mongolia Semi-Arid Grassland Soil-Vegetation-Atmosphere Interaction (Lü et al., 2005), GEWEX (Global Energy and Water cycle Experiment) Asian Monsoon Experiment on the Tibetan Plateau, CEOP (Coordinated Enhanced Observing Period) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau (Ma et al., 2006), and the Dunhuang experiment (Zhang et al., 2001) investigated the characteristics of some parameters associated with the land-surface processes in the arid and semi-arid regions of Northwest China. However, there is no comparable reporting for long-term soil moisture measurements over the Loess Plateau. This study attempts to fill this gap. A time series of continuous measurements (from July 2006 to June 2008) from the Semi-Arid Climate and Environment Observatory of Lanzhou University (SACOL) is used to study the seasonal changes in surface albedo and soil thermal parameters, and their relationship with soil moisture. The observational site represents the character of the climate and other meteorological conditions typical of the Loess Plateau, and the high quality of the measurements will be used to validate satellite retrieved soil moisture products.

2. Site and data

Our study site is near the city of Lanzhou on the southern bank of the Yellow River, and has been established since 2005. SACOL (35.946°N, 104.137°E, 1961 m above sea level) is a typical semi-arid region, with much of the vegetation limited to the rainy season (May–October). The parent soil material is mainly quaternary Aeolian loess with the main soil type being sierozem. SACOL's main objective is to obtain high quality data and use them to increase our knowledge while reducing uncertainties associated with atmospheric aerosols and their radiative impacts. Because the site is a good example of a typical semi-arid region which plays an important role in climate change, the information obtained from SACOL is critical in climate change research. SACOL also plays a critical role in testing and improving the satellite algorithms over the Loess Plateau because of the unusually complete datasets that are obtained to characterize properties of the atmosphere and the surface (Huang et al., 2008).

The SACOL site commenced its operation as a part of the Coordinated Enhanced Observing Period (CEOP) which was initiated as a major step towards bringing together the research activities of the Global Hydrometeorology Panel of the Global Water and Energy Cycle Experiment (GHP/GEWEX) and the related projects of the World Climate Research Programme (WCRP), such as Climate Variability and Prediction (CLIVAR) and Climate and the Cyrosphere (CLiC). All the sensors are calibrated and validated each year.

The main instruments from which we collected data for our study are: (1) a radiation flux observation system and (2) a soil temperature and soil humidity measuring system. Soil moisture was measured at depths of 0.05, 0.10, 0.20, 0.40, and 0.80 m; soil temperature was measured at depths of 0.02, 0.05,

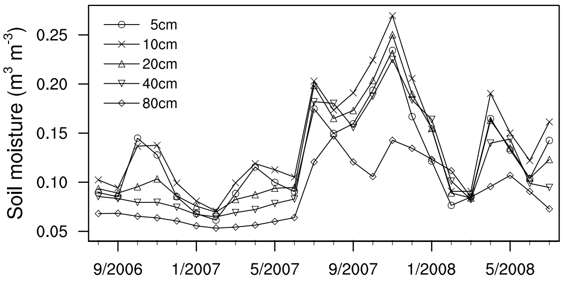

Fig. 1. Monthly mean soil moisture at SACOL.

0.10, 0.20, 0.50, and 0.80 m; soil heat flux was measured at two depths (0.05 and 0.10 m). The instruments and measurement parameters used in this study are listed in Table 1. All the measurements were taken every 30 seconds. A linear interpolation scheme was used to fill in missing data and to construct a regularly spaced data.

3. Diurnal and seasonal cycle of soil moisture

The Loess Plateau has a special kind of climate and is characterized by soil typical of an arid and semi-arid region. Figure 1 shows the characteristics of the seasonal variation of soil moisture at 5 cm, 10 cm, 20 cm, 40 cm, and 80 cm depths for the period from July 2006 to June 2008; the variations in soil moisture at different depths are almost consistent. The surface moisture content is very low and stable during the dry season, and at this time, melting snow is the only source of water, and it is also affected by wind, dust storms, and other phenomena that occur in the dry season. The soil water content increases as the rainy season begins.

Figure 2 shows the seasonal mean of diurnal soil moisture variation in different seasons observed at SACOL. In this figure, we find that soil moisture is different for the four seasons. In the rainy season (summer and autumn), the soil is wetter than in the dry season (spring and winter). The daily amplitude at 5 cm is the greatest but the soil moisture at 5 cm is not the maximum of all the depths. The diurnal variations at 20, 40, and 80 cm do not have obvious changes in contrast to the shallow layer. A similar variation in soil moisture was also reported by Chen et al. (2007). The diurnal variation reaches its minimum around 0900 LST and maximum around 1700 LST. Figure 3 shows the standard deviation of soil moisture at 5 cm. We observed that soil water content varied greatly in the rainy season and less in the dry season. It is natural to suspect that this pattern might be greatly related to precipitation and evaporation.

4. Relationship of soil moisture and albedo

Land surface albedo can be calculated from measurements of the shortwave radiation components as follows:

$$\alpha = S_{\rm u}/S_{\rm d}\ , \quad (1)$$

where $S_{\rm u}$ is the total upward solar radiation (the re-

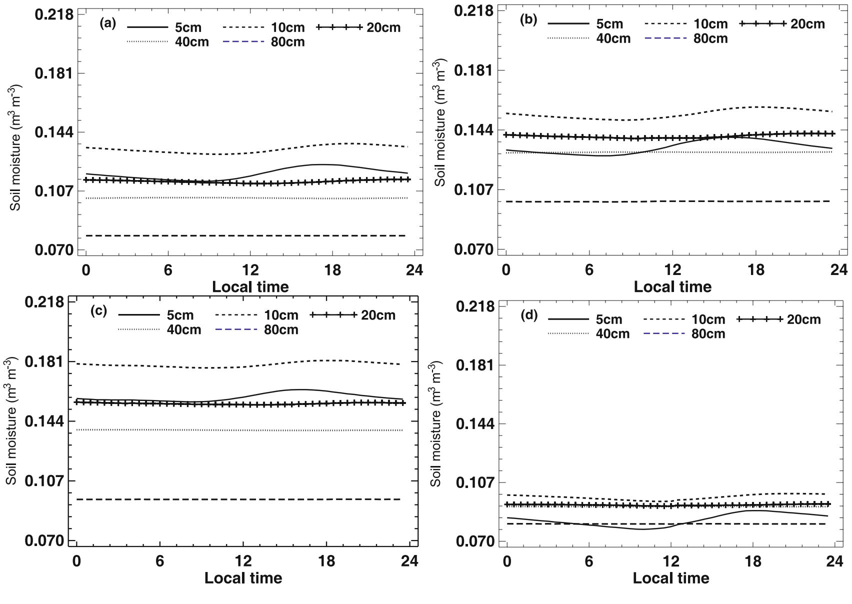

Fig. 2. Seasonal mean of diurnal soil moisture variation for (a) spring, (b) summer, (c) autumn, and (d) winter at SACOL.

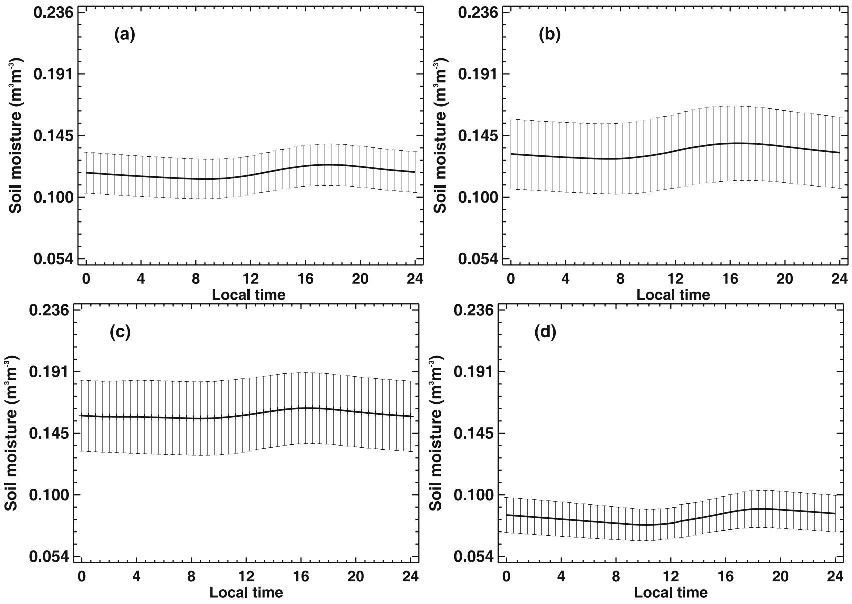

Fig. 3. Standard deviation of soil moisture at 5 cm observed at SACOL for (a) spring, (b) summer, (c) autumn, and (d) winter.

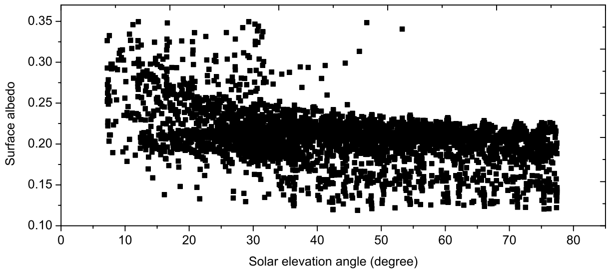

Fig. 4. The influence of solar elevation angle on half hourly surface albedo.

flected solar radiation) and S_{d} is the total downward solar radiation reaching the land surface. The half hourly averages of S_{u} and S_{d} measured by pyranometer (Kipp and Zonen model CM21) are used.

The parameters which influence albedo are based on the conditions at the surface, such as soil moisture, vegetation cover, roughness, and so on. Solar altitude angle and soil moisture are the two main factors which influence the albedo (Li, 2009). In order to study the influence of soil moisture on the surface albedo, it is necessary to first examine the influence of solar elevation angle on the surface albedo. For this purpose, the surface albedo is calculated with Eq. (1). The solar elevation angle can be calculated from the longitude and latitude of the site, Julian day, and mean measurement time. To show accurately the influence of solar elevation angle on the surface albedo, seasonal differences such as snow cover have been taken into account, as well as excluding half hourly radiation data associated with rain and snow days. In addition, sharp peaks in surface albedo are also removed. We selected the soil moisture data corresponding to the albedo data. One can see from Fig. 4 that the solar elevation angle varies from 10° to 80°. It shows that the influence of solar elevation angle on the surface albedo is small enough to be omitted when the solar elevation angle varies from 40° to 80°. Therefore, the daily surface albedo calculated from the solar elevation angle varying from 40° to 80° can be used to study its variation with soil moisture. The satellite data can also be used to calculate the surface albedo and get a similar relationship that was obtained by Li (1995).

Figure 5 shows the relationship between the daily surface albedo and the daily surface moisture content at the 5 cm depth. One can see that the albedo decreases with increasing soil moisture, with the data fit by the following equation:

$$\alpha = 0.323 \times \exp(-\eta_{\mathrm{s}}/0.713) - 0.069\ , \qquad (2)$$

where α is the daily average surface albedo and is the daily average soil moisture at 5 cm. The r^2 is 0.482 for the regression, and the fit standard deviation is 0.00039. Similar exponential relations between the surface albedo and the volumetric soil moisture content have been derived by Hoffer and Johannsen (1969), Lobell and Asner (2002), Liu et al. (2002, 2003), Wang et al. (2005) and Liu et al. (2008).

Comparing the relationship between soil moisture and albedo for different land surfaces such as crops (Liu et al., 2008) and semi-desert (Wang et al., 2005), we find that the relationship is most pronounced for semi-desert areas, followed by the Loess Plateau, and

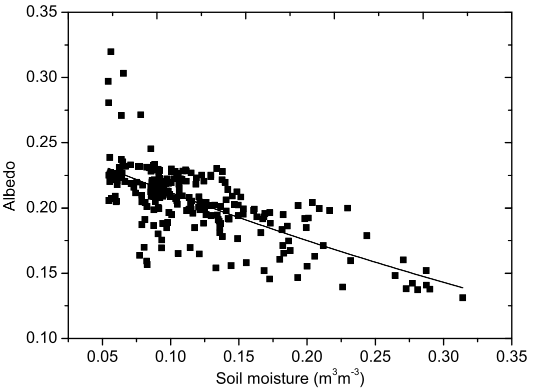

Fig. 5. The relationship between daily surface albedo and daily surface soil moisture (V/V, units: m^3 m^{-3}) at 5 cm depth. The solid line is the fitted relation obtained from Eq. (2).

the crops showing the weakest relationship with an r^2 of 0.4353. Although the Loess Plateau is a semi-arid region, it consists of plains, ridges, and mounds, etc. The parent soil material is mainly quaternary Aeolian loess with the main soil types being sierozem. There is also some loess soil in the terraces with short grass. The growing period at the Loess Plateau is from May to October, and is much longer than the growing period in a semi-desert region (June–August), but shorter than the period associated with a crop region. Precipitation is another important factor to be considered; annual average precipitation is different in these three regions. All these factors contribute to producing different relationships of soil moisture with surface albedo for these three different land surfaces.

5. Soil thermal parameters

Soil thermal capacity $C_{\rm s}$, soil thermal conductivity $\lambda_{\rm s}$, and soil thermal diffusivity $K_{\rm s}$ can be calculated as follows (Zhang and Huang, 2004):

$$C_{\rm s}=\frac{G_1-G_2}{\delta z\left(\dfrac{\partial T_{\rm g}}{\partial t}\right)}\,, \tag{3}$$

$$\lambda_{\rm s}=\frac{G_1+G_2}{2\left(\dfrac{\partial T_{\rm g}}{\partial z}\right)}\,, \tag{4}$$

$$K_{\rm s}=\frac{\lambda_{\rm s}}{C_{\rm s}}\,, \tag{5}$$

where G_1 and G_2 are the soil heat fluxes at 5 and 10 cm below the land surface, respectively, is the soil thickness between the two levels at which the heat fluxes are measured, $\partial T_{\rm g}/\partial t$ is the time rate of change of the soil temperature at 7.5 cm, and $\partial T_{\rm g}/\partial z$ is the soil vertical temperature gradient.

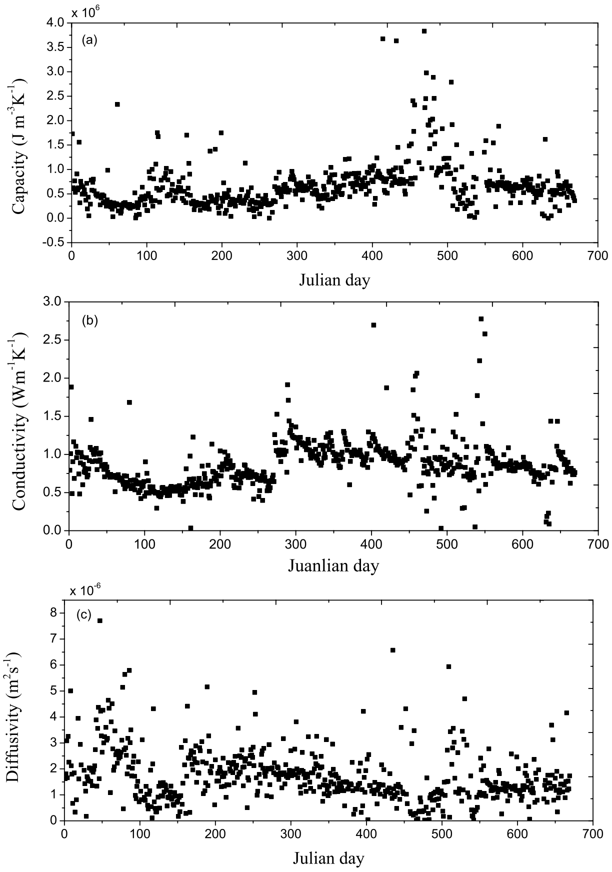

Fig. 6. Time series of daily average (a) soil thermal capacity, (b) conductivity, and (c) diffusivity from September 2006 to June 2008.

The time series of daily average soil thermal capacity, conductivity, and diffusivity from September 2006 to June 2008 are shown in Fig. 6. One can see that the three parameters show large variations between Julian day 90–212 and 450–578. Variations of soil heat capacity and soil thermal diffusivity are small in the monsoon season (Julian day 212–430 and 600–669). Because there is a distinct difference between the thermal properties of ice and water, it is necessary to separate the soil data into frozen and unfrozen data sets. As we find from Fig. 7, which shows the time series of daily temperature and daily soil moisture from September 2006 to June 2008, the soil temperature during days 88–155 and 453–537 is above 0°C, whereas for the rest of the time it was below 0°C. Here, the frozen data detection method proposed by Liu et al. (2008) is adopted. Under dry conditions, the lowest soil moisture is 0.076 when the soil temperature is above zero. Therefore, when the soil temperature at 5 cm is below 0°C, and at the same time the soil moisture at 5 cm is below 0.076, then the soil is considered frozen.

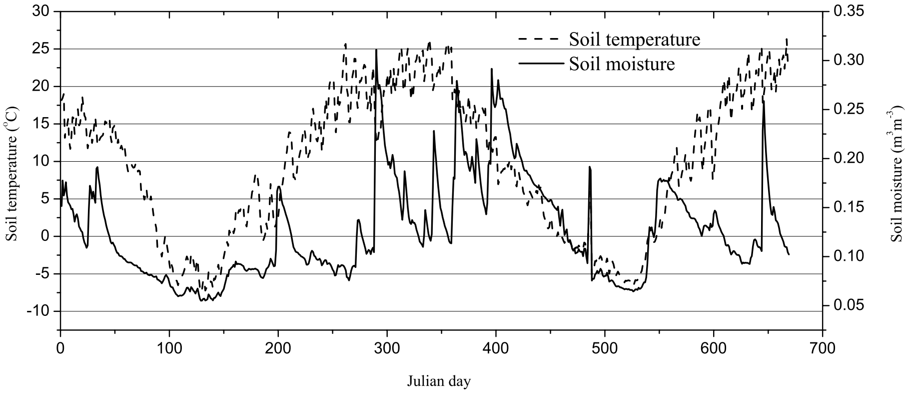

Fig. 7. Time series of daily average soil temperature and soil moisture at 5 cm.

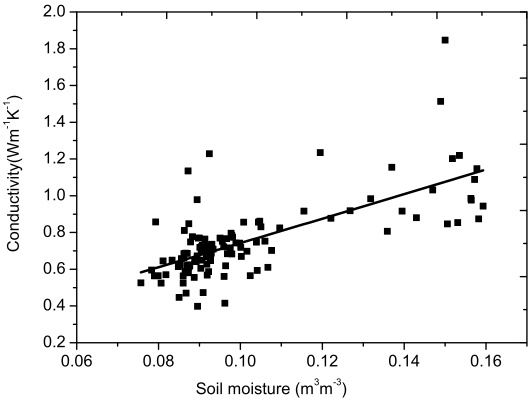

Fig. 8. Relationship between soil moisture and soil thermal conductivity. The solid line shows the fitted relation obtained from Eq. (6).

Figure 8 shows the relationship between the soil moisture at 5 cm and the soil thermal conductivity for soil in unfrozen conditions. The soil thermal conductivity increases with soil moisture. The data are fitted with the following power relationship,

$$\lambda_{\mathrm{s}} = 5.77\eta_{\mathrm{s}}^{0.8954}\,, \tag{6}$$

where λ_{s} is the daily average thermal conductivity and η_{s} is the daily average soil moisture at 5 cm. The r^2 of the regression is 0.4879 and the fit standard deviation is 0.0233.

Figures 9 and 10 show the relationship of soil moisture with heat capacity and soil thermal diffusivity, respectively. The heat capacity changes are relatively small, whereas the thermal diffusivity increases with increasing soil moisture.

6. Comparison with satellite retrieved soil moisture

As the development of soil moisture continues, many algorithms have been proposed and have arrived at correspondingly different satellite soil moisture products. The most promising methods for remote sensing of soil moisture utilize the passive microwave spectrum. Within the microwave spectrum, lower frequencies are less affected by vegetation and can sense a deeper soil layer and are better suited to sensing soil moisture. The lowest frequency radiometer currently in orbit is the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) in-

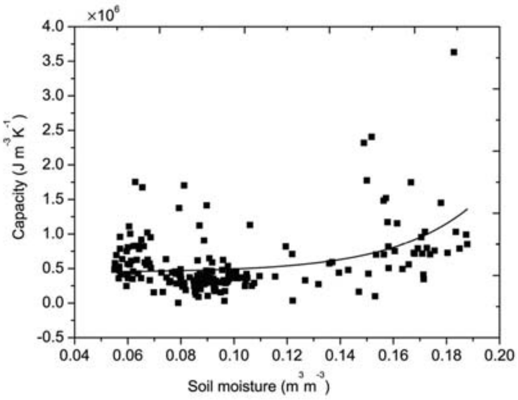

Fig. 9. Relationship between soil moisture and soil heat capacity in the dry season.

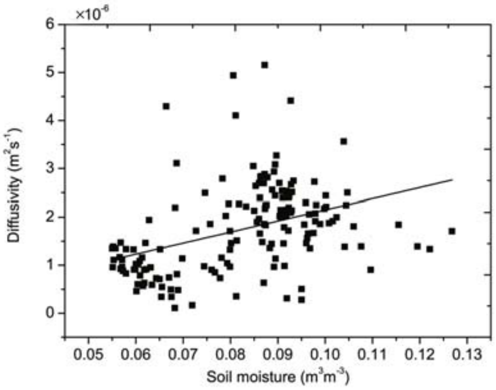

Fig. 10. Relationship between soil moisture and soil thermal diffusivity in the dry season.

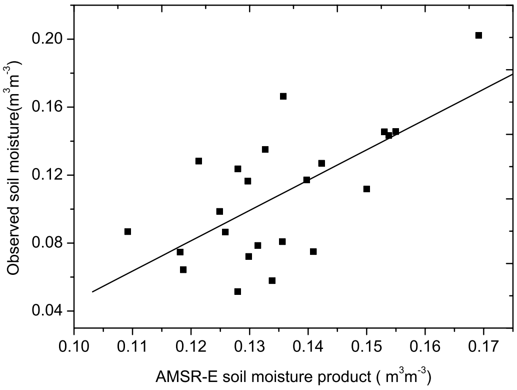

Fig. 11. The relationship of the AMSR-E soil moisture product with observations.

strument, flying on NASA's Aqua satellite, which has operated since 2002. AMSR-E has been the focus of efforts to remotely sense soil moisture. Time series of each of the AMSR-E derived soil moisture products have been compared to in situ observations of precipitation from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/index.jsp). Figure 11 compares the AMSR-E soil moisture at 1 cm with the observed data at SACOL. The soil moisture at 1 cm is calculated from soil moisture at 5 cm and 10 cm with a linear extrapolation method. This shows that the satellite product and observed data have good agreement, with a linear relationship. The data were fit with the following equation:

$$y = 1.7835x - 0.1327 , \tag{7}$$

where y is the observed soil moisture at 1 cm and x is the AMSR-E soil moisture product. The r-squared of the regression is 0.4319. This means that the AMSR-E soil moisture product can represent the variations of soil moisture in the surface to a certain extent. Figure 12 compares the variations of the AMSR-E soil moisture product and precipitation. It shows that the soil moisture was persistently low during the dry season when little precipitation was recorded. However, soil moisture increased rapidly with the increase of precipitation after June, and remained high in the rainy season, before decreasing again in late winter. The soil moisture increased during the two years of monitoring; this result is related directly to the increased precipitation during that period.

7. Conclusions and discussions

The semi-arid regions are most sensitive areas to global warming and are expected to reflect climate change rapidly. They are the transitional zones between arid and semi-humid areas and have fragile ecological systems. The Loess Plateau is a typical semi-arid region, it has unique surface characteristics. The energy and water cycles over the Loess Plateau play an important role in the Asian monsoon system, which in turn is a major component of both the energy and water cycles of the global climate system. Surface albedo, soil moisture, and soil thermal parameters are key surface parameters controlling the energy and water cycles. Accurate parameterizations of these processes will help to improve the accuracy of atmospheric models (Dickinson, 1995). Therefore, soil moisture studies of the Loess Plateau are very important to climate change research. However, there are not any surface observed long-term soil moisture data over Loess Plateau.

In this study, continuous measurements (from July 2006 to June 2008) at SACOL, a semi-arid site on the Loess Plateau, were used to study the seasonal variations of surface albedo, soil thermal parameters, and their relationships with the soil moisture content. This data set is also used to validate satellite retrieval products.

The results show that surface albedo decreases when soil moisture content increases, showing a typical exponential relationship. Soil thermal conductivity increases as the soil moisture content increases in the dry season (pre- and post-rainy season). The thermal diffusivity increases as a power function of the soil moisture in the dry season. Soil thermal capacity is rather stable over a wide range of soil moisture conditions. The AMSR-E soil moisture product and observed data have a linear relationship and the r^2 of the regression between them is 0.4319. The soil moisture increased during the two years of monitoring. AMSR-E soil moisture increased rapidly with increasing precipitation after June, and remained high in the rainy season, before decreasing again in late winter.

Because of the importance of soil moisture and the merits of remote sensing, research on remote sensing of soil moisture has been very active. this is especially the case for microwave remote sensing, which is only influenced slightly by clouds and the atmosphere, and has advantages in the study of global changes to soil moisture. Zhao et al. (2006) used a soil water index (SWI) based on satellite remote sensing and observational soil moisture from agricultural meteorological stations in eastern China. The results show that the retrieved soil moisture is convincing and close to the observations. Rajat et al. (2003) describes the development of a soil moisture pathfinder data set using TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) observations. The TMI-estimated soil moisture during the field experiments compared well with the satellite observations.

Our result shows that the observed soil moisture

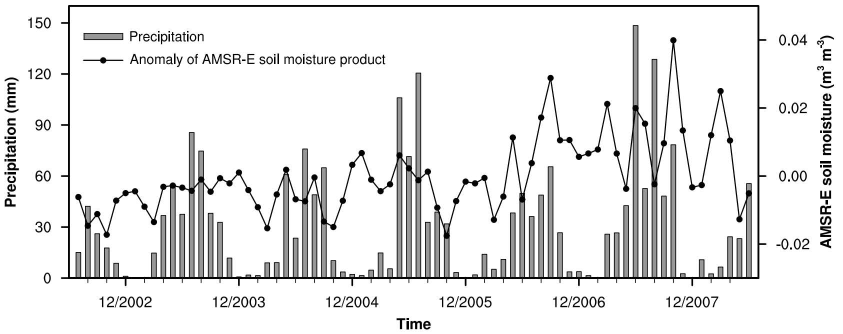

Fig. 12. The variations of the AMSR-E soil moisture product and precipitation from July 2002 to June 2008.

has a good relationship with the AMSR-E soil moisture product, whose retrieval occurs via the Njoku algorithm (Njoku et al., 2003). It is, however, not consistent with the results over other semi-arid regions. Draper et al. (2007) compares the three kind of satellite soil moisture to observed soil moisture data and found that the VUA-NASA (Vrije Universiteit Amsterdam) data, which have soil moisture derived from the AMSR-E C-band, have high correlation with the MSMMN (Murrumbidgee Soil Moisture Monitoring Network) data. But the soil moisture from NASA is persistently very low, and has a low correlation with the MSMMN data. Magagi and Kerr (1997) have tested the use of the ERS-1 wind scatterometer (WSC) to retrieval soil moisture over semi-arid areas (in the Sahelian zone) where there is a close relationship between rainfall, soil moisture, surface roughness, and vegetation cover.

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REFERENCES

Chen, S. Q., S. H. Lu, Y. H. Ao, Y. Zhang, S. S. Li, and L. Y. Shang, 2007: Characteristics of temperature and moisture of Jinta Oasis in summer under different soil moisture and weather conditions. *Journal of Desert Research*, **27**(4), 621–626. (in Chinese)

Delworth, T., and S. Manabe, 1988: The influence of potential evaporation on the variabilities of simulated soil wetness and climate. *J. Climate*, **1**(5), 523–547.

Delworth, T., and S. Manabe, 1993: Climate variability and land-surface processes. *Advances in Water Resources*, **16**, 3–20.

Dickinson, R. E., 1995: Land-atmosphere interaction. *Rev. Geophys.*, **33**(Suppl.), 917–922.

Draper, C. S., J. R. Walker, P. J. Steinle, R. A. M. De Jeu, and T. R. H. Holmes, 2007: Remotely sensed soil moisture over Australia from AMSR-E. *MODSIM 2007 International Congress on Modelling and Simulation*, Lincoln University, Christchurch, New Zealand.

Fu, C. B., and Z. S. An, 2002: Study of aridification in Northern China—A global change issue forcing directly the demand of nation. *Earth Science Frontiers*, **9**, 271–275. (in Chinese)

Gao, Z. Q., D. H. Lenschow, R. Horton, M. Y. Zhou, L. L. Wang, and J. Wen, 2008: Comparison of two soil temperature algorithms for a bare ground site on the Loess Plateau in China. *J. Geophys. Res.*, **113**, D18105.

Hoffer, R. M., and C. J. Johannsen, 1969: Ecological potential in spectral signatures analysis. *Remote Sensing in Ecology*, University of Georgia, Athens (GA), 1–16.

Hu, L. J., and M. A. Shao, 2002: Review on water eco-environment in vegetation restoration in Loess Plateau. *Chinese Journal of Applied Ecology*, **13**(8), 1045–1048. (in Chinese)

Hu, Y. Q., and Y. X. Gao, 1994: Some new understandings of processes at the land surface in arid area from the HEIFE. *Acta Meteorologica Sinica*, **52**(3), 285–296. (in Chinese)

Huang, J. P., and Coauthors, 2008: An overview of the semi-arid climate and environment research observatory over the Loess Plateau. *Adv. Atmos. Sci.*, **25**(6), 906–921, doi: 10.1007/s00376-008-0906-7.

Li, C. Y., 1995: Process of atmospheric radiation. *Introduction to Climate Dynamics*. S. J. Zhou, Ed., Meteorological Press, Beijing, 66–103.

Li, Y., and Z. Y. Hu, 2009: A study on parameterization of surface albedo over grassland surface in the northern Tibetan Plateau. *Adv. Atmos. Sci.*, **26**(1), 161–168, doi: 10.1007/s00376-009-0161-6.

Liu, H. Z., B. M. Wang, and C. B. Fu, 2008: Relationships between surface albedo, soil thermal parameters and soil moisture in the semi-arid area of Tongyu, northeastern China. *Adv. Atmos. Sci.*, **25**(5), 757–764, doi: 10.1007/s00376-008-0757-2.

Liu, W. D., F. Baret, X. F. Gu, Q. X. Tong, L. F. Zheng, and B. Zhang, 2002: Relating to surface moisture to reflectance. *Remote Sens. Environ.*, **81**, 238–246.

Liu, W. D., F. Baret, X. F. Gu, B. Zhang, Q. X. Tong, L. F. Zheng, 2003: Evaluation of method for soil surface moisture estimation from reflectance data. *Int. J. Remote Sens.*, **24**(10), 2069–2083.

Lobell, D. B., and G. P. Asner, 2002: Moisture Effects on Soil Reflectance. *Soil Science Society America Journal*, **66**, 722–727.

Lü, D. R., Z. H. Chen, J. Y. Chen, G. C. Wang, J. J. Ji, H. B. Chen, and Z. L. Liu, 2005: Study on soil-vegetation-atmosphere interaction in inner Mongolia semi-arid grassland. *Acta Meteorologica Sinica*, **63**(5), 571–593. (in Chinese)

Ma, Y. M., T. D. Yao, and J. M. Wang, 2006: Experimental study of energy and water cycle in Tibetan Plateau—The progress introduction on the study of GAME/Tibet and CAMP/Tibet. *Plateau Meteorology*, **25**, 344–351. (in Chinese)

Magagi, R. D., and Y. H. Kerr, 1997: Retrieval of soil moisture and vegetation characteristics by use of ERS-1 wind scatterometer over arid and semi-arid areas. *J. Hydrol.*, **188–189**, 361–384.

Njoku, E. G., T. J. Jackson, V. Lakshimi, T. K. Chan, and S. V. Nghiem，2003：Soil moisture retrieval from AMSR-E. *IEEE Trans. Geosci. Remote Sens.*, **41**(2), 215–229.

Rajat, B., T. J. Jackson, E. Wood, H. L. Gao, P. Starks, D. Bosch, and V. Lakshmi, 2003: Soil moisture estimates from TRMM Microwave Imager observations over the Southern United States. *Remote Sens. Environ.*, **85**, 507–515.

Wang, J. M., and Y. Mitsuta, 1991: Turbulence structure and transfer characteristics in the surface layer of the HEIFE Gobi area. *J. Meteor. Soc. Japan*, **69**, 587–593.

Wang, K. C., P. C. Wang, J. M. Liu, M. Sparrow, S. Haginoya, and X. J. Zhou, 2005: Variation of surface albedo and soil thermal parameters with soil moisture content at a semi-desert site on the western Tibetan plateau. *Bound.-Layer Meteor.*, **116**, 117–129.

Wei, M. Y., 1995: Soil moisture. Report of a workshop held in Tiburon, California, NASA Conference Publication 3319, 80pp.

Zhang, L. M., and Z. P. Shangguan, 2002: Relationship between the soil moisture and the vegetation productivity in the Loess Plateau. *Arid Zone Research*, **19**(4), 59–63.

Zhang, Q., and R. H. Huang, 2004: Parameters of land-surface processes for Gobi in north-west China. *Bound.-Layer Meteor.*, **110**, 471–478.

Zhang, Q., G. A. Wei, and R. H. Huang, 2001: Observation and study of atmospheric drag coefficients in Dunhuang. *Science in China (D)*, **31**, 783–792.

Zhao, D. M., B. K. Su, and M. Zhao, 2006: Soil moisture retrieval from satellite images and its application to heavy rainfall simulation in eastern China. *Adv. Atmos. Sci.*, **23**(2), 299–316, doi: 10.1007/s00376-006-0299-4.