Observation and Experimental Study of the Imbalance of Water Budget over the Loess Plateau of China*

ZHANG Qiang[1,2,3†](张 强), WANG Sheng[1,3](王 胜), WEN Xiaomei[4](问晓梅), and LI Hongyu[1,3](李宏宇)

1 *Key Laboratory of Arid Climatic Change and Disaster Reduction of Gansu Province/Key Open Laboratory of Arid Climatic Change and Disaster Reduction of CMA/Institute of Arid Meteorology, CMA, Lanzhou* 730020

2 *Gansu Provincial Meteorological Service, Lanzhou* 730020

3 *Lanzhou University, Lanzhou* 730000

4 *Baoshan Meteorological Service, Shanghai* 201901

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ABSTRACT

The imbalance of land-surface water budget was discovered in past studies, but there have been few further investigations on the relevant causes. To probe into the problem, annual variations of precipitation and land-surface evapotranspiration were analyzed by using the historical observation data from a comprehensive land-surface observation base of LOPEX (Loess Plateau Experiment). A remarkable imbalance in the land-surface water budget was found, and the total annual imbalance reached 20.6%. Then, the impact factors related to additional water budget components and observational methods were studied. The total annual imbalance could be reduced to 4.3% by using a combination of compensated land-surface water budget components and the surface evapotranspiration values obtained from the large weighing lysimeter rather than from the eddy correlation method.

Key words: Loess Plateau, water budget imbalance over land surface, water resources, evapotranspiration

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1. Introduction

On the global scale, the water fluxes on the earth's surface can be balanced through two processes: precipitation (P) and evaporation (Eltahir and Bras, 1996; Trenberth et al., 2007). However, the characteristics of land-surface water surplus or deficit in each region are very different. On the ocean surface, the surface evaporation is greater than P, and the difference is supplied mainly through runoff from rivers to the ocean (Oki et al., 1995). On the other hand, the surface evaporation on the land surface is less than P, and the difference is used to produce river runoff (Brubaker et al., 1993; Yeh and Famiglietti, 2008). Similarly, most of the mountains and pediment plains also adjust the land-water surplus and deficit through direct runoff. In theory, land-water surplus and deficit should always be in balance. However, in reality, there are frequent imbalances. For example, droughts and floods due to water budget imbalances often occur over the land. Because land-surface water has an annual cycle with seasonal variations, imbalances of land-surface water on the short-term seasonal timescale are relatively common, and land-surface water on the 1-yr or longer timescale should be balanced. However, in recent years, evaporation has increased because of climate warming, and many regions now have water deficits year after year, leading to an increase in drought tendency (Shi et al., 2003).

In addition to land-surface water imbalances caused by climatic factors, a few significant imbalances that are not well explained by climate changes have been found (Rasmusson, 1971; Roads et al., 1994; Roads and Chen, 2000). Land-surface water imbalance is particularly prominent in arid and semi-arid regions. It has been shown that a land-surface water

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†Corresponding author: zhangqiang@cma.gov.cn.

imbalance of up to 100 mm occurs in a northwestern arid area, with annual average rainfall of only about 100 mm (Chen, 2002). In previous studies, it has been concluded that land-surface water imbalances could not be explained due to instrument errors and observation methods, but this argument has become more and more unconvincing as the observational instruments and methods have been largely improved.

In fact, the cause of land-surface water imbalance may be more complicated than one can expect (Ma and Fu, 2007). On the one hand, consideration of the land-surface water budget components has not been comprehensive. For example, in many cases, the contributions of non-P factors to P, such as dew, fog, and soil adsorption water, were not considered. On the other hand, unreasonable replacements for evapotranspiration (ET) have been made because of the lack of proper understanding of this quantity estimated by different methods. Of course, biases in instruments and observations were also important reasons.

So far, the observation, experimental study, and scientific analysis of land-surface water budget imbalances are very limited, and we are also short of objective understanding of the causes of the imbalances. There have been some conflicting or consistent conclusions in previous studies, which have resulted in inaccuracy of global or regional estimates of land-surface water balance (Ninari and Berliner, 2002) and energy balance and the in-depth analysis of land-surface processes (Sun, 2005). The characteristics of the land-surface water budget imbalance problem over the Loess Plateau of China have been introduced by Zhang and Wang (2008) and Zhang et al. (2009). The present study uses synthesized land-surface observation data at a comprehensive observation base site of the LOPEX (Loess Plateau Experiment) in Dingxi, Gansu Province, Northwest China, to analyze the causes and influences of land-surface water budget imbalances. The objective of this study is to further improve the methodology utilized in the analysis of the land-surface water budget.

2. Data and method

This study employs the LOPEX specialized observation data from June 2004 to May 2005 at Dingxi, Central Gansu, together with local conventional weather station observations in the same period as well as short-term manual observations of non-P land-surface water factors such as dew in 2009. The Dingxi site is one of the three fixed observation test sites for the LOPEX (Zhang and Wang, 2008). It is located at 35°35′N, 104°37′E with an elevation of 1896.7 m, and is no more than 300 m away from the Dingxi weather station. The area is a typical multi-gully loess plateau with annual average precipitation of 386.0 mm and evaporation capacity of up to 1400 mm, and it has a semi-arid climate. The observation site is a rain-fed farming area for spring wheat, and it is very open and flat.

In this observation base, long-term observations using large-scale lysimeter, ultrasonic eddy system, and micrometeorological tower were carried out. The sonic anemometer was a CSAT3 from Campbell Scientific Inc. and was set up at a height of 2.5 m, where one can observe turbulent heat flux and water-vapor flux within the surface layer. The accuracy of the instrument has been documented in Yang et al. (2004a). The surface ET could be observed with an L-G-type weighing lysimeter (Ke et al., 1994; Yang et al., 2004b) with accuracy of 0.1 mm and sensitivity of 0.01 mm, and the amended accuracy could be improved to 0.03 mm or better. In addition, short-term manual observations of non-P land surface water contributors, such as dew, and spectrum characteristics of surface objects were carried out from September to October 2009.

During the observation of non-P land-surface water contributors, a plastic drum with a diameter of 9 cm was used to collect an undisturbed soil sample and was placed on the surface of bare soil. The soil was weighed once every 2 hours with an electronic weighing scale to give the change in the non-P land-surface water contributor. To reduce the measurement error, a total of three samples were deployed and combined, and the average value was used.

The L-G weighing lysimeter can automatically detect the instantaneous change in the weight of land-surface material (f_i) in the plate in real time. If the weight reduction of land surface material in the observation plate was less than 0 ($f_i < 0$), it indicated that the land surface in the observation plate had lost some material, and f_i was the instantaneous ET of the land surface. The ET of the land surface in a certain period ($E_{\rm s}$) can be obtained by accumulating the values of instantaneous ET, which can be expressed as follows:

$$E_{\rm s} = \sum \Delta f_i \quad \text{when} \quad \Delta f_i < 0, \tag{1}$$

where $\sum$ is the symbol for summation over time, i is the time, and f is the instantaneous change of material weight in the observation plate in mm.

If the increased weight of land-surface material in the observation plate was more than 0, i.e., $f_i > 0$, this indicated that the land surface in the observation plate had obtained some material, such as precipitation, dry deposition of dust, atmospheric carbon dioxide absorption by crops, and sources of non-P water factors. In these data, the impacts of P and dry deposition of dust could be excluded by subtracting the observed P and dust deposition. Previous studies (Wang et al., 2008) showed that during the growing period of rain-fed wheat on the Loess Plateau, the increased dry weight per plant per day was about 0.007 to 0.01 g. There were about 400 wheat plants grown in the observation plate of the lysimeter, and the total dry weight increase per wheat plant per day was increased by about 4 g in the large-scale lysimeter. This increased value equaled only 0.001 mm of P for the large-scale lysimeter, which had an observation plate area of more than 4 $\rm m^2$, indicating that the increased amount of dry matter caused by absorbing carbon dioxide could be ignored. Excluding the effects of the above factors on the measurement, if f_i was positive, then f_i contained only non-P land-surface water from the atmosphere, such as dew, soil-absorbed water, and fog.

Therefore, after exclusion of P and dust deposition, the observations with the L-G weighing lysimeter could be used to calculate the non-P land-surface water from the atmosphere, such as fog ($W_{\rm f}$), dew (or frost) ($W_{\rm d}$), and soil-absorbed water ($W_{\rm a}$) in mm. Because fog can occur only under surface-layer atmospheric saturation, the situation can be expressed as follows:

$$W_{\rm f} = \sum \Delta f_i, \quad \text{when} \quad f > 0 \text{ and } q = 100\%, \tag{2}$$

where q (%) is relative humidity in the atmospheric surface layer. Dew (or frost) can occur only when the surface temperature is lower than dew point (or frost point) and the surface-layer atmosphere is nonsaturated, which can be expressed as follows:

$$W_{\rm d} = \sum \Delta f_i, \text{when} \quad f > 0, q < 100\%, \text{and } T_{\rm s} < T_{\rm d}, \tag{3}$$

where $T_{\rm s}$ is the surface temperature and $T_{\rm d}$ is the dew (or frost) point temperature. $W_{\rm a}$ can occur only when the surface temperature is higher than dew (or frost) point and the surface-layer atmosphere is nonsaturated, which can be expressed as follows:

$$W_{\rm a} = \sum \Delta f_i, \text{when} \quad f > 0, q < 100\%, \text{and } T_{\rm s} > T_{\rm d}. \tag{4}$$

As a result, the total amount of non-P land surface water $W_{\rm tnop}$ can be expressed as:

$$W_{\rm tnop} = W_{\rm d} + W_{\rm a} + W_{\rm f}. \tag{5}$$

Surface-layer water-vapor flux $E_{\rm t}$ calculated by the eddy-correlation method could approximately represent water vapor flux of land surface, which can be expressed as:

$$E_{\rm t} = \rho \overline{w'q'}, \tag{6}$$

where ρ (kg $\rm m^{-3}$) is air density, and q' (g $\rm kg^{-1}$) and w' (m $\rm s^{-1}$) are specific humidity of the surface layer and vertical velocity fluctuation, respectively, which are directly observable using the ultrasonic vortex instrument. Up to this point, every quantity to be analyzed could be directly observed at the Dingxi test base and the Dingxi weather station or calculated from the observations. The observation of non-P land-surface water by the lysimeter and the observation obtained with the vortex instrument and the lysimeter were excluded for days with the occurrence of P and windy days, thus avoiding the adverse effects of P and wind on the eddy correlation method.

3. Imbalance of the land-surface water budget

In previous analysis of the land-surface water budget, contributions of ET, P, and surface runoff or irrigation were mainly considered. For the semi-arid Loess Plateau in the middle part of Gansu, the rain-fed field was not affected by surface runoff or irrigation factors, so the contribution of surface runoff and irrigation to the land-surface water budget could be ignored. Land-surface ET was a key term in the land-surface water budget, so in the present study, P and land-surface ET were used as main land-surface water-budget terms. The eddy correlation method is currently considered as an advanced method for observing the land-surface ET (Zhang et al., 1992; Li and Li, 2000), and it has been widely used in scientific research and special observation networks.

To analyze the imbalance characteristics of the land-surface water budget over the Loess Plateau, Fig. 1 shows variations of P and land-surface ET and the annual change tendency of their difference. It can be seen that the annual variations of P and land-surface ET were quite consistent but the two had some discrepancies in magnitude. P was sometimes greater than ET in summer, and always less than ET during other seasons. The difference between P and ET varies from –38 to +40 mm month^{-1}, which is very significant. These results indicate that considerable surplus of land-surface water always exists on the Loess Plateau and the imbalance feature of the land-surface water budget is significant.

Because of the intermittency and small probability of P, it is normal for imbalance of the land-surface water budget to occur in the short term; however, balance should be observed on the annual timescale. Figure 2 shows the annual variations of gradual accumulation of P and land-surface ET obtained through accumulating or integrating the observed diurnal values. This figure shows that land-surface ET was always greater than the accumulated P during the process of annual accumulation, and the difference between them was most significant in spring. The results also show that the accumulated annual values of land-surface ET and P were 526.4 and 435.9 mm, respectively, with a discrepancy of 90.5 mm (20.6%). Therefore, on the annual timescale, the land-surface water imbalance was quite significant, and this is not bearable for the water-budget calculation. This raises an important scientific issue: where does the annual surplus between ET and P come from? The errors associated with current instrument accuracy and the observation methods should not be great enough to account for the difference.

4. Causes of land-surface water budget imbalance

In theory, the imbalance of the land-surface water budget may be associated with incomplete consideration of budget components. In arid and semi-arid areas, non-precipitation water sources, such as dew drops, are important components that play a major role in supplementing land-surface water (Kosmas et al., 1998; Ma and Fu, 2007) and may be one of the main causes of imbalance between P and evaporation.

Figure 3 shows the annual change of non-precipitation water (NPW) observed by the lysimeter and the daily change of NPW manually observed during a short period. In Fig. 3a, the total amount of NPW is significant, with annual accumulation up

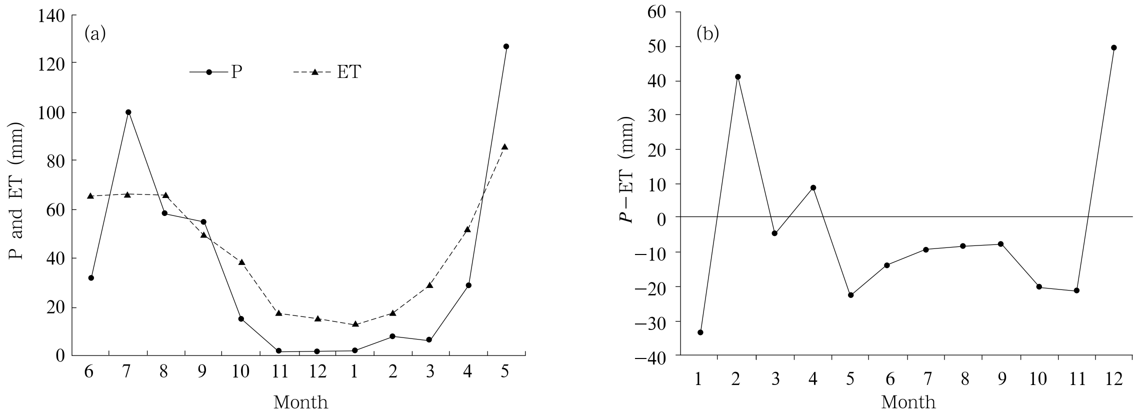

Fig. 1. (a) Annual variations of P and land-surface ET and (b) the difference between P and ET.

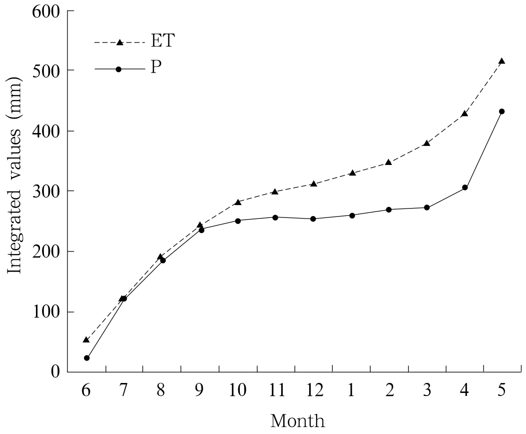

Fig. 2. Annual variations of the integrated values of P and ET.

to 57 mm. Its seasonal variation is obvious, with the amount being the smallest in summer and larger in other seasons. The largest values occur in late autumn up to 12 mm $month^{-1}$. Therefore, NPW can effectively complement the deficit of P relative to ET and serve for the excess consumption. The total annual accumulation of NPW accounts for 63.1% of the annual water deficit (90.5 mm), so the imbalance of land-surface water budget is decreased from 20.6% to 7.6%. It is concluded that NPW is important for the land-surface water balance and is a component of the water budget that must be considered.

To verify the reliability of land-surface water quantity observed by the lysimeter, manual short-term observation of NPW was carried out at Dingxi, the same site, from September to October 2009. Figure 3b shows that the manually observed daily average NPW was about 0.23 mm, similar to that observed at the southern edge of Maowusu Sandy Land (Zhang Xiaoyin et al., 2008). If the daily average NPW was taken as 0.23 mm for all days of October, the monthly accumulation was 6.9 mm, very close to the value of NPW in October in Fig. 3a. This suggests that the annual distribution of NPW shown in Fig. 3a is reasonable.

In addition to the contribution of NPW to the land-surface water surplus or deficit, there may also be contributions from different methods used in the measurements of ET. In Figs. 1 and 2, ET was observed by the eddy correlation method and was actually estimated through the water-vapor flux at a height of 2.5 m within the surface layer. In theory, under conditions of a flat underlying surface and horizontal homogeneity, it is assumed that the water-vapor flux at any height near the surface equals the surface ET. However, in reality, the ideal conditions are not fully met, and differences must exist between the surface ET and the near-surface water-vapor flux.

In principle, the ET observed by the lysimeter was the actual land-surface ET. To illustrate the difference between the surface-layer water-vapor flux by the eddy correlation method and the surface ET by the lysimeter, their annual variations and the difference between them are shown in Fig. 4. It can

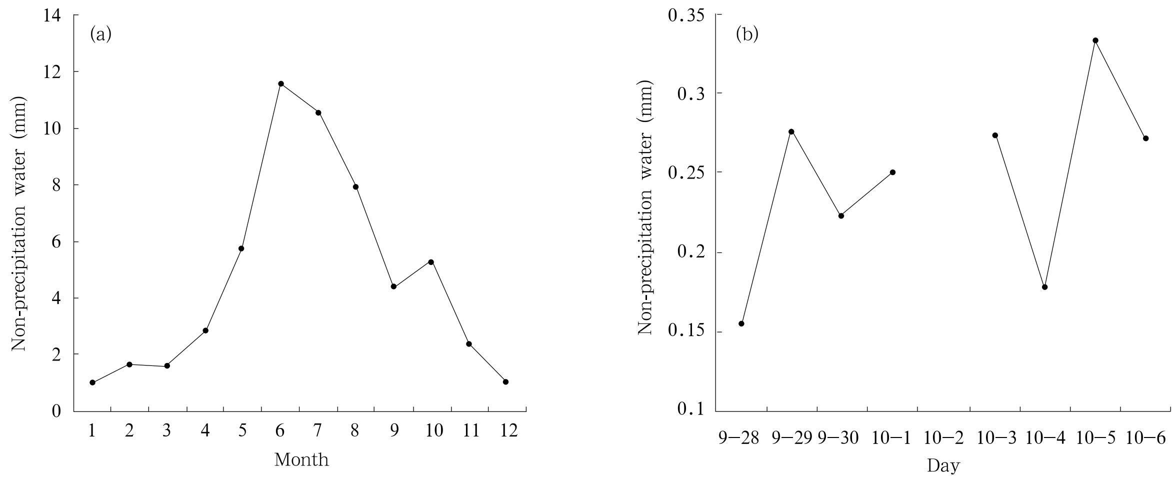

Fig. 3. (a) Annual variation of non-precipitation water observed by the lysimeter and (b) daily variation of non-precipitation water observed by the manual instrument at Dingxi in Central Gansu Province, China.

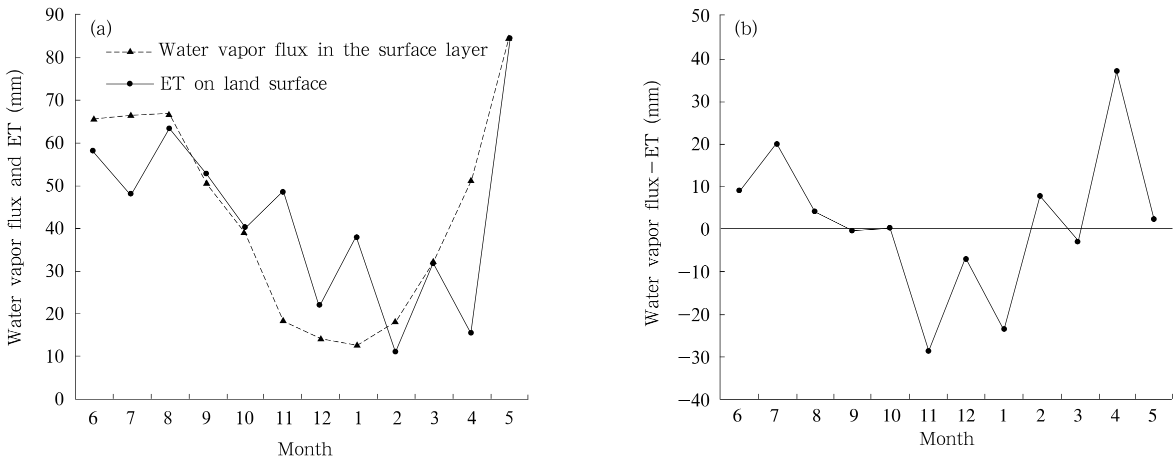

Fig. 4. (a) Annual variations of land-surface ET observed by the L-G lysimeter and the eddy correlation method, and (b) the difference between them.

be seen that the annual variations of surface-layer water-vapor flux and surface ET were roughly consistent and showed an obvious seasonal cycle. They were larger in summer, with a maximum in May, and smaller in winter, with a minimum from January to February. In comparison, the surface-layer water-vapor flux was greater than the surface ET in summer, with a maximum difference of 36.8 mm month^{-1}, and it was smaller than the surface ET in winter, with a maximum difference of −28.7 mm month^{-1}. These differences mean that some advection effects on water-vapor flux may exist during the vertical transport of water vapor from the surface to a certain height level in the near-surface boundary layer (Trenberth, 1999; Zhang et al., 2002). The horizontal advection can complement vertical advection of water vapor in summer, while the opposite effect may occur in winter. These differences may be related to different vegetation distributions in winter and summer. The annual integrated values of surface-layer water-vapor flux and surface ET were 526.4 and 512.1 mm, respectively, with a difference of 14.3 mm. The surface-layer water-vapor flux observed by the eddy correlation method overestimated the surface ET by an amount equivalent to 15.8% of the annual ET surplus. The imbalance of the land-surface water budget can be further reduced by 3.3% using the ET observed by the lysimeter instead of the eddy correlation measurements. This result shows that accurate observation of land-surface ET is very important in quantifying a water surplus or deficit and determining factors causing an imbalance.

The total land-surface water is now defined as the sum of P and non-P terms, and the annual variations of the total land-surface water and surface ET and the differences between them are shown in Fig. 5. Although the annual variations were similar to those shown in Fig. 1, the characteristics did not change with the total water greater than ET for most time of the summer and less than ET at other seasons. However, the overall difference between the two was significantly reduced, and the decrease of the annual average difference was particularly evident.

The variations of total land-surface water and surface ET accumulation values (Fig. 6) show that the land-surface ET was no longer greater than land-surface water accumulation during the whole year. It was greater only in summer and autumn; it was less in winter and spring. Thus, over the annual cycle, the land surface of the Loess Plateau in Central Gansu gained water in summer and autumn and lost water in winter and spring. Further analysis shows that the annual accumulation of total land-surface water and surface ET were 492.9 and 512.1 mm, respectively, with a difference of 19.2 mm. Thus, the remaining imbalance was only 3.8%, which can be tolerated.

If one wants to consider the imbalance of 3.8% to be significant, we believe that 4.3% in the excess evaporation in the region is likely to mean that the

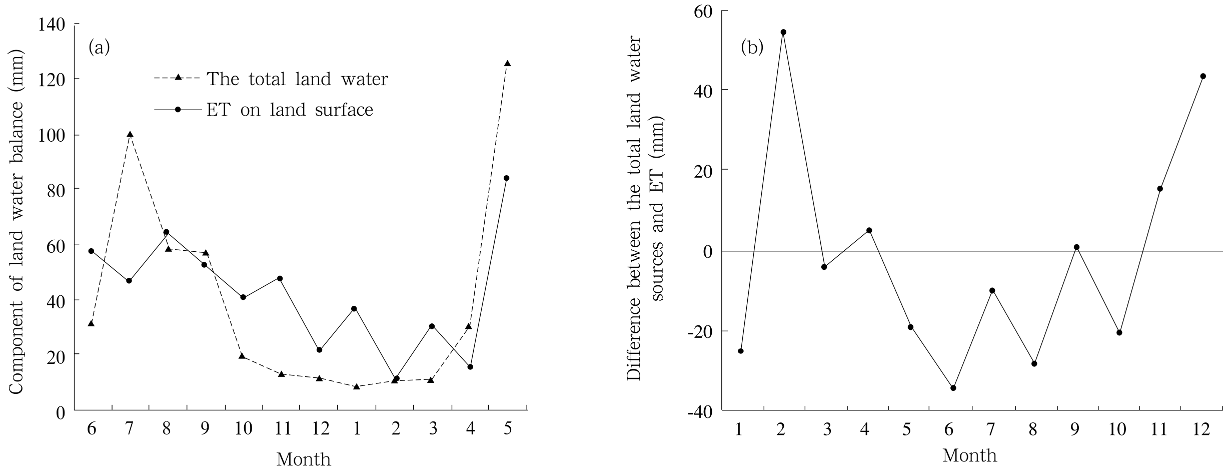

Fig. 5. (a) Annual variations of the total land-surface water and land-surface ET and (b) the difference between the two.

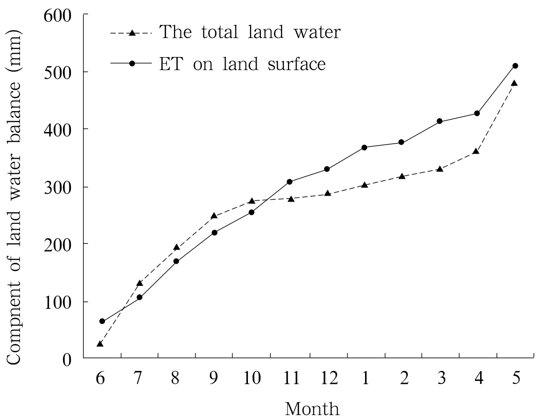

Fig. 6. Annual variations of integrated values of total land water and land-surface ET in the semi-arid region of the Loess Plateau.

land surface is losing water year after year and the soil water content is gradually reduced as a result of increased evaporation caused by climate warming. That the climate warming and excess evaporation occurred mainly in winter defines the problem to some extent. In fact, Zhang Qiang et al. (2008) found that total moisture storage over the Loess Plateau has decreased by 8 to 90 mm in the last 20 years because of climate warming and increased evaporation. This reflects the main trend of overall warming and drying on the Loess Plateau. However, attribution of the 3.8% imbalance to climate warming may have some uncertainty.

The ratio of a factor to the land-surface imbalance is defined as the contribution rate of the factor to the land-surface water-budget imbalance. Figure 7 clearly shows the contribution rates of various factors. The contribution of NPW was the greatest, up to 63.1%, and that of the land-surface ET observation method was roughly the same as that of the global warming, being 15.8% and 21.1%, respectively. Of course, the contribution of the climate change mentioned here also contained some factors that were probably due to observation errors. Considering the land-surface water budget imbalance on the annual scale, errors in the estimation of non-P land water and surface ET arose because of incomplete physical understanding and the biased technical approach. The water imbalance caused by these factors can be eliminated by improvement of physical knowledge and technical methods. However,

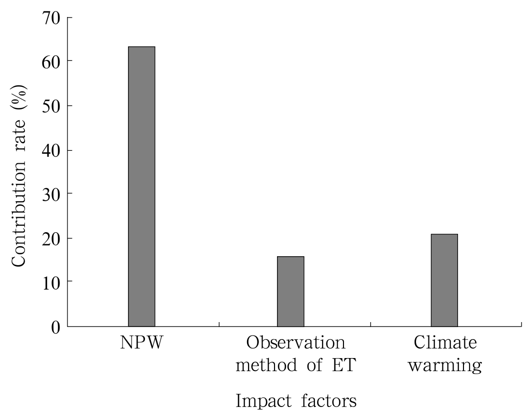

Fig. 7. Contribution rates of different factors to land-water imbalance.

the water imbalance caused by climate warming, as reflected in the annual variations of the regional climate, is hard to be removed.

5. Conclusions and discussion

The problem of land-surface water-budget imbalance is an important scientific issue in land-surface processes and climate change research. On the Loess Plateau, the difference between P and ET is in the range of –38 to +40 mm mon^{-1}; annual land surface accumulated ET is 90.5 mm larger than P and accounts for 20.6% of P. The imbalance of land-surface water budget is prominent.

Non-P land-surface water sources, such as dew drops, are an important component of the total land water balance in this area, with an annual accumulation of up to 57 mm, making it one of the main causes of the imbalance between evaporation and P. If the contribution of NPW sources is considered, the degree of land-surface water imbalance is decreased from 20.6% to 7.6%.

Significant difference exists between surface ET and surface-layer water-vapor flux. If the surface ET observed by the lysimeter rather than by the eddy correlation method is used, the water budget imbalance can be reduced to 3.8%, and the remaining imbalance can be accounted for by increased evaporation caused by global warming.

If the impact of observational errors is taken into account, the contribution rates of NPW, land surface ET observation methods, and climate warming to the land-surface water-budget imbalance are 63.1%, 15.8%, and 21.1%, respectively. Thus, the contribution of non-P water is the most significant, and the effect of the land-surface ET observation method is roughly equal to that of the climate warming. The imbalance caused by NPW and land-surface ET observation method can be eliminated while the imbalance caused by climate warming reflects exactly the trend of drought.

Because of the lack of long-term and continuous observations of NPW, this article presents the characteristics of water budget imbalance in only one year and can only be used as a reference for understanding the laws of water imbalance in this region. The contribution of climate warming to land-surface water-budget imbalance is mostly surmised from circumstantial evidence and theory from other research, and there is a lack of direct observation proving. More systematic observation tests should be performed to verify this hypothesis.

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