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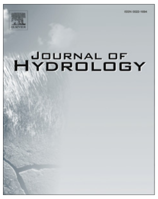

Trends in precipitation recycling over the Qinghai–Xizang Plateau in last decades

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SUMMARY

This study calculated the annual and inter-annual variations in the precipitation recycling ratio (PRR) on the Qinghai–Xizang Plateau (QXP); and by using water mass balance equation; we evaluated the estimated evaporation in the area. The results indicate that the estimated evaporation relate strongly to surface air temperature, relative humidity and wind speed. As temperatures on the QXP increase, the changes of PRR vary by regions within the plateau. Between 1979 and 2008, the PRR decreased in the western QXP, which is an arid area, but it increased in the other areas. The strongest increasing PRR trend is 3.1%/10 a in the northeastern QXP, but a decreasing trend, ranging downward to −2.5%/10 a, was observed in the western QXP. There is a significant seasonal change in precipitation recycling (PR) over QXP. The PR peak values occurred in July in all regions, and PR was very low (approaching 0.0) in winter half-year period. The monthly maximum PRR reached 0.62, which occurred in July over the southeastern QXP, where is a rich center of precipitation. These results imply that there is remarkable change of moisture resource of precipitation in last decades. On the QXP, large-scale moisture advances decrease with increased temperature, and the local moisture cycle is reinforced in wet regions.

1. Introduction

Precipitation recycling, a primary aspect of the hydrological cycle, plays an important role in balancing the water and energy cycles. In general, precipitation over a land region is derived from two sources: (1) water vapor evaporated within the region and (2) water vapor evaporated outside of the region and later transported into it (Brubaker et al., 1993). The first source indicates the importance of interactions between hydrology and regional climate (Brubaker et al., 1993; Eltahir and Bras, 1994, 1996). Many studies have defined the precipitation recycling ratio (PRR) as the ratio of precipitation contributed from water vapor evaporated within the region versus the total precipitation (Budyko, 1974; Brubaker et al., 1993; Eltahir and Bras, 1994, 1996). Using this definition, many models that calculate the PRR have been derived (Budyko, 1974; Brubaker et al., 1993; Eltahir and Bras, 1994; Dominguez et al., 2006).

There is a remarkable regional aspect of precipitation recycling, as well. Budyko (1974) used a simple one-dimensional model to estimate the PRR of the former Soviet Union. His result showed that annually, only about 10% of the precipitation originated from local evaporation in the same region (ranging from 4% in October to 18% in April). Shiklomanov (1989) enhanced Budyko's result by using aerological data, which indicated that the precipitation originating from local evaporation ranged from 0.1% in January and February to 20% in June. Brubaker et al. (1993) extended Budyko's model to a two-dimensional land region (Section 2 describes Brubaker's model in detail). Using a two-dimensional model, Brubaker estimated the PRR in the Eurasian region, the North American region, the South American region and the African region. The highest PRR (about 48%) occurred in the African region, and the lowest PRR (about 0.0%) occurred in the Eurasian region. It seems that the PRR is higher in arid regions. Eltahir and Bras (1994) used the European Center for Medium-range Weather Forecasting (ECMWF) data and a newly developed model to estimate the PRR in the Amazon basin, and they demonstrated that several previous studies had overestimated the PRR in this region. Furthermore, Eltahir and Bras (1996) compared the results obtained with their model and those of others' models and showed a good agreement with Brubaker's result in the Amazon region. Brubaker's method is easier to apply and more reasonable than Eltahir and Bras's model (Trenberth, 1998). Trenberth (1998) used Budyko's model to estimate the global PRR, showing that low values occurred over the southern oceans, the northern Pacific, and the eastern equatorial Pacific. High values (>20%) occurred in the subtropical highs and

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the convergence regions. Burde and Zangvil (2000a) reviewed the studies based on Budyko's model. Burde and Zangvil (2000b) presented a new precipitation recycling model with a consideration of the type of flow field. Considering variation in the storage of atmospheric water vapor, Dominguez et al. (2006) derived an even more complex model that is suitable for estimation on a daily time scale. The study by Dominguez determined that on average, the southeastern and southwestern parts of the United States exhibit high summer PRRs, contrasting with the low values exhibited by the northeast and northwest parts of the country. A notable report by Kang et al. (2004) estimated the PRR over middle and southern China. These researchers found that along the upper Yangtze River, the value is about 20%. Along the middle and lower Yangtze River, the PRR has values as high as 40%. The highest values (approximately 40%) occur in August, September and October, and the lowest values (<25%) occur in May, June and July. Later, these authors (Kang et al., 2005) calculated the PRR over northern China and reported that it is only 15% in the Yellow River Basin. In that study, the highest PRR value (approximately 31%) occurred in August, and the lowest value (<5%) was observed in November, December and January. These studies show that the PRR is an important component in precipitation in most part of China.

The aforementioned studies focus mainly on vast river basins (e.g., the Amazon, Yangtze, or Yellow river basins) or on large and low-altitude continents (e.g., North America, Africa, and Eurasia). The Qinghai–Xizang Plateau (QXP or the Tibetan Plateau) is a geographically unique region with an average elevation of more than 4000 m above sea level. The diabatic heating caused by the high elevation and complex surface processes plays a central role in the East Asian monsoon system (Wu and Zhang, 1998, 1999; Zhang et al., 2003; Wang and Cui, 2011). There are certain special surface characteristics in the QXP (e.g., frozen ground, snow cover and glaciers) that may have particular influence on regional climate change in other parts of East Asia. Wang and Shang (2007) suggested that soil moisture generated by spring thawing of frozen ground in the QXP is closely related to the wet season's start in the QXP. Shang and Wang (2006) further proposed that the soil moisture over the QXP relates to the onset of the southern Asian monsoon. In terms of global warming, studies have reported that the temperature of the QXP increases more quickly than in other regions at similar latitudes. Meanwhile, the temperature increasing is asymmetric, minimum temperature increased faster than maximum temperature. Wang and Guo (2012) reported that during global warming, the precipitation conversion rate has increased markedly in most of the QXP. With temperature increases, the water cycle over the plateau (even the entire East Asian region) will be affected by thawing of frozen ground, snow melting and glacier change. These changes will further influence diabatic heating processes between the surface of the QXP and the atmosphere above, and these changes will have an impact on the circulation and the monsoon in East Asia. Studies also suggest that the southern Asian monsoon has retreated in the last decade (Wang, 2001; Li and Zeng, 2005). This result implies that the moisture transport northward from the Indian Ocean will weaken. However, because the southern QXP is affected by the South Asian monsoon, the mechanism and magnitude of PRR changes in the southern QXP also needs to study. These studies imply that precipitation recycling over the QXP affected by multi-scale process which from surface characteristic to monsoon. The study of PRR over the QXP at different time scales remains largely limited.

PRR has received more attention in past years, and several models calculating the regional PRR have also been developed (Brubaker et al., 1993). Studies propose that one model developed by Brubaker in 1993 is more suitable than other models for estimating PRR on a monthly scale (Trenberth, 1999). In this paper, the precipitation recycling over different regions of the QXP were investigated. Specifically the annual and inter-annual variation of the recycling in last decades is determined in this paper. Section 2 presents the dataset used in this study. Section 3 describes the PR model. Section 4 explains calculation and analysis of the PRR and Section 5 presents the discussion and conclusions.

2. Data and methodology

The Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997) provided the monthly precipitation data with a resolution of 2.5° × 2.5° used in this paper. To calculate the atmosphere's moisture flux and its divergence, the 2.5° × 2.5° resolution monthly specific humidity and wind data from NCEP/NCAR reanalysis (Kalnay et al., 1996) were employed.

The evaporation data was estimated following the method proposed by Brubaker et al. (1993). By using a water mass balance equation and by neglecting changes in atmospheric moisture, the evaporation can be defined as the following:

$$E \approx P + \nabla \cdot \vec{Q} \tag{1}$$

where E, P and $\nabla \cdot \vec{Q}$ (Div$\mathbf{Q}$) are the monthly evaporation, precipitation, and moisture flux divergence, respectively. The monthly evaporation reanalysis data of 1957–2002 from the European Center for Medium-range Weather Forecasting (ECMWF) was used to determine the multiyear mean evaporation conditions over the QXP.

The recycling model was first derived by Budyko (1974), but it is a simple one-dimensional model. Brubaker et al. (1993) extended Budyko's model to a two-dimensional one, which is more suitable for describing the actual recycling conditions (Trenberth, 1998). Trenberth (1998) documented Brubaker's model to be more justifiable than that of Eltahir and Bras (1994). In the work presented here, Brubakers' scheme was used to calculate moisture recycling.

Fig. 1 describes the moisture recycling process. The area of the study region is A (in a one-dimensional model, the area is regressed into a length scale, L, as in Budyko (1974)). F_{in} represents the column integrated moisture transported into a land region, which is calculated by data of wind and specific humidity. Taking the north boundary of the region as an example, the F_{in} is the accumulation of southward moisture transportation in all the grid points. The F_{in} of one region is the sum of that of four boundaries in which region. And F_{out} represents the moisture transported out of a land region. E is the evaporation, and P is the total precipitation. In previous studies, precipitation was considered to be from two sources: (1) moisture transported into the region, or (2) moisture evaporated within the region (Budyko, 1974; Brubaker et al., 1993). Therefore, P_m is defined as the fraction of precipitation from evaporation, and P_a represents the fraction from moisture flux. The average precipita-

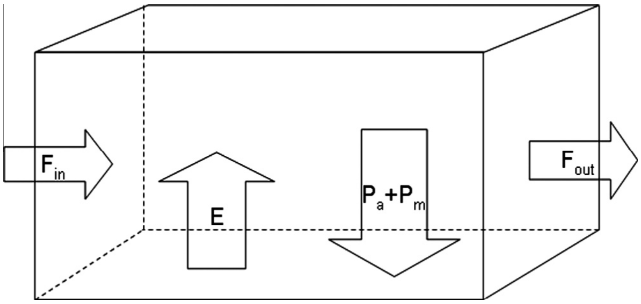

Fig. 1. Schematic diagram for the precipitation recycling processes. F_{in} represents the moisture transported into a land region, and F_{out} represents the moisture transported out of a land region. E is the evaporation, and P (=$P_a + P_m$) is the total precipitation. P_m is defined as the fraction of precipitation from evaporation, and P_a represents the fraction from moisture flux.