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Evaluation of evapotranspiration estimates for two river basins on the Tibetan Plateau by a water balance method

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SUMMARY

Evapotranspiration (*E*) at regional or basin scale is difficult to estimate. This study estimates *E* with a water balance method for the upper Yellow River and Yangtze River basins on the Tibetan Plateau, where in situ data accessibility is especially insufficient. Results indicate that annual terrestrial water storage change in the two basins is negligible, and basin-scale *E* can be reliably estimated by the difference between precipitation and runoff. Thus, four *E* products from Zhang—(Zhang_E), MODIS (MODIS_E), Japanese 25-year reanalysis product (JRA_E), and the newly published Global Land Data Assimilation System with Noah Land Surface Model-2 (GLDAS_E)—are evaluated against *E* estimated by the water balance method. GLDAS_E and Zhang_E had the best performance for the upper Yellow River basin and Yangtze River basin, respectively, with relatively small underestimation. Further analysis showed that the underestimation of GLDAS_E was mainly caused by its negative bias for precipitation, whereas the overestimation of JRA_E was due to overestimation of downward shortwave radiation. MODIS_E greatly overestimated *E* in both basins, which was also caused by high downward shortwave radiation flux inputs from the Global Modeling and Assimilation Office. Thus, more accurate forcing data for these products should be a future focus, since they can improve *E* estimates, at least for the Tibetan Plateau.

1. Introduction

Evapotranspiration (*E*) is one of the major components of the hydrologic cycle. *E* determines partitioning of available energy on the land surface into latent and sensible heat flux, and thus has a major effect on regional and global climate (Bonan et al., 1992; Bonan, 2008). *E* also determines groundwater recharge and surface runoff, which are essential to available water resources (Komatsu et al., 2008). In addition, *E* is the key process linking the hydrologic cycle with other biogeochemical processes, such as the carbon and nutrient cycles (Running and Coughlan, 1988; Xue et al., 2011). Recent research indicates that the hydrologic cycle has intensified and accelerated with recent climate change (Huntington, 2006), which would alter global land surface processes through *E*. However, many studies show that the opposite may have occurred on the regional scale (e.g., Gao et al., 2007, 2012).

The Tibetan Plateau (TP) is the highest plateau in the world, with average elevation of 4000 m. It is essential to Asian monsoon development and concurrent water and energy cycles. As the major Asian water tower, the hydrologic cycle in this area has been observed to have changed in recent years because of climate change, which has influenced runoff of rivers originating from the region (Immerzeel et al., 2010). Therefore, accurate estimation of *E* is considered essential for understanding hydrologic processes on the TP. However, estimation of *E* there is especially difficult, because the area is difficult to access and measurements are limited.

Various methods have been introduced by hydrologists and meteorologists for quantification of *E* (e.g., Xu and Chen, 2005). Estimation of *E* is still challenging, however, especially at the regional or basin scale (e.g., Vinukollu et al., 2011). There are two usual ways to quantify *E*, namely through micrometeorological measurements or using remote sensing data. The first may be constrained by sparse measurement points and difficulties of upscaling to regional scale. The second calculates *E* using surface energy balance, with meteorological inputs (such as temperature) and vegetation indices (such as Normalized Difference Vegetation Index, NDVI) from ground or remote sensing observation (Li et al., 2009). Although the remote sensing method is practical for a large scale,

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it involves a number of uncertainties, including those from the input data and energy balance method itself (Vinukollu et al., 2011). Alternatively, the traditional water balance method can be used to estimate E for a closed basin (e.g., Hornberger et al., 1998; Rodell et al., 2004a), such that

$$E = P - R - \Delta S, \tag{1}$$

where P is total precipitation (mm), R is runoff (mm), and ΔS is change in terrestrial water storage (mm; including surface, subsurface and ground water changes) over a certain period. Normally P and R are obtained from observation, and ΔS is usually assumed negligible over a long period (usually annual scale). Although the water balance method cannot reproduce the spatial pattern of E, it has been widely used for estimation of E at basin or regional scale (e.g., Hobbins et al., 2001).

In recent years, several studies have estimated regional and global E via ground-observed meteorological variables and process-based models, and this has improved understanding of the global water cycle (Cleugh et al., 2007; Mu et al., 2007; Jung et al., 2009; Zhang et al., 2010; Vinukollu et al., 2011). Several E products from reanalysis or land surface models have been generated (Rodell et al., 2004b; Onogi et al., 2007; Dee and Uppala, 2009). Although some studies have evaluated various E products (e.g. Mueller et al., 2011), detailed comparison and evaluation of such products for the TP is rare. These products have great potential to facilitate estimation of hydrologic components on the plateau, where data availability is an issue. However, the estimated E must be carefully evaluated before it is considered useful. The aim of this study is to assess four existing E products for two TP basins, namely the upper Yellow River and Yangtze River basins, against those estimated from the traditional water balance method. The results may help improve E products for the plateau and thereby contribute to better understanding of the hydrologic cycle.

The paper is organized as follows. In Section 2, we describe the study areas and data collection. In Section 3, we show E calculated by the water balance method and validate the results for selected research areas. We also evaluate four E products from various sources. In the last section, we provide several recommendations for improvement of the E products.

2. Materials and methods

2.1. Study region

Two representative river basins were selected to estimate E over the TP, namely, the source regions of the Yellow and Yangtze Rivers on the northern Qinghai–Tibet Plateau (Fig. 1). Two hydrological stations, Tangnaihai and Zhimenda, were chosen as outlets for the upper Yellow River and Yangtze River basins, which have total areas of 121,972 and 137,704 km^2, respectively. Elevation in the region declines from west to east, and is between 3450 and 6621 m a.s.l. The main soil types are alpine cold desert, alpine meadow, alpine steppe, mountain meadow, gray cinnamonic, chestnut, swamp and aeolian (Bing et al., 2012). Vegetation is classified as highland meadow. Climate of the two basins is classified as semi-arid and sub-humid plateau continental, with distinct wet and dry seasons. The study region is strongly influenced by the summer Indian monsoon and East Asian monsoon during summer (Yao et al., 2012). Precipitation generally falls between May and October, during which around 70% of the annual total falls.

For simplicity, E was calculated at 0.5° latitude and longitude, which constitutes 52 and 54 grids for the upper Yellow River and Yangtze River basins, respectively. The spatially averaged E for all grids of each basin is assumed to be the basin-scale E.

2.2. Data sets

Precipitation data are from gridded ($0.5^\circ \times 0.5^\circ$) daily data over East Asia (5–60°N, 65–155°E; Xie et al., 2007), which are available from 1 January 1978 to 31 December 2006. The dataset was obtained from ftp://ftp.cpc.ncep.noaa.gov/precip/xie/EAG. To verify dataset accuracy, we compared the precipitation from Xie et al. (2007) with values from China Meteorological Administration (CMA) stations within the two basins. Fig. 2a shows that there are six meteorological stations in the upper Yellow River basin, and four in the upper Yangtze River basin. Grid-average P values were comparable to those observed at most CMA stations, with average relative error 6.1% (Fig. 2b). Therefore, P from Xie et al. (2007) was used for reference in the water balance method of the following analysis. Monthly runoff data were used in E calculation, and were from observation at the Tangnaihai and Zhimenda stations for the upper Yellow and Yangtze Rivers, respectively (Fig. 1). These runoff data cover the periods 1962–2006 and 1962–2000 for the upper Yellow River and the Yangtze River basins, respectively, and basin-scale estimates of E from the water balance method are determined for these periods. ΔS is from derived measurements of the Gravity Recovery and Climate Experiment (GRACE). GRACE satellites were launched on 17 March 2002 to measure the earth's gravity field, which was mainly due to terrestrial water mass variations over large regions (Tapley et al., 2004). These variations from GRACE measurements may be attributable to surface, subsurface and/or ground water changes, and are therefore essentially identical to ΔS in Eq. (1) (Rodell et al., 2004b). Previous studies have demonstrated the usefulness of GRACE-derived ΔS for closure of the terrestrial water budget (e.g., Rodell and Famiglietti, 2002).

Using the estimated E from the water balance method as a reference, four E datasets were evaluated for the two basins. These are E from the research group of Zhang et al. (2010) (hereafter Zhang_E, http://www.ntsg.umt.edu/project/et), E from MODIS (Mu et al., 2007; hereafter MODIS_E, http://www.ntsg.umt.edu/project/mod16), E from the Japanese 25-year reanalysis product (Onogi et al., 2007; hereafter JRA_E, http://jra.kishou.go.jp), and E from the Global Land Data Assimilation System with Noah Land Surface Model-2, which was newly published in September 2012 (Rodell et al., 2004a; hereafter GLDAS_E, http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings). Detailed description of the four E datasets is shown in Table 1. Since both precipitation and all E datasets have different spatial resolutions, we interpolated all data to a standard 0.5° grid.

3. Results and discussions

3.1. Estimation of E by water balance method

Fig. 3 shows annual variation of estimated E (P–R) and corresponding E products for the two basins. The estimated annual E from the water balance method had large variation over recent years. Averages were 359.7 and 306.6 mm/year, or 69% and 77% of total precipitation in the upper Yellow and Yangtze basins, respectively (Table 2). P–R for the upper Yellow basin had a significant increasing trend (Mann–Kendall (M–K) test, $p < 0.05$), accompanied by a decreasing trend (M–K test, $p < 0.05$) for runoff and insignificant trend for precipitation (M–K test, $p > 0.05$). This is consistent with the findings of Yang et al. (2011). In contrast, no significant trend was observed for E, R and P in the upper Yangtze basin (M–K test, $p > 0.05$).

When calculating E by the water balance method, we assumed negligible water storage across the two basins ($\Delta S \approx 0$). This is reasonable in most cases for long periods (e.g., Hobbins et al., 2001). However, this assumption could be questionable for the TP,