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A worldwide evaluation of basin-scale evapotranspiration estimates against the water balance method

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SUMMARY

Evapotranspiration (ET) plays a critical role in linking the water and energy cycles but is difficult to estimate at regional and basin scales. In this study, we present a worldwide evaluation of nine ET products (three diagnostic products, three land surface model (LSM) simulations and three reanalysis-based products) against reference ET (ET_{wb}) calculated using the water balance method corrected for the water storage change at an annual time scale over the period 1983–2006 for 35 global river basins. The results indicated that there was no significant intra-category discrepancy in the annual ET estimates for the 35 basins calculated using the different products in 35 basins, but some products performed better than others, such as the Global Land surface Evaporation estimated using the Amsterdam Methodology (GLEAM_E) in the diagnostic products, ET obtained from the Global Land Data Assimilation System version 1 (GLDAS 1) with the Community Land Model scheme (GCLM_E) in LSM simulations, and ET from the National Aeronautics and Space Administration (NASA) Modern Era Retrospective-analysis for Research and Applications reanalysis dataset (MERRA_E) in the reanalysis-based products. Almost all ET products (except MERRA_E) reasonably estimated the annual means (especially in the dry basins) but systematically underestimated the inter-annual variability (except for MERRA_E, GCLM_E and ET simulation from the GLDAS 1 with the MOSAIC scheme – GMOS_E) and could not adequately estimate the trends (e.g. GCLM_E and MERRA_E) of ET_{wb} (especially in the energy-limited wet basins). The uncertainties in nine ET products may be primarily attributed to the discrepancies in the forcing datasets and model structural limitations. The enhancements of global forcing data (meteorological data, solar radiation, soil moisture stress and water storage changes) and model physics (reasonable consideration of the water and energy balance and vegetation processes such as canopy interception loss) will undoubtedly improve the estimation of global ET in the future.

1. Introduction

Land evapotranspiration (ET) is an essential component in global water, energy, and carbon cycles, and provides a link between the atmosphere and the Earth's surface (Betts et al., 1996; Jiménez et al., 2011; Tang et al., 2014; Zhang et al., 2012, 2015). It is also an important indicator of hydrologic and heat variations under a changing climate and anthropogenic interference (Brutsaert and Parlange, 1998; Ohmura and Wild, 2002; Wang and Dickinson, 2012). Accurate quantification of ET is thus critical for understanding the hydro-climatologic processes and the interactions of the Earth system (Rodell and Famiglietti, 2002). However, the estimation of large-scale ET from ground-based measurements alone remains challenging due to the sparse network of point observations and the high spatial heterogeneity and temporal variability of ET (Xu and Singh, 2005; Xue et al., 2013). To address this limitation, a number of global ET products have been derived in recent years, including remote sensing-based products (Su, 2002; Mu

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et al., 2007, 2011; Zhang et al., 2009, 2010; Miralles et al., 2011b; Yang et al., 2013), reanalysis outputs (Simmons et al., 2006; Onogi et al., 2007), land surface model (LSM) simulations (Rodell et al., 2004a; Dirmeyer et al., 2006) and the estimates based on empirical upscaling of in situ observations (Jung et al., 2009).The available ET products have great potential for facilitating estimations of hydrological and energy components and their intrinsic hydro-climatic variability (Roderick and Farquhar, 2011). However, large-scale evaluation among different ET products, which is a prerequisite for their use in global and regional hydrological and energy budget studies, is constrained due to the lack of reference observations (Xu and Chen, 2005).

The global network FLUXNET enables scientists to assess terrestrial ET at different time scales across numerous sites of diverse vegetation types (Running, 1998; Wang and Dickinson, 2012; Tang et al., 2014). However, eddy-covariance (EC) ET measurements need to be treated with caution with respect to regional ET evaluations due to their relatively short period and sparse spatial coverage (particularly in the Southern Hemisphere and the tropics) as well as the lack of energy balance closure observed at some EC sites. An alternative approach is to compare ET products with the reference ET (ET_{wb}) calculated from the terrestrial water budget (observed precipitation P minus the sum of runoff Q and terrestrial water storage change ΔS at the basin scale) for closed basins (Swenson and Wahr, 2006; Sheffield et al., 2009). During the past two decades, a number of studies have focused on ET evaluation in the conterminous United States (Rodell et al., 2004a; Velpuri et al., 2013; Han et al., 2015), West Africa (Andam-Akorful et al., 2014), Tibetan Plateau (Xue et al., 2013; Li et al., 2014), and at the global scale (Ramillien et al., 2006; Rodell et al., 2011; Mueller et al., 2011; Zhang et al., 2010, 2012; Zeng et al., 2014) using the annual or monthly water balance. At the annual scale, for example, Zhang et al. (2010) evaluated the multiyear (1983–2006) averaged satellite-based global ET product (ZHANG_E) against the ET_{wb} derived from observed discharge and gauge-based precipitation (GPCC) and found ZHANG_E was generally in agreement with ET_{wb} in most global basins. Mueller et al. (2011) showed that the intra-category spreads were similar in seven global rivers when comparing the multiyear means (1989–1995) of existing ET products from observation-based datasets, reanalysis-based products, LSMs and Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) simulations. Moreover, Zhang et al. (2012) found the decadal trends (1983–2006) in ET_{wb} did not match those in evaporation estimated from three simple diagnostic models, especially in 110 global wet basins. In the previous studies, the water storage changes were often neglected in ET_{wb} calculations based on annual-scale water balance. However, the water balance may not always close at an annual scale when ΔS is assumed unchanged in many global river basins due to the effect of snow thaw-melt (Dai et al., 2009; Lettenmaier and Milly, 2009) and anthropogenic impacts such as water diversion, reservoir regulation, agricultural irrigation (Condon and Maxwell, 2014). Therefore, a more comprehensive global reevaluation using the ET_{wb} estimates (considering the inter-annual variability of ΔS) as benchmark values is still imperative (Wan et al., 2015).

With the launch of the Gravity Recovery and Climate Experiment (GRACE) satellites in March 2002, the terrestrial water mass variations (which contribute significantly to the observed water storage change) could be reasonably inferred over sufficiently large regions (Wahr et al., 2004; Landerer and Swenson, 2012). Moreover, the influences of natural processes (e.g. glaciers, snow and frozen soil moisture) and anthropogenic interferences such as reservoir operations and inter-basin water transfers could also be reflected in GRACE-retrieved total water storage anomalies (TWSA). However, the temporal coverage of GRACE data is relatively short (2002 onward) for the validation of historical ET products. Recently, several attempts have been made to extend the TWSA or basin-scale ET_{wb} (considering the water storage change) series to the period before 2002 using empirical or statistical methods (Zeng et al., 2014; Li et al., 2014; Long et al., 2014). Although some uncertainties still exist in these methods (Sun, 2013), the calculated $ET_{wb}$is expected to be more accurate by considering the inter-annual variability of ΔS for the evaluations of global ET products. The objectives of this study are to (1) evaluate nine ET products including three diagnostic products, three LSM simulations and three reanalysis-based products against the reference ET (ET_{wb}) calculated from the bias-corrected water balance method (considering the ΔS) at the annual scale for 35 global river basins, and (2) discuss the potential influences of the forcing data on the different ET products. The paper is organized as follows: data collection and the methodology used in this study are described in Section 2. In Section 3, the evaluation results of the nine ET products are presented for wet and dry basins located in different climate zones. The potential impacts of the forcing data on the ET products are also discussed in this section. In the final section, we summarize the results and provide several recommendations for the improvements of the ET products.

2. Data and methods

2.1. Global ET products

Nine published global ET products (three diagnostic products, three LSMs simulations and three reanalysis-based products) were evaluated against ET_{wb} in this study (Table 1). The diagnostic products include (1) ZHANG_E (1983–2006) derived from the Numerical Terradynamic Simulation Group (http://www.ntsg.umt.edu/project/et), which was calculated using the modified Penman–Monteith method driven by MODIS data, meteorological observations and satellite-based vegetation parameters (Zhang et al., 2010); (2) JUNG_E (1981–2011), which integrated the point-wise ET observations at FLUXNET sites with geospatial information retrieved from the remote sensing and surface meteorological observations in a machine-learning algorithm (Jung et al., 2010) (https://www.bgc-jena.mpg.de/geodb/projects/Home.phs); and (3) GLEAM_E (Global Land surface Evaporation: the Amsterdam Methodology), which estimated three sources of land evaporation separately through different land surface types, namely, (1) bare soil, (2) short vegetation, and (3) vegetation with a tall canopy, using a set of algorithms (e.g. the Priestley-Taylor approach was applied for the calculation of potential evaporation) (Miralles et al., 2011a, 2011b). Moreover, the ice and snow sublimation in the pixels covered with snow was also estimated based on a separate routine (Miralles et al., 2011a). Three LSM simulations: GNOAH_E (from 1948 until present) was obtained from the Global Land Data Assimilation System version 2 (GLDAS-2) with the Catchment Noah scheme, and GCLM_E and GMOS_E, obtained from GLDAS-1with the Community Land Model and the MOSAIC schemes, respectively (Rodell et al., 2004b) (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings). Additionally, the reanalysis-based products included (1) JRA55_E (1958 onward) from the recently released Japanese 55-year reanalysis (JRA55) product (Kobayashi et al., 2015) (http://jra.kishou.go.jp/JRA-55/index_en.html); (2) ERAI_E (1979 onward) from the ERA-Interim global atmospheric reanalysis dataset (Berrisford et al., 2011) (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/), and (3) MERRA_E (1979 to present, Lucchesi, 2012) from the National Aeronautics and Space Administration (NASA) Modern Era Retrospective-analysis for Research and Applications (MERRA) reanalysis dataset (http://disc.sci.gsfc.nasa.gov/mdisc/).