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Multi-model and multi-sensor estimation of evapotranspiration over the Volta Basin, West Africa

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Abstract

The estimation of large-scale evapotranspiration (ET) is complex, and typically relies on the outputs of land surface models (LSMs) or remote sensing observations. However, over some regions of Africa, inconsistencies exist between different estimations of ET fluxes, which should be investigated. In this study, we evaluate and combine different ET estimates from MODerate resolution Imaging Spectroradiometer (MODIS), Global Land Data Assimilation System (GLDAS), and terrestrial water budget (TWB) approach over the Volta Basin, West Africa. ET estimates from water balance equation are obtained as residuals from monthly terrestrial water-storage (TWS) changes derived from Gravity Recovery and Climate Experiment (GRACE), Tropical Rainfall Measurement Mission (TRMM)'s rainfall data, and in-situ discharge from Akosombo Dam (Ghana). An averaged estimate of ET time series is derived from all the ET estimations, under study, while taking into account their uncertainties. The resulting ensemble averaged ET was then used to

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assess each of the individual ET estimates. Overall, out of the 7 investigated ET estimates (2 from the water balance approach of which one considers water storage using GRACE-derived TWS and the other ignoring it, 4 from GLDAS and 1 from MODIS), only MODIS (28.12 mm/month), GLDAS-NOAH (32.74 mm/month) and TWB (32.84 mm/month) were found to represent the range of variability close to the computed averaged reference ET (30.25 mm/month). ET estimations inferred from MODIS were also found to represent relatively lower magnitude of uncertainties, i.e., 3.99 mm/month over the Volta Basin (cf. 7.06 and 18.85 mm/month for GLDAS-NOAH and TWB-based ET estimations, respectively).

Keywords: Evapotranspiration, GLDAS, GRACE, MODIS, terrestrial water-storage changes, TRMM, Volta Basin

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1. Introduction

Evapotranspiration (ET) represents the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere, which makes it an important hydrological component to relate the water, energy, and carbon cycles (Alton et al., 2009). ET is identified as the major factor that determines groundwater recharge and surface runoff; two critical components of available water storage (Komatsu et al., 2008). Observing the variability of ET is vital for many regions, such as the Lake Volta basin in West Africa, since its dynamic reflects the atmosphere-hydrosphere-biosphere interactions over the region (Fisher et al., 2011; Jung et al., 2010). In fact, ET accounts for approximately 90% of precipitation in the Volta River basin of West Africa (Andreini et al., 2000). In addition, estimation of ET over the Volta Basin is necessary owing to its vulnerable response under global warming (Oguntunde et al., 2006). Several studies, e.g., Lebel et al. (2000); Kasei et al. (2009); Oyebande & Odunuga (2010); Nicholson (2013) indicated that the whole West African sub-regions (including the Volta Basin) have experienced reduced rainfall amounts since the 1970s, which most likely coincided with the observed rising global temperature, leading to the last decade drought.

The intensification of agriculture in West Africa leads to a change in surface and subsurface characteristics, which directly affects ET rates (Kunstmann & Jung, 2007) that, in turn, could affect the regional rainfall patterns. For the Volta Basin, for example, the influence of climate variability and change has been shown by Jung & Kunstmann (2007) to account for a spatial mean increase of 5% ($\sim$ 45 mm) of mean annual change in rainfall. **Weaker change in the precipitation than in the rainfall, infiltration excess change exceeds the precipitation change, revealing a highly nonlinear relationship (e.g., Jung & Kunstmann, 2007). Under the influence of climate change,** Neumann et al. (2007) reported positive and negative trends in temperature and precipitation respectively within the basin. This phenomenon could lead to the occurrence of dry periods due to possibly increased ET rates and reduced precipitation. Being one of the most vulnerable agricultural factors to climate change, understanding ET patterns in the basin is therefore crucial to food security and the general socio-economic health of the region (see, e.g., Estes et al., 2013; Kousari & Ahani, 2012).

Despite being a critical hydrological variable, direct measurement of ET is difficult especially in large basins such as the Volta (Su, 2002). Routine monitoring of ET requires a dense distribution of hydro-meteorological stations with long-term data records (e.g., temperature, wind patterns, rain, solar radiation, humidity, precipitation, etc.). In the Volta Basin, such hydro-meteorological stations are sparsely distributed (Adjei et al., 2012; Opoku-Duah et al., 2008), necessitating the use of remotely sensed data and hydrological models as alternative means for estimating ET and other hydrological quantities. Previous methods employed to obtain ET estimates over the basin include the Surface Energy Balance Algorithm for Land (SEBAL) (see, e.g., Hendrickx et al., 2006; Hafeez et al., 2007; Opoku-Duah et al., 2008; Compaoré et al., 2008) and the Advection-Aridity relationship model (Oguntunde, 2004). SEBAL has an advantage that it can be applied without using ground measurements, and has demonstrated potential in mapping ET worldwide (Bastiaanssen et al., 1998). Other option, for example, could be the satellite-based energy balance based on Mapping Evapotranspiration with Internalized Calibration (METRIC) procedure for calculating ET (see, e.g., Allen et al., 2007; Santos et al., 2008; Pôças et al., 2013).

Opoku-Duah et al. (2008), for instance, found that MODerate resolution Imaging Spectroradiometer (MODIS) driven by SEBAL evapotranspiration estimates under-performed by up to 2 mm/day against point observations such as eddy correlation, and the Penman-Monteith method. Spatial scale mismatch was reported to be the main reason for the obtained inconsistency. Compaoré et al. (2008) used SEBAL to map evaporation in the White Volta sub-basin, at the begin and end of a dry season using Landsat and MODIS images, and established that SEBAL had potential for mapping ET over tropical areas. Schüttemeyer et al. (2007) used the modified Makkink formula by considering incoming solar radiation obtained from Meteorological Satellite (Meteosat) data and the green vegetation fraction using enhanced vegetation index from MODIS. They reported daily mean errors ranging from 5% to 35% of measured ET and a seasonal error smaller than 5% over the Volta Basin.

At a global scale, model data such as those of Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004b) and MODIS Global Evapotranspiration Project (MOD16) (Mu et al., 2013) are important sources that can also be applied at regional scale, e.g., over the Volta Basin to infer on ET. Their uncertainties and validity for the basin are, however, unknown. It is therefore vital to validate them using independent approaches, e.g., terrestrial water budget (TWB) approach (Rodell et al., 2004a, 2011; Xue et al., 2013; Zeng et al., 2014). Based on the principle of mass conservation, one can use independently derived components of the hydrological cycle to estimate ET. Until recently, application of the water balance approach was limited due to limited accessibility to direct measurements of terrestrial water-storage component, especially over large areas. With the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite mission in 2002 (Tapley et al., 2004), however, quantification of total water-storage (TWS) and its changes is now possible (Cazenave & Chen, 2010). The TWB approach, which considers GRACE-based TWS changes has been used as an alternative method for estimating ET as residuals (see, e.g., Rodell et al., 2004a; Ramillien et al., 2006; Boronina & Ramillien, 2008; Cesanelli & Guarracino, 2011; Moiwo et al., 2011; Sahoo et al., 2011; Rodell et al., 2011; Long et al., 2014; Zeng et al., 2014).

For instance, Rodell et al. (2004a) indicated that TWB-based ET estimates agreed well with those provided by the European Center for Medium range Weather Forecasting (ECMWF) and the Global Land Data Assimilation System (GLDAS) over Mississippi River Basin with root-mean-square-error (RMSE) of 19.50 and 24.90 mm/month, respectively. Ramillien et al. (2006) achieved similar results to those of Rodell et al. (2004a) over 16 selected river basins and showed that GRACE-derived ET estimates were comparable to those of global land surface models (LSM), namely: Land Dynamics Model (LaD), Organising Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE), GLDAS, and a conceptual WaterGap Hydrological Model (WGHM) model. Across West Africa, only a few GRACE applications have been carried out, with emphasis on the Niger Basin and the Sahel region (see, e.g., Grippa et al., 2011; Boy et al., 2012; Hinderer et al., 2012) and on basins in Sub-Saharan Africa (e.g., Xie et al., 2012). Grippa et al. (2011) showed that GRACE data can reproduce TWS inter-annual variability over the Sahel region. Xie et al. (2012) used seven years of GRACE data to calibrate a semi-distributed regional scale hydrological model, the soil and water assessment tool (SWAT). A statistical approach to predict GRACE-derived total water storage in relation to the major teleconnections and precipitation changes in West Africa is addressed in Forootan et al. (2014b). However, to the best of our knowledge, the estimation of TWB-based ET over the Volta Basin has not been carried out in the previous studies.

Recently, Zeng et al. (2014) implemented the TWB method to evaluate the estimated global monthly ET through coupling water balance model with a machine learning algorithm. They found that the water balance learning machine based ET agreed with a RMSE of 26.7 mm/month, while MOD16 ET products (Mu et al., 2013) presented a RMSE of 34.32 mm/month against ET estimated from water balance approach. Recently, Long et al. (2014) assessed the uncertainties in ET output of North American Land Data Assimilation System (NLDAS)'s models (Mitchell et al., 2004), two remote sensing-based products (MODIS and AVHRR) and GRACE-inferred ET using the "three-cornered hat" method, and found the relative uncertainties in ET to be moderate in MODIS– and AVHRR-based ET (10–15 mm/month), and highest in GRACE-inferred ET (20–30 mm/month) without *a priori* knowledge of the true value of ET.

As a contribution to the estimation of ET over the data scarce Volta Basin, this study aims at (i) evaluating ET estimates over the Volta Basin from four existing GLDAS-simulations of Variable Infiltration Capacity (VIC) (Liang et al., 1994), NOAH (Ek et al., 2003), MOSAIC (Koster & Suarez, 1996), Community Land Model (CLM) (Dai et al., 2003), those derived from MODIS (Mu et al., 2013), and the water balance approach, and (ii) once the time series of ET estimations and their uncertainties have been determined using the three-cornered hat method (Long et al., 2014, e.g.), they are used to generate an ensemble-averaged ET estimation over the Volta Basin, which is adopted as a reference in this study to access uncertainties of various approaches under investigation. To use the water budget equation, precipitation data from the Tropical Rainfall Measuring Mission (TRMM) and the observed discharge from the Akosombo Dam in Ghana have been included.

2. Study Area

2.1. Geography

The Volta Basin, located at the semi-arid West African savanna zone, has its water resources shared amongst six riparian countries namely; Ghana, Burkina Faso, Mali, Ivory Coast, Togo and Benin (Fig. 1), and drains a total area of about 417,382 km^2 (van Zwieten et al., 2011). The topography is mostly flat and elevations do not exceed 1000 m in most parts. The Volta River has three main tributaries – the Black Volta, White Volta and Red Volta, and drains into the Gulf of Guinea and Atlantic Ocean completing a journey of about 1,200 km (Shahin, 2002). Lake Volta is one of the most important physiographic features in Ghana with a submerged area of 8,500 km^2 (Oguntunde et al., 2006). It is the largest man-made lake in the world extending from the Akosombo Dam in southeastern Ghana to approximately 400 km to the north (Shahin, 2002). It is fed by numerous tributary rivers to the Volta River; thus, the volume of water in the reservoir and the area shrinks during dry seasons and swells during the rainy seasons (Tanaka et al., 2002).

[Figure 1 around here.]

Volta Basin has an estimated population of over 20 million people with a growth rate of 3% per year, which relies on its water resources (Kasei et al., 2009). Additionally, Opoku-Duah et al. (2008) reported that over 70 million people of West Africa depend on the Volta Basin for food, water resources, housing and transport. A large number of dams and reservoirs have been constructed within the basin for irrigation, domestic, power generation, fisheries, and industrial purposes (see, e.g., Leemhuis et al., 2009; van Zwieten et al., 2011), posing threats to sustainable water resource management. Efficient management of water resources within the basin, therefore, is of extreme importance for socio-economic development of the region. This calls for regular monitoring of its hydrological variables, and their consequent impacts on water resources to ensure a sustainable use.

2.2. Climate

The basin's climate is mainly governed by the southwestern monsoon and the northeastern trade winds (*harmattan*), which exhibits a north-south gradient. The climatic gradient results in differing climatic conditions in the southern and northern sections of the basin as evidenced by the unimodal and bimodal rainfall regimes in the north and south respectively (Sultan et al., 2005). Farmers in the basin have widely reported the delays in the onset of rainy seasons over the past several decades (van de Giesen et al., 2010). Jung & Kunstmann (2007), using a simulated scenario, reported a delay in the onset of rainy seasons, with an increase in inter-annual precipitation variability over the Volta Basin as a consequence of global climate change. In addition, it experiences extreme climatic conditions, and is highly vulnerable to droughts and floods (cf., van de Giesen et al., 2010; Taylor et al., 2006; Samimi et al., 2012).

Annual precipitation rates decrease from 1,200–1,500 mm/year in the coastal south to 300–500 mm/year in the Sahelian north. The semi-arid regions have variable rainfall patterns with extreme cases of droughts and sporadic floods and has an annual average rainfall between 1,150 mm in the north and 1,380 mm in the south. Owusu et al. (2008) reported that the El

Niño Southern Oscillation (ENSO) teleconnection patterns induce extreme precipitation events in the basin. Consequently, recent droughts and floods have largely been coincident with El Niño/La Niña events. Temperatures vary between approximately 16°C and 40°C depending on the season, time of day, and elevation (Oguntunde et al., 2006), with an average air temperature of approximately 27.8°C. Jung & Kunstmann (2007) reported a mean annual temperature increase of 1.2–1.3°C based on regional climate simulations. The mean relative humidity rises up to about 80% in September and falls to about 20% in January (Gyau-Boakye & Tumbulto, 2000). Forootan et al. (2014b) showed that using the statistical relationships between precipitation and water storage changes, forced by sea surface temperature patterns, one can fairly predict the main annual and inter-annual variability of water storage over West Africa.

3. Methods and Data

To perform an inter-comparison among ET estimates, several datasets have been used. In Section 3.1, a summary of the main products is presented while in Section 3.2, the methods of ET estimations are discussed.

3.1. Datasets

The time span of the all dataset applied in this study (i.e., GRACE, TRMM, GLDAS, MODIS, in-situ discharge and atmospheric water storage dataset from ERA-Interim) cover a period from January 2003 to December 2012 due to data overlap in that time span.

3.1.1. GRACE Level 2 Products

The Release–05 (RL05) Level 2 products (L2) as described in Bettadpur (2012a,b), i.e., potential spherical harmonic coefficients (i.e., Stokes's coefficients) used in this study were derived from three official processing centers: Center for Space Research (CSR), University of Texas; Jet Propulsion Laboratory (JPL); the GeoForschungsZentrum (GFZ), available at ftp://podaac-ftp.jpl.nasa.gov/allData/grace/L2/. Additionally, water storage changes derived from climatological data (cf. sections 3.1.6 and 3.2.2) were used to independently assess the quality of GRACE-derived water-storage changes over the Volta Basin. Data from these three centers were used due to their unique processing procedures that yield different terrestrial water-storage anomalies (e.g., Bruinsma et al., 2010; Klees et al., 2008). The time span of the dataset covered the period from January 2003 to December 2012, with the data for June, 2003, January and June of 2011, and May and October of 2012 missing. These missing GRACE derived terrestrial water-storage anomalies were estimated using the previous and the next month's (e.g., Ramillien et al., 2006). Cross-validation (not presented here) shows that this method presents a RMSE of 19.69 mm/month.

Because GRACE alone cannot directly provide degree one Stokes's coefficients ($C_{1,0}$, $C_{1,1}$ and $S_{1,1}$), which represent the changes in the geocenter due to mass redistribution in the Earth system, they were replaced by values from the results provided by Swenson et al. (2008) to improve estimates of mass variability. Including these coefficients would represent impacts on the amplitude of the annual and semi-annual GRACE-derived water storage estimations. The zonal degree two coefficients ($C_{2,0}$) were replaced by the values derived from Satellite Laser Ranging (SLR) (Cheng & Tapley, 2004; Cheng et al., 2013) because GRACE-derived $C_{2,0}$ coefficients present relatively high uncertainties. The secular decrease in $C_{2,0}$ resulted primarily due to glacial isostatic adjustment, and is modulated by ocean and ice mass redistribution (e.g., Cox & Chao, 2002). The processing scheme is provided in section 3.2.1.

3.1.2. Tropical Rainfall Measuring Mission (TRMM)

TRMM is a joint mission between the United States (NASA) and Japan (Japan Aerospace Exploration Agency) (Huffman et al., 2007). TRMM is designed to monitor tropical rainfall in the latitude range ±50°. In this work, we used monthly averaged 3B43 V7 rainfall rate products with a spatial resolution of 0.25° (e.g., Fleming & Awange, 2013), which are inferred from not only the TRMM observations, but also employs data from a number of other satellites and ground-based rain gauge data (Huffman et al., 2007). The data was obtained from NASA's Goddard Earth Sciences and Data and Information Service Center (GES DISC) available at `http://mirador.gsfc.nasa.gov/`. TRMM observations have been used in several studies of rainfall over Africa (e.g., Nicholson et al., 2003; Adeyewa & Nakamura, 2003) and specifically over the Volta Basin (e.g., Adjei et al., 2012; Thiemig et al., 2012, 2013). Adjei et al. (2012) reported that there is the tendency of TRMM to underestimate rainfall in the Black Volta sub-basin especially in the wet season. In addition, Thiemig et al. (2013) reported that TRMM captures the intra-seasonal variability, the spatial distribution pattern, the average annual precipitation, and the timing of the highest annual precipitation event well over Volta Basin. Thiemig et al. (2012) found that interpolated rainfall derived from ground observations agrees well with TRMM, exhibiting only a slight underestimation of 11%.

3.1.3. Global Land Data Assimilation (GLDAS)

GLDAS is a global hydrological model that generates a series of global land surface state (e.g., soil moisture, snow water equivalent, surface temperature) and flux (e.g., evapotranspiration and sensible heat flux), e.g., Rodell et al. (2004b). It incorporates both ground- and space-based observation systems to produce optimal estimates of land surface state of flux. Four products, namely: MOSAIC, NOAH, CLM and VIC simulate GLDAS's hydrological fields. Hence, the total ET field which is the sum of transpiration from vegetation and surface evaporation with a spatial resolution of 1° was used. The GLDAS data were retrieved from `http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings`.

3.1.4. MODIS Global Evapotranspiration Project (MOD16)

The MOD16 global ET data is provided by Earth Observing System of the National Aeronautics and Space Administration (NASA/EOS) as part of global ET project, and are available at `http://www.ntsg.umt.edu/project/mod16`. The estimates are derived from MODIS-based vapor pressure deficit, solar radiation and air temperature, as well as a network of eddy towers and global meteorological data (Cleugh et al., 2007; Mu et al., 2011). The MOD16 algorithm in Mu et al. (2011) is based on an improved version of Mu et al. (2007), which is also based on the Penman-Monteith equation, Monteith (1965). The MODIS data (i.e. MOD16) is available at 8-day, monthly, and annual intervals. Analysis for this study is based on monthly products with a spatial resolution of 0.5°.

3.1.5. In-situ discharge

In addition to the satellite- and model- derived datasets, monthly discharge rates from Akosombo Dam (cf. Fig. 1) were also used to estimate ET using the water balance approach (section 3.2.2). The data was obtained from the Water Research Institute of Ghana covering the the time span from February 2003 to December 2012 and the records are complete. Before the construction of the Akosombo Dam in 1964, the river flow was extremely irregular as one can see by inspecting Fig. 9.4 of (Shahin, 2002, p. 394) that shows the discharge observed at the Senchi hydrological station (downstream of Akosombo Dam). The filling of the Volta Lake took four years (1964-68) after the completion of the dam construction and since then, Volta Lake has helped to stabilize the out flow reaching the most downstream and key station at Senchi (Shahin, 2002, p. 394).

3.1.6. Precipitable water and vapor flux divergence

The specific humidity (q), the eastern (u), and the northern (v) direction winds from ERA-Interim (Dee et al., 2011), the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), were used to calculate the vapor flux divergence $\boldsymbol{\nabla} \cdot \mathbf{Q}$ and precipitable water W in Eqs. (2) and (5) of Yirdaw et al. (2008), respectively. They are used in this study with a spatial resolution of $1°$ in order to check the GRACE-derived water-storage changes (see sub-section 3.2.2). The data were retrieved from `http://apps.ecmwf.int/datasets/data/interim_full_daily/`.

3.2. Methods

3.2.1. Computation of GRACE-derived water-storage changes

Monthly GRACE derived gravity coefficients exhibit correlated errors and short-wavelength noises that manifest themselves as stripes in the spatial maps of terrestrial water-storage anomalies (Swenson & Wahr, 2006). We removed the stripes using a de-correlation filter known as the P4M6 filter scheme proposed by Chen et al. (2010), which is a variation of the method described in Swenson & Wahr (2006). An exhaustive comparison of the suitability of the filter methods available can be found, e.g., in Werth et al. (2009) and Duan et al. (2009). For spherical harmonic coefficients of orders 6 and above, a degree 4 polynomial was fitted by least squares and removed from even and odd coefficient pairs (Chen et al., 2010; Swenson & Wahr, 2006). The resulting de-stripped terrestrial water-storage anomalies, which still contained some inherent errors, were smoothed using a Gaussian filter with half-width radius of 300 km (half-width) (Wahr et al., 1998).

For each monthly solution, the long-term mean of 2003 to 2013 was removed from the monthly spherical harmonic coefficients. Estimates of monthly terrestrial water-storage anomalies were obtained from the residual coefficients using an integration approach described in Wahr et al. (1998). A regional average of the terrestrial water-storage was then computed by defining the mask following the method described in Swenson & Wahr (2002). In addition, we used GLDAS-NOAH estimated total water content (i.e., soil moisture, canopy water, snow and ice) to compute basin scale gain factor as described in Landerer & Swenson (2012); total water content values from NOAH simulated GLDAS were first converted to Stokes's coefficients and the two step approach used in filtering GRACE data applied. The results were then reconverted to the spatial domain in the original grid. The original unfiltered GLDAS-derived total water content grid was used as a reference to compute basin scale gain factor as:

$$\varepsilon = \sum_{t_1}^{t_n} (\Delta S_T - k\Delta S_F)^2, \quad (1)$$

where ε is the leakage obtained by finding the root mean difference between the true signal ΔS_T and the filtered signal ΔS_F. The gain factor k, is obtained through a least squares minimization. It is important to note that the scale factor does not match the GRACE-derived water-storage to those of GLDAS rather, it only gives the relative signal attenuation and restores the signal to its "original" form (Landerer & Swenson, 2012). Thus, when working with other gridded datasets (e.g., GLDAS, MODIS and TRMM), one only needs to scale the GRACE signals with the gain factor for consistent comparisons.

3.2.2. Terrestrial water budget

Evapotranspiration estimates using the instantaneous water balance equation in a given basin is expressed as (Brutsaert, 2008, p. 142):

$$ET = P + [(Q_{\text{ri}} + Q_{\text{gi}}) - (Q_{\text{ro}} + Q_{\text{go}})] - \frac{dS}{dt}, \quad (2)$$

where P is the area mean rate of precipitation; Q_{ri} is the total surface inflow, Q_{ro} is the total surface outflow, Q_{gi} is the total groundwater inflow, and Q_{go} is the total groundwater outflow rates, all per unit area; and S is the water volume stored per unit area. For the Volta Basin study case, where its area is bounded by natural divides, the groundwater terms can be considered negligible and the surface inflow is zero (Brutsaert, 2008, p. 142). In such situation, $Q = Q_{\mathrm{ro}}$, i.e. the mean net surface runoff rate per unit area from the basin, thus Eq. (2) can be simplified as:

$$ET = P - Q - \frac{dS}{dt}. \tag{3}$$

To obtain monthly values of ET, daily precipitation and discharge measurements must be aggregated to agree with the monthly terrestrial water-storage changes. Since the water balance approach uses station measured net stream flow (hereafter referred to as discharge), it is not able to provide the spatial variation of ET; however, it is ideal for estimating ET at the basin scale.

Equation (3) can be solved directly for ET as:

$$ET = P - Q - \Delta S, \tag{4}$$

where P presents the monthly values of precipitation, Q stands for discharge, and

$$\Delta S = S(t_2) - S(t_1), \tag{5}$$

indicates water-storage variation between times t_1 and t_2 in which the subscripts 1 and 2 refer to the beginning and the end of the month. For a long period (usually an annual time-scale) ΔS is usually assumed negligible (Xue et al., 2013), i.e., $\Delta S = 0$ assuming a steady state. We will investigate (section 4.2) whether this assumption, i.e. $ET \approx P - Q$, is reasonable at seasonal time scale over the Volta Basin.

Given that the difference between S and δS is a constant value, i.e., mean of the study period, the following equation can be derived from numerical differentiation using the central derivative operator (Ramillien et al., 2006):

$$\Delta S_i = \frac{1}{2} \left(\delta S_{i+1} - \delta S_{i-1} \right), \tag{6}$$

where ΔS_i is the approximation of water-storage changes during month i. Equation (6) will be used to provide ΔS in Eq. (4).

Another possibility for (3) is based on the standard combined atmosphere-land water balance equation (Serreze et al., 2006; Landerer et al., 2010)

$$\frac{dS}{dt} = -\left(\frac{\partial W}{\partial t} + \mathbf{\nabla} \cdot \mathbf{Q} \right) - Q, \tag{7}$$

where $\partial W / \partial t$ represents the change in precipitable water (W) in the atmosphere (the water depth of the vapor in the column) and $\mathbf{\nabla} \cdot \mathbf{Q}$ is the divergence of the horizontal water vapor flux $\mathbf{Q}$ integrated from the surface to the top of the column. Equation (7) will be used to assess the relative consistence between GRACE-derived water-storage changes (ΔS) and those estimated using climatological data from ERA-Interim (ΔS^*).

3.2.3. Uncertainty

Error estimates for remote sensing missions often rely on ground truth validation (Wahr et al., 2006). For GRACE-derived mass anomalies, the relative uncertainties were estimated using only GRACE fields as shown by Wahr et al. (2006). However, GRACE errors can be better estimated using full covariance matrix (Jensen et al., 2013) and error in the background model as shown, e.g., by Forootan et al. (2014a). For the background model, GRACE Atmosphere and Ocean Dealiasing Level 1B (GRACE-AOD1B) product (Flechtner, 2007) have been used to reduce high frequency non tidal oceanic and atmospheric mass changes. However, Forootan et al. (2014a) show that two jumps occur in the atmospheric part of the GRACE-AOD1B products during January-February of the years 2006 and 2010 due to changes of vertical and horizontal resolution in the European Centre for Medium-Range Weather Forecasts operational analysis (ECMWFop).

In fact these jumps impact on GRACE-derived water-storage anomalies inverted from spherical harmonic coefficients and must be corrected for either through updating uncertainty budgets or by applying corrections to estimated trends, amplitudes and phases (Forootan et al., 2014a). These biases were accounted for by modifying monthly GRACE L2 products using an improved model of atmospheric mass variations namely ITG3D-ERA-Interim. This model is based on a modified 3D integration approach (ITG3D) using long-term consistent atmospheric fields from the ERA-Interim (Forootan et al., 2013, 2014a).

The uncertainties in monthly estimates of ET can be computed at 95% confidence level ($\pm\sigma_{ET}ET$) by error propagation through Eq. (4) as suggested by Rodell et al. (2004a):

$$\sigma_{ET} = \frac{\sqrt{\sigma_P^2 P^2 + \sigma_Q^2 Q^2 + \sigma_{\Delta S}^2 \Delta S^2}}{|P - Q - \Delta S|}, \tag{8}$$

where σ_P, σ_Q and $\sigma_{\Delta S}$ are the uncertainties in the monthly precipitation, observed discharge, and GRACE-derived water-storage changes, respectively. Here we assume an error of 10% for precipitation (P) consistent with Thiemig et al. (2012), and a conservative value of 10% for the observed discharge (Q). Di Baldassarre & Montanari (2009) pointed out that the uncertainty in discharge data is often considered to be negligible with respect to other approximations affecting hydrological studies. The error for GRACE-derived water-storage anomalies (δS) was estimated by using the calibrated error of spherical harmonic coefficients propagated, e.g., in Eq. (28) of Swenson & Wahr (2002). To account for the month-to-month variations in Eq. (6), the $\pm\sigma_{\Delta S}\Delta S$ is obtained by multiplying the error in water-storage anomaly by $\sqrt{2}$.

3.2.4. Multi-linear regression analysis (MLRA)

Following Awange et al. (2011), multi-linear regression analysis (MLRA) can be applied to examine the temporal variabilities of the hydrological quantities such as estimated ET. Rodell et al. (2011) pointed out that it is useful to examine the mean annual cycles, in which the confidence is greater, due to the uncertainty in the monthly water budget estimates. Hence, for a given time series, the model used in this work is given by taking into account a constant (a_0), linear (a_1), annual and semi-annual amplitudes (A_1 and A_2, i.e., occurring once and twice a year, respectively) and phases (ϕ_1 and ϕ_2) as in Awange et al. (2011):

$$y(t) = a_0 + a_1 t + \sum_{k=1}^{2} A_k \cos(k\omega t - \phi_k), \tag{9}$$

where t is a given time point expressed in years; y is the original input series; $\omega = 2\pi/T$, where $T = 1$ year in this study; and k represents the rank of the harmonics ($k = 1$ and $k = 2$ correspond to the annual and semi-annual components, respectively). The parameters were estimated using a least squares fitting procedure with their corresponding accuracies. The ET, ΔS, and precipitation time series are then analyzed to look for amplitude ratio, phase lag, and linear trends.

3.2.5. Ensemble average (ET_a)

Since the ET measurements are scarce over the Volta Basin, an ensemble average approach can be used to combine the available ET estimates while considering their uncertainties. A combined ET time series can be created based on the six ET products (Modis, VIC, NOAH, MOSAIC, CLM, GRACE) as:

$$ET_a(t) = \sum_{i=1}^{6} w_i(t) ET_i(t), \tag{10}$$

where $w_i(t)$ is the time-dependent normalized weight given as

$$w_i = \frac{\frac{1}{\sigma^2_{ET_i}}}{\sum\limits_{j=1}^{6} \frac{1}{\sigma^2_{ET_j}}}, \tag{11}$$

which reflects the quality of $ET_i(t)$ at time t. The uncertainties for GLDAS models (VIC, CLM, NOAH and MOSAIC) and MODIS were estimated using the generalized three-cornered hat method (Gray & Allan, 1974; Premoli & Tavella, 1993) while TWB-based ET from Eq. (8). This method provides individual estimation of uncertainties if at least three time series of the same process are available (Koot et al., 2006).

4. Results and Discussions

4.1. Evaluation of GRACE-derived water-storage changes

Time series of total water-storage changes from February 2003 to November 2012 derived from three different processing centers of CSR, GFZ, and JPL are shown in Fig. 2(a). Overall, the results presented in Fig. 2(a) show a good agreement among the three processing centers over the study region.

Cross-correlation was carried out between the three time series of water-storage changes and values of 0.98 between CSR and GFZ, 0.98 between CSR and JPL, and 0.97 between GFZ and JPL were found. All the three GRACE solutions show comparable standard deviation signals between 40.44 mm (CSR), 39.65 mm (GFZ) and 41.14 mm (JPL) capturing the range of variability. The results from CSR, GFZ, and JPL are therefore statistically identical (comparison of variances at the 95% confidence level) over the Volta Basin. For the remainder of this study, we utilized only the water-storage changes estimated from GFZ due to the fact that it had the smallest standard deviation and also calibrated uncertainties of the spherical harmonic coefficients were available.

[Figure 2 around here.]

Assessing temporal bias between $P - ET$ and GRACE data might give in-sights to the biases reported in the reanalysis data. Independently, we estimated monthly water-storage changes (ΔS^*) for Volta Basin from climatological data ($P - ET$) calculated by using the datasets described in sub-section 3.1.6 from ERA-Interim and observed discharge data (Q) applying Eq. (7). Velicogna et al. (2012) stated that there is an unknown bias in $P - ET$ from reanalysis, which is difficult to estimate. Here, we find a bias of -25.15 mm/month to close the water budget from February 2003 to November 2012 at Volta Basin, and a RMSE of 41.05 mm/month between the two time series ($P - ET$ and GRACE). The cross-correlation value associated with the ΔS^* and GRACE-derived ΔS solutions is 0.51. The standard deviation of each time series is 39.72 mm/month for GRACE and 35.88 mm/month for

ΔS^* with a standard deviation (SD) of the differences of 32.44 mm/month. The signal-to-noise ratio (SNR) for GRACE and ΔS^* is 1.2 and 1.1, respectively, indicating that further investigation of these products should be performed over this particular basin.

The linear trend, amplitudes, and phases were estimated through a least squares fitting procedure with their corresponding uncertainties as in Eq. (9), and are summarized in Table 1. The Volta Basin shows a decrease in ΔS of -0.00 $\pm$0.37 mm/year from GRACE and -4.49 $\pm$0.70 mm/year for ΔS^*, which is equivalent to -1.85 $\pm$0.29 km^3/yr. The SNR of inter-annual trends for the water-storage changes are 0.01 mm/year and 6.4 mm/year for GRACE and ΔS^*, respectively, indicating that GRACE trend is insignificant. Both time series are characterized by wide variability between dry and wet seasons and from year to year, which coincides in phase (-0.1 $\pm$ 0.2 months) but the ΔS^* signal has a smaller amplitude (amplitude ratio of 1.7).

[Table 1 around here.]

The TRMM rainfall shows a similar seasonal pattern (Fig. 2(b)) to those derived from GRACE products. The two time series (TRMM and GRACE) present cross-correlation value of 0.93 and phase lag of approximately -0.5 $\pm$0.1 months at the maximum peaks (rainfall lags water-storage changes) with an amplitude ratio of 1.7. The derived large ratio indicates that the annual variations of the water-storage within the Volta Basin is dominated by precipitation. A possible explanation for this phase shift is the evidence of the basin saturation at 51 mm/month of equivalent water height at the annual time-scale (e.g., Crowley et al., 2006; Ferreira et al., 2014). Additionally, an insignificant trend of -0.49 ±0.60 mm/year that would suggest a decrease in precipitation over the basin during the period under consideration was seen. Paeth et al. (2011) have reported an anomalous wet condition occurred along of the Guinean Coast in July 2007 responsible for 2007 flood in sub-Saharan Africa (cf., Fig. 2(b)). The authors have attributed this to the La Niña event in the Tropical Pacific, anomalous heating in the Tropical Atlantic associated with greater depth of the monsoonal westerlies and enhanced activity of African easterly waves. Also, the available fresh water $P - ET$ (Fig 2(c)) shows a significant decrease in the basin at a rate of -4.10 ±0.70 mm/year while discharge has a significant increase of 0.39 ±0.04 mm/year (cf. Table 1).

4.2. Evaluation of global evapotranspiration estimates for Volta Basin

To compare different estimations of ET over the Volta Basin, we computed basin averaged values from GRACE, GLDAS and MODIS data, as well as, an approximation $ET \approx P - Q$ (Fig. 3) that provide seven time series (2 from TWB approach of where one considers GRACE-derived TWS (ET_{TWB}) and the other ignoring it (ET_{P-Q}), 4 from GLDAS-(NOAH, MOSAIC, VIC, CLM), and 1 from MODIS). The error bars in ET_{TWB} were calculated using the Eq. (8) at 95% confidence, for details see sub-section 3.2.3. The results of the comparisons of the GLDAS-simulated, TWB-derived, and MODIS regional ET, as well as $P - Q$ values, show distinct values among them (Fig. 3). The GLDAS solutions (VIC, CLM, NOAH and MOSAIC) are not in agreement with each other, for example, VIC seems to overestimate ET. It is also worth noting that the VIC model seems to have higher amplitudes compared to the other three models. As can be seen from Fig. 3, ET series are quite diverse and makes the decision on which approach provides the best ET estimation over the Volta Basin, relative to the ensemble average ET_a even more difficult. Finally, a combined series ET_a was computed using a weighted average of ET_{TWB}, ET_{MODIS}, ET_{CLM}, ET_{MOSAIC}, ET_{VIC} and ET_{NOAH} (details are presented in sub-section 3.2.5).

[Figure 3 around here.]

To infer on the solution that yields the best ET estimates over the Volta Basin, we provide a concise statistical summary of how well the different models match each other in terms of correlation coefficient (R), SD, and root-mean-square-error (RMSE) computed for each dataset with the TWB-based results is provided here. Thus, the relative performance of the different models can be inferred from Table 2. The best performing solution must have the highest correlation coefficient, lowest RMSE, and closest standard deviation relative to the reference model (ET_a). Generally, all the investigated ET products in Fig. 3 show good correlations with ET_a, with ET_{TWB} being the lowest (0.82) possibly due to the high uncertainties in ΔS (Fig. 2(a)). The MODIS solution seems to underestimate ET in the basin with a bias of -5.30 mm/month, while ET_{TWB} overestimate with a bias of 4.86 mm/month. Ruhoff et al. (2013) showed that MOD16 algorithm has a tendency to underestimate the average ET at the basin scale for almost all land use and cover types. Zeng et al. (2014) also reported that MOD16 ET tends to be underestimated, specially for basins with high ET values.

[Table 2 around here.]

RMSE of 19.39 mm/month was derived when comparing TWB-based ET to that of ET_a. The corresponding RMSEs for MODIS and GLDAS models (NOAH, CLM, MOSAIC, and VIC) were 6.63 mm/month, 11.77 mm/month, 12.16 mm/month, 18.41 mm/month, and 20.38 mm/month, respectively (e.g., Table 2). Thus, the TWB-based (ET_{TWB}) result is closer to the reference (ET_a) compared to those of VIC (ET_{VIC}). Among GLDAS simulations of ET, those derived from NOAH, CLM and MOSAIC seems to be more accurate than VIC over the Volta Basin. Estimates of VIC were found to represent a pattern that is not consistent with ET_a estimations. It should be mentioned here that the RMSE of the TWB-estimated ET values are in agreement with previous studies (e.g., Rodell et al., 2004a; Ramillien et al., 2006; Cesanelli & Guarracino, 2011; Zeng et al., 2014), i.e., our GRACE estimations are closer to the ensemble mean.

The Taylor diagram (Taylor, 2001) (Fig. 4) presents the results of statistical comparisons between the ET_a and ET obtained from the four products of GLDAS (VIC, NOAH, MOSAIC and CLM), TWB-based, and that estimated from MODIS. Among the individual standard deviation of each time series, only MODIS (28.12 mm/month), NOAH (32.74 mm/month) and GRACE (32.84 mm/month) were found to represent the range of variability close to the reference (30.25 mm/month). Additionally, sample comparison of variances show that MODIS-estimated ET, NOAH-simulated ET and TWB-based ET are identical of those derived from ET_a. Xue et al. (2013) pointed out that the uncertainties in the GLDAS ET products come from various sources such as meteorological and surface cover data, as well as the algorithms that are used for its estimations. Further research is necessary to assess their impact on the simulated ET. However, from this particular study, by considering the methodology and dataset applied as well as time span, the NOAH model was found to simulate ET best over Volta Basin compared to the others GLDAS's three models (i.e., CLM, MOSAIC and VIC).

[Figure 4 around here.]

In addition, from our numerical analysis, we the assumption of $\Delta S = 0$ (i.e., assumed steady state) could be questionable over the Volta Basin. Mean annual ΔS is approximately 4% of the corresponding $P - Q$ (Figure 5(a)). However, for semi-arid regions with a pronounced separation between wet and dry seasons (cf. Figure 5(b)), it is reasonable to consider this term in the water balance approach at seasonal time scales, while estimating ET in the basin. From Table 2 and Fig. 4 the improvement of the ET_{TWB} in comparison with ET_{P-Q}. Additionally, the advantage of including GRACE-derived ΔS is that the phase and amplitude of the annual cycle of ET can be ascertained as shown in Rodell et al. (2011). For example, the annual phase and amplitude of ET_{P-Q} are 84.7 mm/month and -5.1 months, ET_{TWB} are 38.6 mm/month and -4.4 months, and ET_a are 45.1 mm/month and -4.6 months, respectively.

[Figure 5 around here.]

It should be mentioned here that the results obtained from the method proposed in this study are based mainly on GRACE-derived water-storage changes, TRMM precipitation data, and in-situ discharge data at Akosombo Dam. This discharge data was regularized over the study period impacting the water balance over the Volta Basin. Thus, we expect that the TRMM-estimated precipitations (P) are perhaps biased by approximately 11% (underestimation) as shown, e.g., in Thiemig et al. (2012). However, Rodell et al. (2011) concluded that precipitation is not be the most important determinant of bias in modeled ET. Because the modeled ET comes from different data and methods, and they are similar to each other over Volta Basin, it can sufficiently be concluded that they are a good representation of the reality.

5. Conclusion

This study assessed different estimations of evapotranspiration (ET) products based on remote sensing and hydrological model simulations, over the Volta Basin, West Africa, what so far has been elusive due to data scarcity in the region. The proposed approach did not use ground data, which are usually required to validate remotely sensed products, and as such is advantageous where ground data are scarce or not available. The findings could be of use, e.g., to hydrologists, climatologists, and water resources managers in helping them chose the appropriate ET product. However, the method does not allow an estimation of the absolute error of the ET time series and as such, requires that all the products be evaluated and analyzed together. Comparing seven ET estimations to their ensemble mean (ET_a), this study found that remote sensing-based ET estimated by MODIS presents an uncertainty of 3.99 mm/month, while TWB-based ET presents 18.85 mm/month. Among GLDAS-simulated ET, that of NOAH indicated an uncertainty of 7.06 mm/month and the other three models (MOSAIC, CLM and VIC) represented larger errors of 9.97, 12.22 and 15.40 mm/month, respectively.

However, only those ET of MODIS, NOAH and GRACE represent similar patterns to that of the computed reference (ET_a). It is worth to mentioned here that the water-storage changes are important as can be seen an improvement of 45% in terms of RMSE (cf., Table 2), and cannot be neglected while using the water balance approach at a seasonal time scales. Although ET estimated from GRACE has higher RMSE (19.39 mm/month) relative to the reference, it is comparable to the accuracies obtained in previous studies. Further research is needed to improve the estimation of uncertainties and the combination of ET time series.

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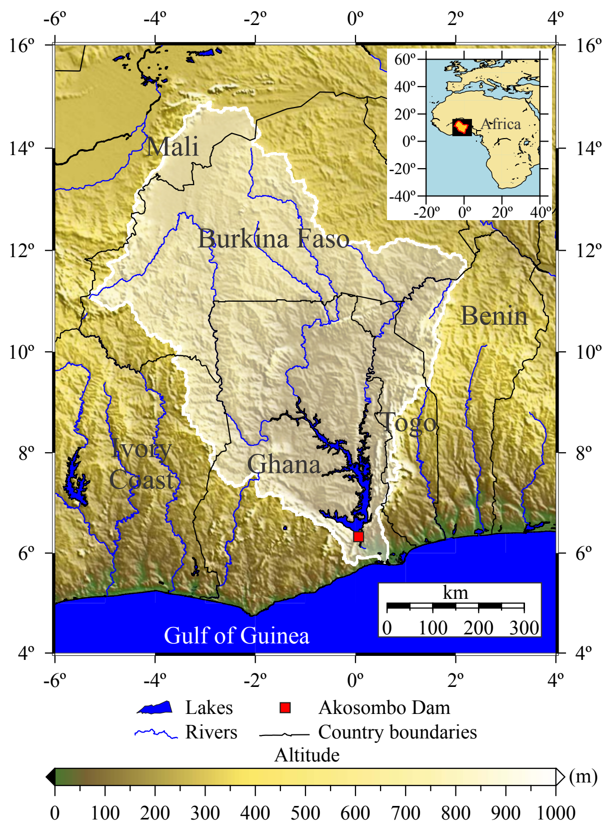

Figure 1: The Volta River Basin (shadowed portion with an area of approximately 417,382 km^2) and its riparian countries in West Africa. The scale is related to the parallel 10° N.

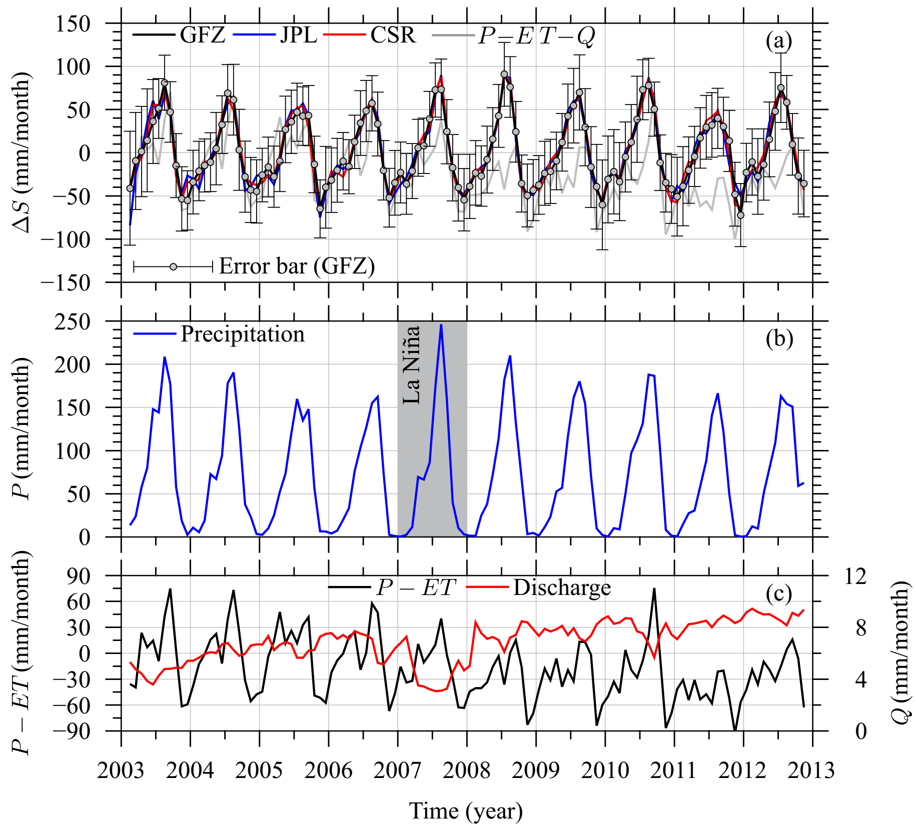

Figure 2: (a) Monthly Gravity Recovery and Climate Experiment (GRACE)-derived water-storage changes (ΔS) from the three different processing centers (Center for Space Research (CSR), Jet Propulsion Laboratory (JPL), *GeoForschungsZentrum* (GFZ)) and as a residual from $P - ET - Q$ using ERA-Interim reanalysis and river discharge data. (b) Tropical Rainfall Measurement Mission (TRMM) precipitation; the gray rectangle shows the La Niña event in 2007. (c) $P - ET$ by using ERA-interim, and *in-situ* discharge data.

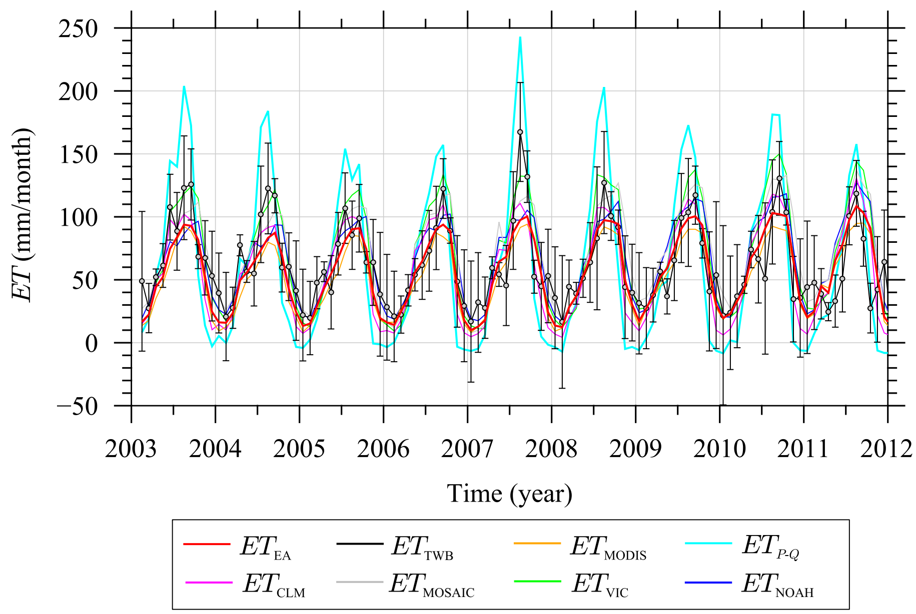

Figure 3: Monthly evapotranspiration from four versions of Global Land Data Assimilation System (GLDAS) (CLM, MOSAIC, NOAH and VIC) and those estimated by MODIS, GRACE, ensemble average and $P - Q$ over Volta Basin.

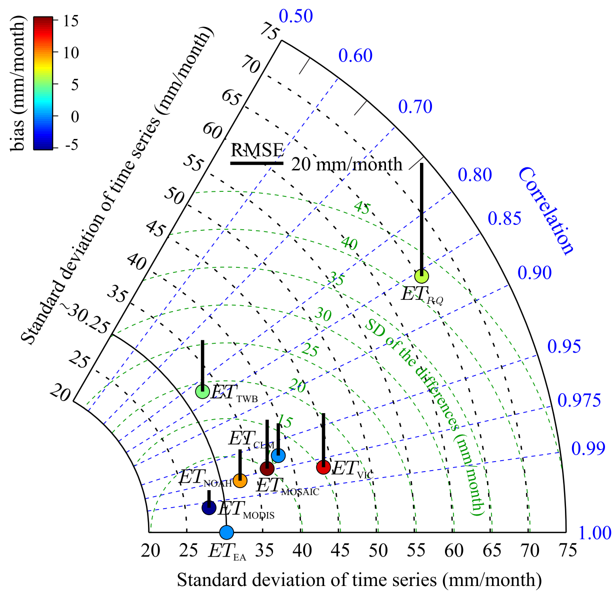

Figure 4: Taylor's diagram of statistical comparison between the time series of ensemble average ET (Ref.) and MODIS as well as GLDAS (VIC, NOAH, MOSAIC and CLM) and TWB-based.

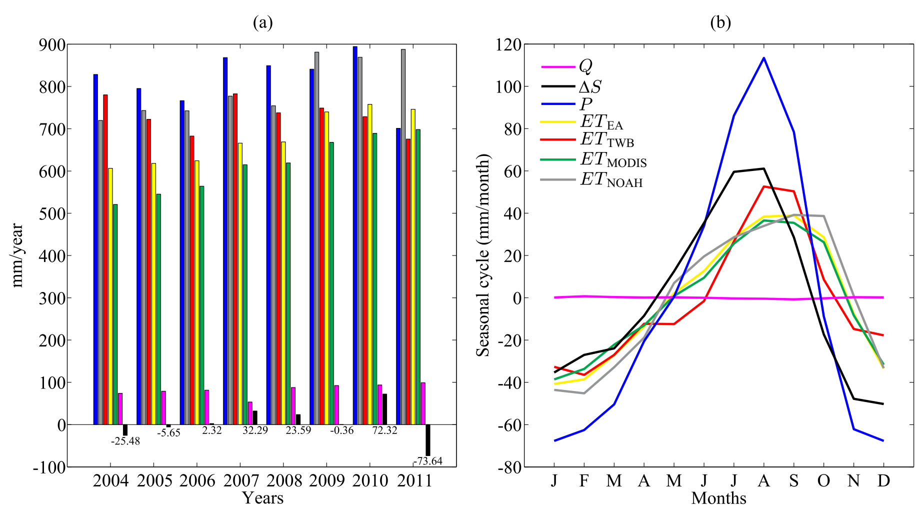

Figure 5: (a) Annual, basin averaged, totals of different ET products and the hydrological quantities $P-E$, Q, ΔS and P. (b) Mean annual cycle (using the calendar year) of different ET products and the hydrological quantities Q, ΔS and P for the period 2004-2011.

Table 1: Coefficients for least squares best fit over the time window of February 2003 to November 2012 at 95% confidence level.

Variable	Trend (mm/month/year)	Amplitude (mm/month)		Phase (°)	
		Annual	Semi-annual	Annual	Semi-annual
ΔS	-0.00 ±0.37	50.6 ±1.5	18.2 ±1.5	-167.8 ± 1.7	76.0 ± 4.7
ΔS^*	-4.49 ±0.70	29.5 ±2.8	22.8 ±2.8	-171.0 ± 5.5	133.4 ± 7.1
P	-0.49 ±0.60	84.3 ±2.4	26.3 ±2.4	-152.1 ± 1.6	95.5 ± 5.3
$P - ET$	-4.10 ±0.70	29.1 ±2.8	22.8 ±2.8	-171.6 ± 5.5	133.4 ± 7.1
Q	0.39 ±0.04	0.5 ±0.1	0.1 ±0.1	46.4 ±17.8	-37.0 ±131.7

Table 2: Statistical results over Volta Basin of MODIS, GLDAS (VIC, NOAH, MOSAIC and CLM), GRACE-derived and $P - Q$ (precipitation minus discharge) compared with ensemble average.

Model		Summary			
		R	SD (mm/month)	bias (mm/month)	RMSE (mm/month)
ET_{TWB}		0.82	18.85	4.86	19.39
ET_{MODIS}		0.99	3.99	-5.30	6.63
GLDAS	ET_{VIC}	0.98	15.40	13.42	20.38
GLDAS	ET_{NOAH}	0.98	7.06	9.44	11.77
GLDAS	ET_{MOSAIC}	0.97	9.97	15.51	18.41
GLDAS	ET_{CLM}	0.96	12.22	0.05	12.16
ET_{P-Q}		0.86	42.47	6.15	42.73