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Assessing total water storage and identifying flood events over Tonlé Sap basin in Cambodia using GRACE and MODIS satellite observations combined with hydrological models

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A B S T R A C T

In this study, satellite observations including gravity (GRACE), terrestrial reflectance (MODIS), and global precipitation (TRMM) data, along with the output from the PCR-GLOBWB hydrological model, are used to generate monthly and sub-monthly terrestrial water storage (TWS) estimates and quantify flood events over the Tonlé Sap basin between 2002 and 2014. This study is the first time GRACE data have been used to investigate the hydrological processes over the Tonlé Sap basin. To improve the accuracy of the TWS estimates from GRACE, a signal restoration method was applied in an effort to recover the signal loss (i.e., signal leakage) inherent in the standard GRACE post-processing scheme. The method applies the correction based on the GRACE observations only, requiring no external data or hydrological models. The effectiveness of the technique over the Tonlé Sap basin was validated against several independent data sets. Based on the GRACE observations since 2002, the 2011 and 2013 flood events were clearly identified, and measured to have basin-averaged TWS values of 42 cm (40% higher than the long-term mean peak value) and 36 cm (34% higher) equivalent water height, respectively. Those same years also coincide with the largest observed flood extents, estimated from the MODIS data as 6561 km^2 (91% above the long-term mean peak value) and 5710 km^2 (66% above), respectively. Those flood events are also linked to the observed inter-annual variations of water storage between 2010 and 2014. It was shown that those inter-annual variations mainly reflect the variations in the surface water and groundwater storage components, influenced by the change of the precipitation intensity. In addition, this study presents a new approach for deriving monthly and sub-monthly TWS variations over a regularly inundated area by using MODIS reflectance data in addition to GRACE solutions. The results of this study show that GRACE data can be considered as an effective tool for monitoring certain small-scale (82,000 km^2) hydrological basins.

1. Introduction

The main goal of this study is to quantify flood events in the Tonlé Sap basin in Central Cambodia at both basin and sub-basin scales. It is shown that a combination of several satellite data products in this data-sparse region can yield valuable insight into flood pulses during the last 15 years.

The Tonlé Sap basin has an area of approximately 82,000 km^2 and contains the largest freshwater lake (Tonlé Sap Lake) in Southeast Asia, which serves as the primary fresh water resource for various food and agricultural activities of Cambodia (Lamberts, 2001). Apart from precipitation, the Tonlé Sap Lake regularly receives water from the Mekong River through the Tonlé Sap River. In addition, the Mekong River brings sediment and nutrients to the soil, making the Tonlé Sap basin favorable for fisheries and the cultivation of rice and other crops. The agricultural activities in the Tonlé Sap basin require irrigation, and the irrigated area has been expanded in the past decade in line with the implementation of a national strategic plan (Yu & Diao, 2011). This has facilitated agriculture growth in the area, so that now more than half of the Cambodian rice fields are located within the basin. Importantly, several new hydro-electric power plants have been constructed in the regions upstream of the Mekong River (outside Cambodia). These developments have altered the natural flows of Mekong mainstream, which has a direct impact to on the Tonlé Sap water level (Arias et al., 2012; Cochrane, Arias, & Piman, 2014; Kummu et al., 2014). Compounded by climate variability, the frequency and intensity of drought and flood events in the region have become more severe and have led to the destruction of irrigation fields and

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civilian casualties (NCDM, and UNDP, 2014). It is clear that for the development and prosperity of all of the countries dependent on the Mekong and Tonlé Sap basins, improved long-term monitoring of the region's water resources is needed. Such monitoring will serve intergovernmental agencies like the Mekong River Commission (MRC), which aim to optimize the usage of water resources during the country's development while minimizing the harmful effects on people and the environment of the region. Despite the clear need for hydrological information, the vast and inaccessible nature of the Tonlé Sap area makes it difficult to collect in situ observations. As a result, remote sensing observations have to be exploited. This study is a first attempt to provide a comprehensive assessment of the large-scale variations of the water storage as well as to explore flood events in the Tonlé Sap basin over the past decade, using various data sets delivered by remote sensing satellites.

In several studies in the past, terrestrial surface reflectance data have been used to identify the spatial flooding patterns over the Tonlé Sap Lake (Arias et al., 2012; Sakamoto et al., 2007; Xiao et al., 2005). However, that analysis did not allow the total water storage variations to be accurately quantified. To address this issue, data from the Gravity Recovery And Climate Experiment (GRACE) satellite mission (Tapley, Bettadpur, Ries, Thompson, & Watkins, 2004) are used in our study. In contrast to the terrestrial surface reflectance observations, GRACE senses the total Terrestrial Water Storage (TWS) variations in all components (e.g., surface water, soil moisture, and groundwater) (Bettadpur, 2012). For this reason, GRACE data have been used in many hydrological applications at both global and regional scales, e.g., groundwater depletion in India (Rodell, Velicogna, & Famiglietti, 2009), flood prediction for Mississippi River basin (Reager, Thomas, & Famiglietti, 2014) and characterization of regional (e.g., Amazon, Zambezi, Texas) drought signatures (Thomas, Reager, Famiglietti, & Rodell, 2014). However, to date GRACE data have never been applied to study hydrological processes over the Tonlé Sap basin. The results based on GRACE data are supported and validated by means of other satellite remote sensing datasets and hydrological models.

One of the challenges in using GRACE data is their temporal resolution, which is limited to one month, as well as their coarse spatial resolution (typically >300 km). Unconstrained GRACE products require the application of some form of spatial filtering to reduce the effects of high-frequency errors inherent to the publicly available GRACE fields. This spatial filtering redistributes the signal over the filter radius, commonly referred to as signal leakage, requiring additional processing to restore this leaked signal if accurate TWS results over a specific target area are desired. Several signal restoration methods have been described in the literature for this purpose. Landerer and Swenson (2012) applied a scaling factor computed as the ratio between the true TWS and filtered TWS, based on a hydrological model. The procedure is simple but may introduce a bias caused by the dependency on a particular hydrological model. Baur, Kuhn, and Featherstone (2009) applied a correction based on known signal geometry. Their method was developed to restore the signal along the coastal zone of Greenland. The method does not rely on external data and can be very effective, but requires a controlled environment, where the surrounding signal is smaller than the target one, and the signal location is known. More recently, Chen et al. (2013, 2014) proposed a strategy similar to that of Baur et al. (2009) but without the known signal geometry requirement. The main idea is to mitigate the leakage out signal (from land to ocean) using GRACE data directly, so that the signal damping effect near the coast is effectively reduced (Chen et al., 2013). This strategy is straightforward, easy to implement, and has been proven effective for inland applications (Chen, Li, Zhang, & Ni, 2014). As will be shown later, the results produced compared well with independent validation data, suggesting the approach is suitable for this study as well.

Apart from GRACE observations, precipitation data from the Tropical Rainfall Measuring Mission (TRMM, Kummerow, Barnes, Kozu, Shiue, & Simpson, 1998), as well as three hydrological models are used in an attempt to better understand the processes responsible for the observed TWS variations. The hydrological models used are: (i) the Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis-Interim (ERA-Interim) Full Resolution (Dee et al., 2011); (ii) the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004); and (iii) the PCRaster Global Water Balance (PCR-GLOBWB) (Sutanudjaja, van Beek, de Jong, van Geer, & Bierkens, 2014; van Beek, Wada, & Bierkens, 2011; Wada, Wisser, & Bierkens, 2014). In contrast to the ERA-Interim and GLDAS models that construct TWS based on soil moisture storage, the PCR-GLOBWB model also contains surface water and groundwater storage components and can be used to distinguish the contribution of different storage components to the TWS.

Furthermore, the coarse temporal and spatial resolution of GRACE requires supporting information to cover smaller temporal and spatial scales. This information is obtained from the terrestrial surface reflectance data provided by the Moderate-Resolution Imaging Spectroradiometer (MODIS; Vermote, Kotchenova, & Ray, 2011), which form images with a spatial resolution of 500 m every 8 days. To distinguish the open water from soil and vegetation, the Normalized Different Water Index (NDWI; McFeeters, 1996) is used. In the first instance, NDWI data are used to quantify variations of the inundated area, which is essential for flood area planning. However, by using an empirical relationship between GRACE (TWS) and MODIS (NDWI-based) data over the inundated area, it is also possible to estimate the TWS variations from the MODIS data. This is important because it enables the estimation of TWS variations at sub-monthly time scales. To the author's knowledge, this is the first time that TWS variations have been produced from MODIS data.

This paper begins with an overview of the Tonlé Sap basin, given in Section 2. The description of all data and their processing are presented in Section 3. The GRACE signal restoration scheme is described in Section 4.

Section 5 focuses on the results obtained. The performance of the signal restoration method, as well as of the hydrological models, is evaluated in Section 5.1. Precipitation is analyzed in Section 5.2. In Section 5.3, we demonstrate the usage of MODIS data to estimate the TWS variations over the Tonlé Sap Lake floodplain. Section 5.4 is focused on the investigation of the inter-annual signal over the Tonlé Sap basin. Finally, Section 6 discusses and summarizes the main results of the study.

2. Study region

The Tonlé Sap basin extends over eight major Cambodian provinces and occupies approximately 46% of the land area of Cambodia. Tonlé Sap Lake (Fig. 1) located in the center part of the basin has an area in the dry

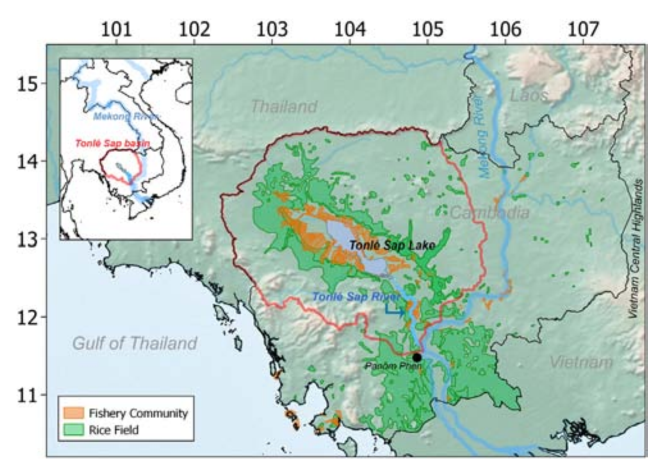

Fig. 1. Geographical location of the Tonlé Sap basin (red line). The shapefiles of the Tonlé Sap basin, Tonlé Sap Lake, fishery community and rice field were obtained from the Open Development Cambodia website (http://www.opendevelopmentcambodia.net/maps/downloads). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)