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An improved approach to monitoring Brahmaputra River water levels using retracked altimetry data

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ABSTRACT

Satellite altimetry is an important tool for monitoring water levels over oceans and inland water bodies, particularly over poorly gauged or ungauged areas. This study uses satellite altimetry (Jason-2/3 and Envisat) to derive water levels of the Great Brahmaputra River (GBR) originating from the Tibetan Plateau. Although the width of the river channels of the Lower Brahmaputra River (LBR) is ~1 km, the Upper Brahmaputra River (UBR) (which is part of the Yarlung Zangbo River of China) and the Middle Brahmaputra River (MBR) located in high-mountain regions have river widths that are generally less than 400 m. This poses considerable challenges for existing retracking algorithms to obtain accurately retrieved water levels. In this study, an improved approach for deriving water levels in high-mountain regions with complex terrain is proposed, comprising (1) an improved footprint selection and (2) an improved waveform retracking, called the 50% Threshold and Ice-1 Combined algorithm (TIC). It was applied to river channels of varying widths, ranging from 200 m in the UBR to more than 1 km in the LBR. Results show an increase in both the accuracy and sampling of water levels. Most of the derived water levels at 13 virtual stations (VSs) along the GBR agree reasonably well with gauged water levels (for VSs in the UBR) or published results (for VSs in the LBR). The standard deviation of the difference between the TIC-derived water levels and gauged data at the VSs ranges from 0.3 m to 0.8 m with the highest improvement percentage relative to the unretracked ranges reaching 80% in the UBR. In addition, the developed approach increases water level sampling by reasonably demarcating the buffer zone for footprint selection, thereby generating more water levels in the time series than the published results for VSs in the LBR. However, 3 out of the 13 virtual stations show poor performance for Envisat, primarily due to the extremely narrow river channels. Furthermore, TIC can potentially be applied to estimate water levels near ground tracks of altimetric missions, even where there is no crossover between the river and the track. It could also be applied to other altimetric missions, which would further contribute to monitoring water levels and potentially river discharge in high-mountain regions with narrow river channels.

1. Introduction

River water level data are important variables used in hydrological studies and related applications such as flood forecasting, water supply determination, and dam design (Jarihani et al., 2013; Tarpanelli et al., 2017), but such data can be difficult to obtain, particularly in ungauged or poorly gauged basins. Satellite remote sensing offers the unprecedented opportunity to obtain freely accessible water level heights, particularly in remote and isolated regions. Many altimetric missions such as the TOPEX/Poseidon, Jason-1, 2, and 3, ERS-1/2, Environmental Satellite (Envisat), ICESat, CryoSat-2, SARAL/AltiKa, and the upcoming SWOT show promise in providing data in such regions and have provided data of two decades that can be used to monitor the dynamics of water bodies on the Earth (Alsdorf et al., 2007; Biancamaria et al., 2015; Birkinshaw et al., 2010; Bjerklie et al., 2003; Papa et al., 2012; Tarpanelli et al., 2013; Tarpanelli et al., 2015; Tourian et al., 2016; Zhang et al., 2011).

Satellite altimetry uses either a radar or laser to measure the range between the surface of water and the satellite and was initially developed to monitor sea levels. In recent years, it has been widely applied to coastal zones and inland water bodies, which are important underexploited domains (Van Dijk et al., 2016). Monitoring variations in water level without being affected by weather and cloud is a vital aspect of radar altimetry (Frappart et al., 2006; Getirana et al., 2013; Michailovsky et al., 2013; Santos da Silva et al., 2010). According to Frappart et al. (2006), radar altimetry performs well in estimating

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Table 1

Summary of relevant studies monitoring water levels in coastal/inland water bodies using satellite altimetry (this current paper is also added). Key results are coded as follows: (1) development of a new waveform retracking method, (2) use of multisource satellite altimetry, and (3) use of additional data-processing approaches. There is no code in the "Key results" column for study results unrelated to either of these codes.

Study	Altimetric missions used	Length of ground track along water bodies (m)	Key results
Biancamaria et al. (2017)	Jason-2, Envisat, and SARAL/AltiKa	From 130 to 2000	2. Multisource satellite altimetry used 3. Experimental DIODE/DEM tracking mode used to observe steep-sided narrow river valleys
Yuan et al. (2017)	Jason-2	~1700	1. Multi-subwaveform Multi-weight Threshold Retracker (MSMWTR) method developed
Sridevi et al. (2016)	Envisat, Jason-2, and SARAL/AltiKa	More than 1000	2. Multi-mission satellite altimetry used
Tourian et al. (2016)	TOPEX/Poseidon, Envisat, SARAL/AltiKa, CryoSat-2, and Jason-2	From ~200 to ~600	2. Multi-mission satellite altimetry applied 3. Geodetic approach used to improve temporal resolution of water level time series
Schwatke et al. (2015)	TOPEX/Poseidon, Jason-1/2, ERS-2, Envisat, and SARAL/AltiKa	From ~300 to more than 1000	2. Multi-mission satellite altimetry used 3. Extended outlier rejection and Kalman filter approach used
Kuo and Kao (2011)	Jason-2	~200	3. GPS campaigns launched for geolocating Google Earth Images and the virtual station.
Crétaux et al. (2011)	TOPEX/Poseidon, Jason-1/2, Envisat, and GFO	Mostly more than 1000 (global lakes)	2. Multi-satellite altimetry used 3. Multi-satellite approach used to increase precision of water levels
Santos da Silva et al. (2010)	ERS-2 and Envisat	From ~100 to more than 1000	2. ERS-2 and Envisat used 3. Off-nadir and slope corrections conducted to increase accuracy of water levels
Birkinshaw et al. (2010)	ERS-2 and Envisat	~400	2. ERS-2 and Envisat used
Hwang et al. (2006)	Geosat/GM	More than 1000 (near the coasts)	1. Improved threshold method proposed
This study	Jason-2/3 and Envisat	From ~200 to more than 1000	1. TIC developed to derive accurate water levels 2. Jason-2/3 and Envisat jointly used 3. Improved footprint selection adopted to increase data points in water level time series

water levels for continental rivers with a root-mean-square error (*RMSE*) of 30 cm. The ability of satellite altimetry to monitor water levels in continental water bodies has been demonstrated in many published studies (Crétaux et al., 2011; Sulistioadi et al., 2015; Sun et al., 2012). In the Amazon basin, Envisat and European Space Agency's ERS-2 have been used to derive water levels with an accuracy of 0.4 m (Santos da Silva et al., 2010). Jason-2 has been shown to be very useful and accurate in detecting variations in sea-surface height, with an accuracy of 3.4 cm, and with a relatively high temporal resolution of 10 days compared to other altimetric missions (Birkett and Beckley, 2010; Dumont et al., 2009). Its application in inland water bodies, such as lakes and rivers has also been tested with good results (Cheng et al., 2010; Guo et al., 2009; Tourian et al., 2016). Paris et al. (2016) reported that it has an accuracy reaching a few tens of centimeters in continental water bodies. A summary of a selection of papers that have used satellite altimetry for monitoring coastal/inland water bodies is presented in Table 1.

The principle of radar altimetry is as follows. Pulses from the microwave instrument onboard a satellite are echoed by the Earth's surface (water, farmland, vegetation, building, or ocean) and then received by the onboard receiver. The range between the satellite and the Earth's surface is obtained by measuring the two-way time involved for the entire process. The waveform, which is the shape of the reflected pulse, is a proxy of the natural attributes on the Earth's surface and can be used to determine the range. In general, the waveform reflected by oceans has a Brown-like shape (Brown, 1977) with a maximum value and then a gentle descent. For inland water bodies, waveforms with a quasi-specular shape are most likely associated with rivers, but multiple specular waveforms predominate over narrow rivers due to the influence of land cover. Consequently, the midpoint of the leading edge may generally not be the nominal gate (32 for Jason-2/3 and 46 for Envisat) as expected. Therefore, various waveform retracking algorithms have been developed to correct for the distance between the actual leading edge and the nominal gate.

Two main retracker types have been developed for waveform retracking. The first type is based on the well-known Brown ocean model (Brown, 1977), which was the pioneering method used to process waveforms in oceans. The β-algorithm was firstly developed by Martin et al. (1983), with the aim of measuring continental ice sheets. Although Vignudelli et al. (2011) determined that this retracker has no relationship with physical properties, it is still considered to be a first retracker type as it is linked with the Brown model. By adopting five or nine parameters, it can be used to fit single or double-peak waveforms. However, despite this advantage it is often unable to converge (due to complex waveforms) and is thus not effective enough for use with narrow rivers in high-mountain regions (Roscher et al., 2017). Other variants of the Brown model are physical-based retrackers, including the Brown-Hayne theoretical ocean model (Moore and Williams, 1957) and the NOCS non-linear ocean retracker (Challenor and Srokosz, 1989).

Retrackers belonging to the second type are known as empirical retrackers. They do not consider the physical mechanism of the waveform and use only statistical methods to locate the leading edge of the waveform. The advantage of doing so is obvious: they are easy to implement and are relatively robust compared with the former type, particularly when applied to inland water bodies. These retrackers have been shown to be effective in the retrieval of water levels (Kuo and Kao, 2011; Lee et al., 2010; Santos da Silva et al., 2010; Tseng et al., 2014). Retracking algorithms, such as the Offset Centre Of Gravity (OCOG) (Bamber, 1994), 50% Threshold (Davis, 1997) and Ice-1 (Dumont et al., 2011) all belong to this group.

Specifically designed for measuring ice sheets in polar regions, the Ice-1 algorithm also has the potential for use with inland water bodies. It performs well for large rivers (Sridevi et al., 2016) and it is considered to be the most suitable algorithm for use with continental hydrology (Frappart et al., 2006). Its performance has also been studied in rivers with widths on the order of a few hundred meters (Paris et al., 2016). However, the study of Santos da Silva et al. (2010) showed that using the Ice-1 algorithm in rivers within the Amazon basin provided highly variable quality in water level time series, with *RMSEs* ranging from 12 cm to several meters. Although off-nadir detection has contributed to improving the accuracy of water level time series, using the