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Research papers

Monitoring recent lake level variations on the Tibetan Plateau using CryoSat-2 SARIn mode data

Liguang Jiang[a,*], Karina Nielsen[b], Ole B. Andersen[b], Peter Bauer-Gottwein[a]

[a] Department of Environmental Engineering, Technical University of Denmark, Bygningstorvet 115, 2800 Kgs. Lyngby, Denmark
[b] National Space Institute, Technical University of Denmark, Elektrovej 327, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

Lakes on the Tibetan Plateau (TP) are of great interest due to their value as water resources but also as an important indicator of climate change. However, in situ data in this region are extremely scarce and only a few lakes have gauge measurements. Satellite altimetry has been used successfully to monitor lake levels. In this study, Cryosat-2 SARIn mode data over the period 2010–2015 are used to investigate recent lake level variations. The estimated water levels of the 70 largest lakes (> 100 km^2) on the TP show that 48 lakes reveal a rising trend (avg. 0.28 ± 0.06 m/yr) while the other 22 show a slightly decreasing trend (avg. −0.10 ± 0.04 m/yr). To compare with the change rates during 2003–2009, ICESat data which cover 42 of the 70 lakes are also used. When combining the data, the results show that during the period of 2003–2015, 28 lakes maintained a rising trend and the change rates are comparable. Lakes in the northern part of the TP experienced pronounced rising (avg. 0.37 ± 0.10 m/yr), while lakes in southern part were steady or decreasing even in glaciated basins with high precipitation. Factor analysis indicates that driving factors for lake change are variable due to high spatial heterogeneity. However, autumn/winter temperature plays an important role in lake level change. These results demonstrate that lakes on the TP are still rapidly changing under climate change, especially in northern part of the TP, but the driving factors are variable and more research is needed to understand the mechanisms behind observed changes.

1. Introduction

The Tibetan Plateau (TP), with an average elevation of more than 4000 m-amsl and an area of approximately 2.5 million km^2, is China's largest and the world's highest highland. The TP plays a significant role in the regional and global climate system due to its large area and high altitude (Wu et al., 2007; Yanai and Li, 1994). It is important for Asian monsoon development and water-energy cycles (Molnar et al., 2010). The TP has the largest ice mass outside the Arctic and Antarctic regions. The snow and ice masses feed many large rivers which provide water to more than 1.4 billion people (Immerzeel et al., 2010). The TP is characterized by thousands of lakes, which cover an area of 41,831 km^2 (Wan et al., 2014). Therefore, the TP is also called the "Asian water tower" (Lu et al., 2005). Besides their value as water resources, lakes are critical landscape units which play an important role in the land surface energy cycle and thus impact the regional climate and water circulation. However, most of the lakes have experienced great changes during the past three decades and are still changing rapidly due to climate change. The investigation of Wan et al. (2014) indicated that about 30 new lakes appeared and 5 existing lakes have dried up and vanished in the period of 1975–2006. In addition, most of the 13 largest lakes (> 500 km^2) experienced drastic changes. For instance, Siling Co has expanded by 600 km^2 accounting for about 26% of total area since 1976 (Zhou et al., 2015), while the size of Qinghai Lake first decreased by 231 km^2 and then expanded by 134 km^2 during 1973–2013 (Shen et al., 2013).

Satellite radar altimetry has been a successful technique and widely used to monitor lake level variations (Berry et al., 2005; Birkett, 1995; Crétaux et al., 2016; Crétaux and Birkett, 2006; Gao et al., 2013; Kleinherenbrink et al., 2015; Liao et al., 2014; Song et al., 2014, 2015a,b,c). It has become a very important alternative data source to in situ observations, especially in remote areas where in situ data are not available, e.g. the TP. Compared to conventional radar satellite missions (Topex/Poseidon, Jason, ERS, ENVISAT, etc.), the new generation of radar altimetry, CryoSat-2, has some advantages. The CryoSat-2 mission, launched in April 2010, has been operational for 6 years in April 2016. Cryosat-2 features a delay/Doppler

* Corresponding author.
E-mail address: ljia@env.dtu.dk (L. Jiang).

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technology. Its primary instrument, the Ku-Band Synthetic Aperture Interferometric Radar Altimeter (SIRAL), has three measurement modes: low resolution mode (LRM), synthetic aperture radar mode (SAR) and SAR interference mode (SARIn). Additionally, CryoSat-2 has a repeat period of 369 days and an inclination of 92 degrees, thus it covers a larger area than previous missions. Meanwhile, it has a subcycle of 30 days, that is to say, the density of ground tracks is high, thus many lakes are visited (European Space Agency and Mullar Space Science Laboratory, 2012; Kleinherenbrink et al., 2014; Nielsen et al., 2015).

The TP is a crucial testing ground for application of altimetry on inland water because of its numerous lakes (Fig. 1) and the lack of gauge-based observations. Ice, Cloud, and land Elevation/Geoscience Laser Altimeter System (ICESat/GLAS) demonstrated its value in monitoring lake level change (Phan et al., 2012; Song et al., 2013; Zhang et al., 2011). In the past few years, a growing number of studies have used ICESat/GLAS to retrieve lake level time series (Li et al., 2014; O'Loughlin et al., 2016; Phan et al., 2012; Wang et al., 2013; Zhang et al., 2011). Nevertheless, the application of CryoSat-2 in hydrology community is still in its infancy. Kleinherenbrink et al. (2015) first presented the application of CryoSat-2 SARIn mode data over the period February 2012 to January 2014 to monitor lakes on the TP. However, more research is needed to explore the full potential of Cryosat-2 in monitoring of inland water level.

In this paper, we investigate water level change of large lakes (> 100 km^2) on the TP using CryoSat-2 SARIn mode data of 2010–2015. We apply the Narrow Primary Peak Threshold (NPPT) retracker (Jain et al., 2015), which has proven to provide valid results for inland water applications (Nielsen et al., 2015; Villadsen et al., 2016). In terms of height precision, the NPPT retracker is seen to outperform the ESA L2 data (Jain et al., 2015), but for studies of lake level change there is only in-significant difference depending on the choice of NPPT versus L2 retracker. Finally we estimate the along-track mean water level for each pass using a robust method (Nielsen et al., 2015). Lake level changes are compared during two periods of 2003–2009 and 2010–2015, and the potential causes of lake change are investigated.

2. Data and methods

2.1. Water mask

Landsat 8 OLI and Landsat 7 ETM+ images were downloaded via the United States Geological Survey (USGS) EarthExplorer (http://earthexplorer.usgs.gov/) to delineate the lake masks. The acquisition dates of all images are between May to December of 2014 to get high quality images over lakes. In total, 34 scenes of Landsat 8 OLI and 18 of Landsat ETM+ were used to derive the lake mask. Considering the efficiency and quality of different methods, a threshold-based approach was used combined with visual examination. The thresholds of DN 35–40 and 5000–5600 was used to extract the lake body with band 5 (Landsat 7) and band 6 (Landsat 8) depending on the date of image acquisition.

2.2. CryoSat-2

2.2.1. Lake level estimation

The ESA level 1b baseline B data product in SARIn mode was used as input. The waveforms were retracked using the Narrow

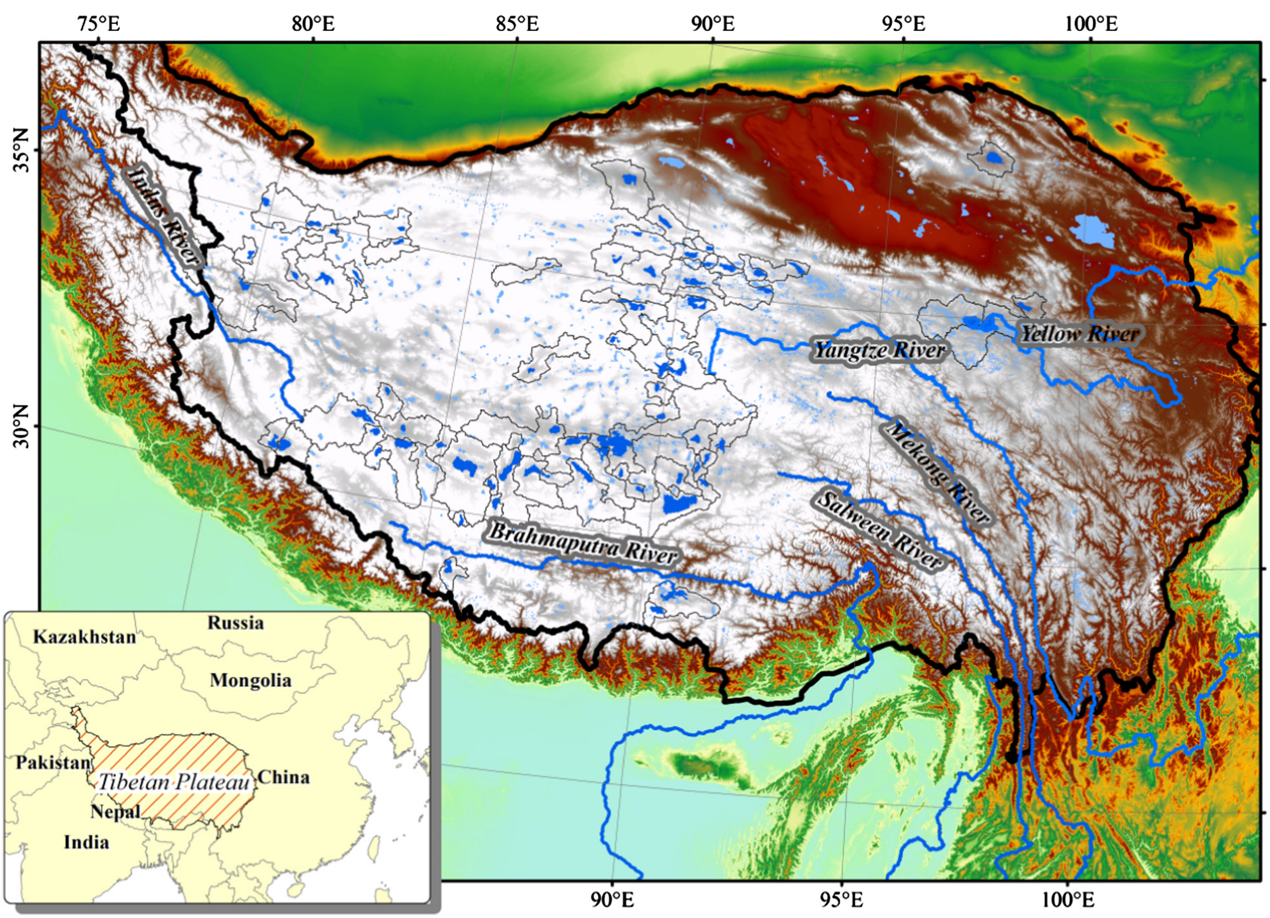

Fig. 1. Topographic map of the Tibetan Plateau and distribution of large rivers and lakes (studied lakes are shown in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)