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Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data

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ABSTRACT

Estimation of the water storage changes in the lakes of the Tibetan Plateau (TP) is essential for an accurate evaluation of climate change in this alpine region and its impact on the surrounding hydrologic environment. Because of the remoteness and poor accessibility of these alpine lakes, and a lack of lake bathymetric data, estimating their mass budget over the TP poses a considerable challenge. However, the integration of optical remote sensing images, satellite altimetry data, and gravimetry data makes it possible to monitor the overall variations in lake water storage in this extensive region. The ICESat/GLAS altimetry data used in this study reveal that most of the lakes in the TP showed a significant upward tendency (0.2–0.6 m/year) in water level between 2003 and 2009, particularly those lakes that are supplied with a large proportion of glacial meltwater. A series of lake area data derived from Landsat MSS/TM/ETM + imagery over the past four decades indicate that during the 1970–1990 period most of the lakes experienced severe shrinkage, with only some of those in central and western Tibet undergoing expansion. During the 1990–2011 period, in contrast, the majority of the lakes on the TP displayed a remarkably expansion tendency. The total lake area increased from 35,638.11 km^2 in the early 1970s to 41,938.66 km^2 in 2011. Based on the statistical relationships between the extent of the lake surface area and lake water levels from 2003 to 2009, an empirical model for each of the region's 30 lakes is established to estimate the lake water level from the corresponding area data, thereby reconstructing time series of lake level data for each lake from the 1970s to 2011. Based on time series of lake area and water level data, a time series of lake water volume is also reconstructed. The results show that total lake water storage increased by 92.43 km^3 between the early 1970s and 2011, with lakes with an area larger than 100 km^2 accounting for 77.21% of the total lake water volume budget. Moreover, the GRACE signals confirm a similar spatial pattern in water mass changes, i.e., a significantly positive water mass balance in the north and center of the TP and mass loss in southeastern Tibet and along the Himalayas. The water mass budget (6.81 km^3/year) derived from satellite gravimetry signals in the Chiangtang Plateau are in good agreement with the estimated rising rate of 6.79 km^3/year of lake water storage in this region based on the empirical model developed in this study. The mechanism of lake water storage changes is discussed and analyzed with reference to previous studies.

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1. Introduction

The Tibetan Plateau (TP), known as the "Water Tower of Asia" and "The Third Pole," is highly relevant to global climate dynamics and the Asian monsoon system (Krause et al., 2010). There is a large number of alpine lakes on the TP, with the total lake surface area surpassing 44,990 km^2 (Jiang & Huang, 2004). As the alpine hydrologic environment has been minimally disturbed by human activities, such as agricultural settlements and irrigation, it has become an important indicator of climate change. In the past few decades, climate change, characterized by a rapidly rising temperature, changing precipitation patterns, and evapotranspiration, has had a substantial impact on the water storage of the inland lakes spread over the TP. In particular, the rapidly rising temperature has accelerated the retreat of glaciers and permafrost thawing, which have become the predominant inflow sources for many expanding lakes (Yao et al., 2007; Ye et al., 2007; Zhu et al., 2010). Therefore, accurate estimation of the seasonal and interannual water storage changes in these alpine lakes is not only of great importance to furthering our understanding of their responses to climate change, but is also crucial for the effective modeling of the TP's hydrological and ecological processes (Birkett, 2000; Deniz & Yidiz, 2007; Medina et al., 2008; Mercier et al., 2002).

A small number of typical lakes have been investigated in terms of their surface extent using medium- and high-resolution optical satellite images. For instance, Wang et al. (2007) adopted aerial photos and Landsat and CBERS imagery to investigate fluctuations in the typical

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lakes of the TP between 1969 and 2001. Bian et al. (2009) and Meng et al. (2011) monitored the stable expansion process of the Siling Co in central Tibet, and Kropáček et al. (2011), Phan et al. (2012), and G. Q. Zhang et al. (2011a, 2011b) reported lake level changes derived from satellite altimetry. These studies indicate that lakes with an inflow of glacial meltwater tend to expand rapidly, whereas those that are supplemented primarily by rainfall runoff are generally stable or even shrinking. However, most studies of inland alpine lakes have focused on the qualitative detection and analysis of variations in either lake surface area or water level over the past several decades (Liu et al., 2009; Wang et al., 2007; Ye et al., 2007, 2008), which is insufficient to accurately express the water balance of lake basins in response to climate change. Furthermore, because of the remoteness and inaccessibility of the lakes on the TP, and the high cost of research in the region, direct hydrologic observations or measurements, including of water volume, have been limited to the few lake basins with traditional water observation stations, such as Lake Qinghai (Ding & Liu, 1995; Li et al., 2005), Namco Lake (B. Zhang et al., 2011), Yamdrok Lake (Bian et al., 2009), and Zabuye Salt Lake (Qi & Zheng, 2006). To date, there have been no estimations of total water volume or mass changes in all lakes across the plateau owing to a lack of direct and comprehensive observations of water storage.

In this study, we first analyze the extent of and elevation changes in typical TP lakes using data derived from optical and satellite altimetry images, respectively. We then establish the statistical relationship between the surface area and water level of each lake to reconstruct time series of water level data based on lake area data derived from optical satellite images over a longer time scale. Furthermore, for the first time, we estimate time-series lake water storage by combining time-series area and water level data, and analyze the changes therein. Lastly, we use Gravity Recovery and Climate Experiment (GRACE) data to estimate the mass change in water storage over the plateau, and compare these estimations with the results of empirically modeled lake water storage changes. The remainder of this paper is organized as follows. Section 2 introduces the TP's alpine lakes and hydrological environment. Section 3 describes the datasets and methodology used to estimate the lake level, surface extent, and lake water storage changes. In Section 4, we present the lake change results derived from multi-mission satellites, including variations in the water level of typical lakes from satellite altimetry, lake surface extent changes from the 1970s to 2011 from Landsat imagery, water storage variations estimated by empirical models, and time-series of mass changes from GRACE satellite gravimetry. The spatial and temporal heterogeneity of hydrologic environment changes and their relationship with climate change are discussed in Section 5, and our conclusions are presented in Section 6.

2. Study area

The TP, located in central Asia, is Earth's highest and most extensive highland, with an average elevation exceeding 4000 m (Fig. 1). There are more than 1,500 lakes on the plateau, 312, 104, 7, and 3 of which cover surface areas larger than 10 km^2, 100 km^2, 500 km^2, and 1,000 km^2, respectively. As a whole, the TP's lakes account for 49% of the total lake area of China (Bian et al., 2006). In summer, the plateau's climate is influenced by the currents of tropospheric tropical easterlies, subtropical westerlies, stratospheric easterlies, and the southwestern monsoon from the Indian Ocean (Liu et al., 2008), which results in precipitation being concentrated in the June to September period. In winter, the climate is dominated by cold and dry westerlies, including polar region westerlies, tropospheric subtropical westerlies, and stratospheric westerlies. Hence, most of the TP's alpine lakes expand with the supplement of rainfall runoff and glacial meltwater in summer and autumn, freeze in winter, and then thaw completely in May. Because of the broad spatial extension and strong topographic effect of the area's many huge mountain ranges, the overall climate of the plateau can be divided into several sub-climate zones, the lakes in which exhibit different responses to climate change.

3. Materials and methodology

3.1. Materials

3.1.1. ICESat satellite altimetry data

In this study, Ice, Cloud, and land Elevation Satellite (ICESat) data were used to estimate the water level fluctuations of alpine lakes. The primary objective of the ICESat mission is to measure changes in the elevation of the Greenland and Antarctic ice sheets and that of polar sea ice (Kwok et al., 2004; Xie et al., 2011; Zwally et al., 2008). Numerous studies have shown this dataset to be useful in measurements of land surface area, atmosphere and cloud height, vegetation canopy

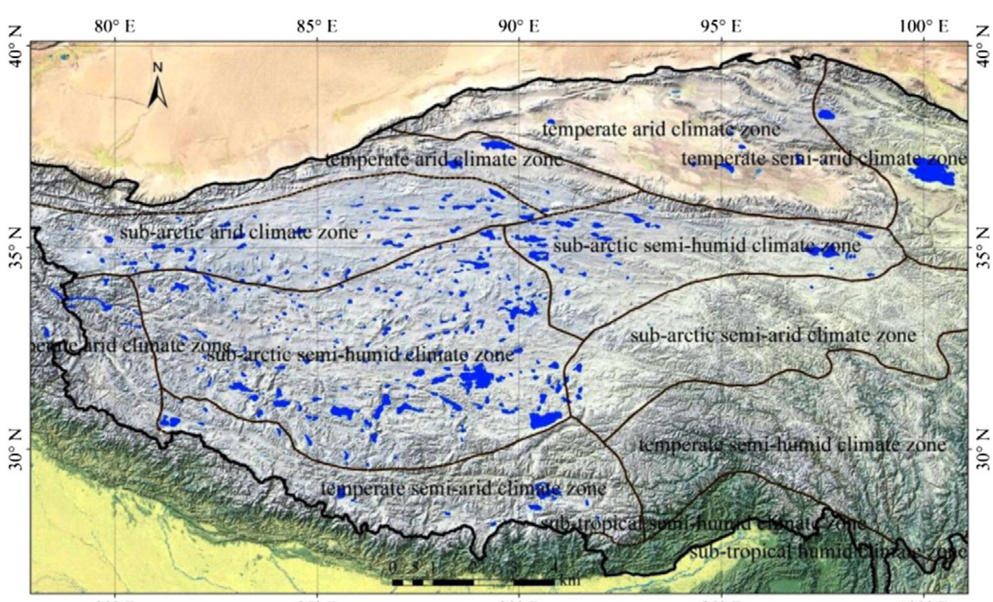

Fig. 1. Alpine lake distribution and climatic characteristics of the Tibetan Plateau.

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