Journal of Hydrology 514 (2014) 131–144

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts

Chunqiao Song [a,d,*], Bo Huang [a,b,*], Linghong Ke [c], Keith S Richards [d]

[a] Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin 999077, Hong Kong
[b] Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Shatin 999077, Hong Kong
[c] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon 999077, Hong Kong
[d] Department of Geography, University of Cambridge, CB2 3EN Cambridge, United Kingdom

ARTICLE INFO

Article history:
Received 24 September 2013
Received in revised form 8 April 2014
Accepted 8 April 2014
Available online 19 April 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Fritz Stauffer, Associate Editor

Keywords:
Tibetan Plateau
Lake
Water level
Satellite altimetry
ICESat
GRACE

SUMMARY

Using ICESat laser altimetry data, we examine seasonal and abrupt changes in the water level of 105 closed lakes on the Tibetan Plateau (TP) from 2003 to 2009. The cluster analysis method is applied to categorize different temporal evolution patterns of lake level, and the links between abrupt lake-level variations of the different clusters in specific seasons and key climatic variables during 2003–2009 based on 12 weather stations are further analyzed. The results show that seasonal lake-level variations were featured by strong spatio-temporal heterogeneity. Most lakes, especially in south Tibet, the central and northeastern Tibetan Plateau, showed large water-level increases (0.307 ± 0.301 m/year) in warm seasons (March–October), while showed declines or minor fluctuations (-0.091 ± 0.202 m/year) in cold seasons (November–February). Many small lakes in the Changtang Plateau and northern TP showed negative water budgets in warm seasons due to low precipitation and strong evaporation, but positive water budgets depending on seasonal snow meltwater supply in cold seasons. These lakes can be partitioned into eight clusters according to the common characteristics of seasonal and consistent abrupt lake-level variations. Lakes of Clusters 4 and 5 are not analyzed in detail because of their scattered distributions. The abrupt lake-level rises or declines for Clusters 1, 2, 3, 7 were inferred to be closely associated with dramatic changes in precipitation and evaporation. For example, most lakes in Cluster 1 experienced the substantial water-level rises (~0.99 m on average) in the warm season of 2005, which were largely attributable to the high precipitation and low evaporation in this season. The abrupt changes of water level for lakes in Clusters 6 and 8 (in the Changtang Plateau and northern TP) were probably associated with more snow meltwater supply. Time series of GRACE-observed terrestrial water storage changes confirm that the abrupt lake-level changes in specific seasons are associated with abnormal hydro-climatological conditions. Besides, the limitations of spatial pattern analysis of lake variations classification based on cluster analysis and the possible primary causes of lake level fluctuations are discussed.

1. Introduction

Climate change and variability imposes important influences on the terrestrial water resources of the earth. As lakes are the primary water reservoirs on the land, monitoring lake water dynamics and understanding how climate affects lakes are essential for managing water resources and related ecosystem services (Bracht-Flyr et al., 2013; Wang et al., 2013). The Tibetan Plateau (TP) in central Asia is well known as the earth's 'Third Pole' and the 'Asian Water Tower' (Yanai et al., 1992). This region contains thousands of lakes and many mountain glaciers and is also the origin of several large Asian rivers, such as the Yangtze, Yellow River, Salween and Mekong, which supply more than one billion people of China and other downstream countries in south-east Asia (Immerzeel et al., 2010). During recent decades, climatic changes have transformed the cryosphere and hydrologic environment substantially on the TP (Kang et al., 2010; Palazzi et al., 2013; Song et al., 2014b; Yao et al., 2007, 2012; Ye et al., 2007).

Numerous prior studies monitored changes in lake area on the TP using optical remote sensing images (Bian et al., 2006; Meng et al., 2012; Wu and Zhu, 2008; Ye et al., 2008, 2007), with a focus on some of larger lakes (such as Namco, Silingco, Lake Qinghai) and

* Corresponding authors at: Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin 999077, Hong Kong. Tel.: +852 39436536.

E-mail addresses: songcq@cuhk.edu.hk (C. Song), bohuang@cuhk.edu.hk (B. Huang).

http://dx.doi.org/10.1016/j.jhydrol.2014.04.018
0022-1694/

analysis on the relationships between lake expansion and glacier retreating. As the water level provides more sensitive and accurate measurements of lake dynamics, water level changes in lakes on the TP have been monitored based on traditional gauge data (Bian et al., 2009; Meng et al., 2012; Qi and Zheng, 2006) or satellite altimetry data, for instance, Kropáček et al. (2012), Phan et al. (2012a), Song et al. (2013, 2014a), Wang et al. (2013) and Zhang et al. (2011a,b) applied time-series satellite altimetry data to detect lake level changes on the TP. These studies paid more attention to investigate annual change trends of lake level over the plateau. There are few studies on examining the abrupt and seasonal lake level variations and identifying spatial and temporal consistency of different lakes over the plateau. Besides, the relationship between lake level variations and climatic forces keeps still unclear. At present, the increased meltwater supply from mountain glaciers was generally considered to be the primary factor causing most lakes to expand based on concurrent trends of lake growth and temperature increase. However, as reported in Phan et al. (2013), there may be more than half of Tibetan lakes (~900 lakes examined) that are not linked to glaciers within watersheds. Thus, it is questionable whether glacier meltwater is the main driving factor of lake growth over the plateau.

In this study we first extract lake level data during 2003–2009 based on the ICESat (the Ice, Cloud, and Land Elevation Satellite) altimetry. As the temporal coverage of less than seven-year is not robust to monitor long-term tendencies of lake levels, the seasonal and abrupt changes of lake level are examined in detail. The cluster analysis method is further used to distinguish different styles of temporal evolution of lake level variations across the plateau so that the common marked characteristics of water-level changes of lake groups can be identified. Then, we try to explore the links between abrupt water-level changes for different clusters of lakes and anomalies of climatological conditions in warm and cold seasons. Due to the sparse distribution of meteorological stations and lack of hydrologic observations, time-series terrestrial water storage changes of lake basins derived from satellite gravimetry data are further analyzed to identify whether the years or seasons of abnormal changes in hydro-climatological conditions such as high precipitation or high temperature induced glacier melting, correspond to the singularities in lake level time series.

2. Study area

The TP is located in high Asia (25° 59′–40° 29′ N, 73° 27′–104° 30′ E). It is the highest and most extensive highland on Earth with an average elevation exceeding 4000 m, surrounded by many huge Asian mountain ranges (Fig. 1). There are more than 1500 lakes on the plateau, 312, 104, 7 and 3 of which are larger than 10 km^2, 100 km^2, 500 km^2 and 1000 km^2, respectively. The lake area of the TP accounts for 49% of the total lake area of China (Ma et al., 2010). In summer, several regional or large-scale atmospheric circulations including the Indian summer monsoon and the East Asian Summer Monsoon bring most of the precipitation to the plateau. In winter, the climate is dominated by cold and dry westerlies (Yao et al., 2012). Hence, most closed lakes experience expansion in summer and autumn, supplemented by rainfall runoff and glacial meltwater. Lakes generally begin to freeze in winter and do not completely thaw until April or May of the next year. Due to the broad spatial extent and strong topographical effect of the high mountain ranges, the climate over the study area is characterized by large spatial heterogeneity. Thus, lakes in different geographical areas show different responses to the climate variability.

3. Data and methods

3.1. Study data

3.1.1. ICESat altimetry data to extract lake water level data

In this paper, ICESat altimetry data were used to derive time-series water level variations of lakes on the TP. It can provide global elevation measurements of flat surface with the vertical accuracy of several or ten more centimeters (Urban et al., 2008; Zhang et al., 2013; Zwally et al., 2002). The data set has been widely used for measuring atmosphere and cloud height, vegetation canopy height, and inland lake and river water levels (Schutz et al., 2005; Urban et al., 2008; Zwally et al., 2002). Although some studies have pointed out that different weather conditions, such as air pressure changes, stormy waves may cause some deviations in lake level measurement, and also that the varying signal penetration depths into lake water or ice during freezing and thawing periods, may lead to some bias or anomalies (Phan et al., 2012a; Urban et al., 2008). Many earlier studies have evaluated the good performances of ICESat altimetric data for measuring lakes on the TP by comparing with water level data from hydrological station observation and radar altimetry to (Phan et al., 2012a; Wang et al., 2013; Zhang et al., 2011b). Due to the lack of gauge-based water level data, in this paper, three lakes (Silingco, Namco, and Lake Qinghai) were selected as examples, and the lake surface extents interpreted from Landsat images are compared with water level variation from the ICESat estimates. As shown in Fig. 2, it suggests that the variations of water level and lake area show a good agreement, and both can depict the intra-annual and inter-annual variability of selected lakes very well. The correlation coefficients between lake area and water level time series for three lakes are more than 0.85.

NASA's National Snow and Ice Data Center (NSIDC) provides all ICESat's L2 Global Land Surface Altimetry Data (GLA14), which contain corrected surface elevations based on one of the two implemented re-tracking approaches, called 'alternative parameterization', which is tuned to capture the last reflection of the signal. All ICESat/GLA14 Release-33 data covering the TP from 2003 to 2009 were downloaded and processed. With the GLAS Visualizer and NSIDC GLAS Altimetry elevation extractor Tool (NGAT), the time-series elevation data, together with latitude, longitude and geoid information, were extracted from GLAS14 altimetry products. Lakes were selected, that have an area greater than 10 km^2 and appear in the ICESat data for at least 5 years. Given these requirements, water level changes of 105 closed lakes were processed and analyzed as shown below.

3.1.2. Meteorological data

Weather stations are sparsely distributed across the TP, especially in the western plateau. Through the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), we obtained yearly and monthly meteorological data from 12 stations close to lakes (shown in Fig. 1), including air temperature (*T*), maximum and minimum *T*, precipitation (*P*), the number of rainfall days, sunshine duration, wind velocity, actual vapor pressure, and relative humidity. Since the pan evaporation data cannot be directly acquired, we applied the FAO Penman–Monteith model (Allen et al., 1998; Monteith, 1965) to estimate monthly potential evapotranspiration (ET). The value of the reference evapotranspiration calculated with mean monthly weather data is comparable with the monthly composite value of the daily ET values calculated with daily average weather data for that month (Allen et al., 1998). The snow depth data applied in this study were derived from three passive microwave sensors: SMMR, SSM/I and AMSR-E, provided by the Environmental & Ecological Science Data Center for West