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Climate change driven water budget dynamics of a Tibetan inland lake

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ABSTRACT

Understanding the hydrologic processes of inland lake basins in the Tibetan Plateau (TP) could provide insights into the responses of Tibetan lake dynamics to climate change. An efficient approach for this purpose is to represent complex hydrologic behaviors of such Tibetan lake watersheds with plausible hydrologic models. In this study, water level fluctuations of Lake Nam Co, an inland lake in the central TP, were investigated using a lumped lake-watershed model. The degree-day factor method was introduced to improve the model applicability in glacier-covered basins. The model simulated the hydrologic processes as well as the lake water budget. Remote sensing images (Landsat MSS, TM, ETM+ and OLI) from 1972 to 2015 were used to identify the glacier and lake boundaries. Multisource climate data (e.g., ground point observation, 0.25° gridded APHRODITE and TRMM 3B42 v7 precipitation products) were used to drive the hydrologic model at a monthly time step. Results of trend analysis showed that basin-wide annual air temperature increased by the rate 0.04 °C/yr from 1961 to 2015. Mean annual precipitation slowly increased from 1961 to the mid-1990s, and then rapidly increased from the late-1990s to the mid-2000s, and finally obviously decreased after the mid-2000s. As a response to climate change, glaciers decreased by 62.69 km^2 (29%) and lake area increased by 91.83 km^2 (4.7%) from 1972 to 2015. The analysis of lake water budget suggested that, the total basin runoff and on-lake precipitation contributed 1.36 km^3/yr (66%) and 0.7 km^3/yr (34%), respectively, to mean annual water gain of the lake. Glacier runoff was 14% of the basin runoff and 10% of the total water gain of the lake. The percentages of lake evaporation, water seepage and water surplus were 65%, 20% and 15%, respectively. Lake level increased with the rate of 0.14 m/yr for the study period 1961–2015. It could be concluded that precipitation was the dominant controlling factor for the different magnitudes of lake level rising rates of 0.10, 0.41 and 0.06 m/yr for the periods of 1961–1998, 1999–2008 and 2009–2015, respectively.

1. Introduction

Hydrologic cycles of most inland lake watersheds on the Tibetan Plateau (TP) are not closely monitored because of the lack of observation abilities in the harsh environment (Lei et al., 2014; Li et al., 2014a). Understanding the hydrologic processes of lake watersheds in the TP could provide insights into the responses of Tibetan lake dynamics to climate change, because the levels and areas of closed lakes are significant indicators of climate change (Zhang et al., 2011a). The increasing precipitation and warming climate in the TP interfere with the seasonal regulation of mountainous glacier and snowpack to regional water resources (Immerzeel et al., 2010; Li et al., 2015; Li et al., 2014b). Changes in glacier and seasonal snowmelt considerably influence the lake surface area and hydrochemical conditions in the TP, which produces a very close connection among glacier retreatment, lake dynamics and climate change (Wu et al., 2014). Therefore, investigation of hydrologic processes in the plateau's lake watershed could play an important role in Tibetan environment research.

To understand the hydrologic processes and lake dynamics of lake watersheds in the TP, some research efforts have been made recently to investigating the dynamics of lake area, water level and water storage (Kropáček et al., 2012; Wang et al., 2009; Zhang et al., 2011a; Zhang et al., 2013b) and to simulate the long-term water budget of these lakes (Krause et al., 2010; Wu et al., 2014). Remote sensing is an effective method for investigating lake dynamics in the TP (Gao et al., 2013; Zhang et al., 2011a). Based on Landsat TM and CBERS, Bianduo et al. (2009) found that four small lakes near Lake Nam Co expanded from 1975 to 2005, especially during the period of 2000–2005. With the water balance analysis method, Morrill (2004) investigated the changes of Lake Ahung Co in the TP and found that, an increase in summer monsoon precipitation combined with decreased lake evaporation and basin evapotranspiration (ET) are responsible for the lake level rise during the period of 1995–2001. Li et al. (2007) also used water balance models to investigate the dynamics of the largest

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saline lake, Lake Qinghai, whose level decreased by 3.35 m between 1959 and 2000. Results of this study suggested that the drying and warming climate were the main contribution to the lake level decrease, whereas human activities only contributed about 1%. Based on ICESat altimetry data, Zhang et al. (2011b) and Phan et al. (2012a) analyzed the lake level changes on the TP, and found that the trend of area averaged lake level from 2003 to 2009 was upward with a rate of 0.2 m/yr. However, the trend in space was different that most of the southern Tibetan lakes had a downward lake level change while most lakes on the central TP showed a coherent lake growth (Phan et al., 2012b). Using multi-mission satellite data, the analysis time of lake change could be back to the early 1970s (Kropáček et al., 2012; Lei et al., 2013; Song et al., 2013; Song et al., 2015a; Wan et al., 2014; Zhang et al., 2014). The previous studies showed that most of Tibetan lakes are in growth between the early 1970s and the late 2000s (e.g., Zhang et al., 2014). In addition, both remote sensing data and field survey confirmed that, for most lakes on the central TP, lake expansion was relatively slow during the early 1970s and 1999, but has accelerated rapidly since the late 1990s (Lei et al., 2014; Lei et al., 2013). Song et al. (2014) found that the lake growth could be attributed to the large water level increases in warm seasons for most closed lakes on the TP. The analysis of lake dynamics and climate change in recent decades suggested that, the increased precipitation and runoff (including the increased glacier meltwater), and decreased potential evaporation are the driving forces of lake expansion in the central TP (Lei et al., 2013; Liao et al., 2012). Lake Nam Co, which is the third largest saline lake in the TP, has recently attracted many studies on water cycle (Krause et al., 2010; Wu et al., 2014; Zhang et al., 2011a; Zhou et al., 2013; Zhu et al., 2010). Krause et al. (2010) simulated the hydrologic process of the Nam Co basin with downscaled ECHAM5 data, and suggested that glacier melt was an important contribution to the water level rise of Lake Nam Co. Zhou et al. (2013) estimated the water budget of Lake Nam Co for the period of 2007–2011 based on observations at Nam Co station and three river basins that drains to the lake. The lake water gain was greater than lake evaporation, which indicated a water imbalance. It was concluded that there was significant subsurface water seepage from the lake because there is no surface outflow. Additionally, Wu et al. (2014) used a dynamical monthly water balance model to simulate the long-term (1980–2010) water level changes in Lake Nam Co, and their results also supported that there was water seepage in this inland lake. Chen et al. (2014) showed that, as a response of the warmer and wetter climate of the Nam Co basin, the increasing rate of 3.8 km^2/yr for lake level from 2000 to 2011 was much higher than the rate of 0.87 km^2/yr from 1977 to 1999. Song et al. (2015b) found that, based on the ICESat-derived lake levels, the lake growth trend of Nam Co slowed down in the period of 2009–2013 compared to the phase 2003–2008, and further suggested that the wetting climate of the Nam Co basin began to crease or even reverse since 2006 may be an important reason.

This paper aims to examine the water budget of Lake Nam Co (central TP) for the study period 1961–2015 with a relatively more accurate precipitation input and a surface- and subsurface-coupled water balance model compared to some previous studies. The previous studies as mentioned above have showed the different slopes of lake growth of Nam Co, including the break points in the late 1990s and the late 2000s. Thus, a relatively long analysis period could help to better understand the lake dynamics and water balance of Nam Co basin. In this paper, a monthly lake-watershed model was improved to simulate glacier/snow melt, the hydrologic process and the changes in the lake level/area/water storage of Lake Nam Co. The long-term water budget simulation of Lake Nam Co from 1961 to 2015 was compared to lake level data derived from remote sensing data.

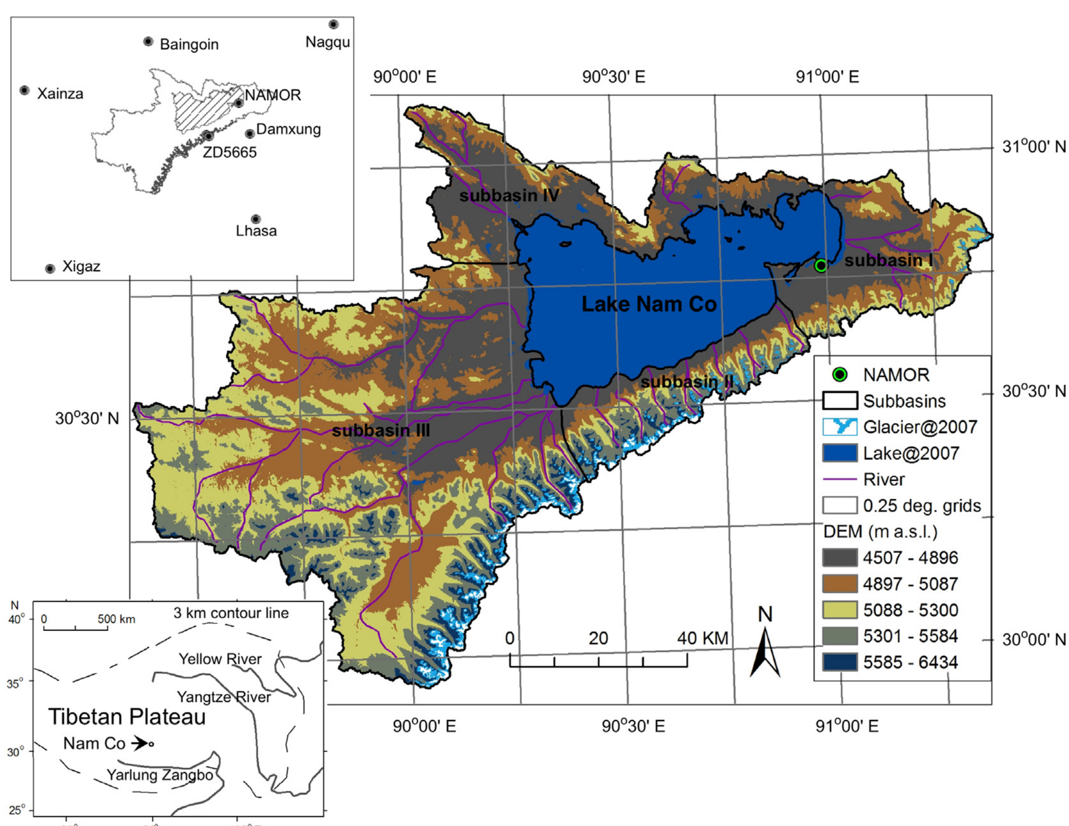

Fig. 1. Location of Nam Co basin and the distribution of glaciers and stations.