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COMMENTARY

Spatial asymmetry of lake level changes across the Tibetan Plateau over the past multi-timescales

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The Tibetan Plateau (TP), often referred to as the 'Third Pole', encompasses half of China's total lake area. In recent decades, lakes across the TP have undergone remarkable expansions under warming and wetting climate conditions. This rapid lake expansion, particularly in the central-southern TP, has profoundly impacted the regional eco-environment. For instance, lake growth has altered geomorphology, reduced salinity, inundated grasslands, and disrupted local infrastructure and communities. Furthermore, hydrological reorganization within lake catchments, typically occurring over centuries to millennia, has accelerated dramatically in the last 20 years due to this rapid expansion.[1] A notable case is the overflow of Zonag Lake in 2011, which triggered outbursts in downstream lakes, severely impacting the regional ecosystem and damaging critical infrastructure such as the Qinghai-Xizang highway and railway. Similarly, the overflow of Selin Co in September 2023 disrupted provincial road S208, posing significant risks to infrastructure and local eco-environment .

Fluctuations in the water levels of closed lakes serve as valuable indicators of long-term changes in moisture availability and the strength of major atmospheric systems such as the Indian summer monsoon (ISM), East Asian summer monsoon (EASM), and the Westerlies (Figure 1). Historical changes in lake levels provide essential insights into atmospheric circulation patterns across various geological periods, offering crucial context for anticipating how these lakes respond to future climate change. As a result, the dynamics of lakes on the TP have garnered considerable attentions within the broader discourse on global climate change.

HETEROGENEOUS CHANGES IN LAKE LEVELS ACROSS MULTIPLE TIMESCALES

Satellite radar and laser altimetry data have been widely utilized to map water bodies, monitor water level changes, and analyze volume variations on interannual to decadal scales since the 1970s. Over this period, the water budgets of closed lakes across the TP have exhibited pronounced temporal variability and spatial heterogeneity.[2] Many lakes in the central and northern TP have experienced rising water levels, while those along the Himalayan Mountains and in the southern TP have shown relative stability or slight declines.

For longer timescales, paleoshoreline sediments provide robust evidence of past lake expansions and water-level changes. Well-preserved shorelines, some up to ~200 m above modern lake levels, surround many lakes on the TP and provide direct evidence of historical changes in lake volume. This geographic heterogeneity in lake level changes is evident not only on decadal timescales but also on centennial and millennial scales. For instance, shoreline reconstructions from Qinghai Lake indicate low water levels during the early Holocene, followed by highstands around 6-5 ka (ka=thousands of years before present), with lake-levels approximately 9 meters higher than present. This pattern with early Holocene low lake levels and mid-to-late Holocene peaks has also been observed in other lakes across the northeastern TP. In contrast, many lakes in the southern and central TP experienced their maximum expansions during the early Holocene (10-7 ka), followed by a gradual regression (Figure 1).

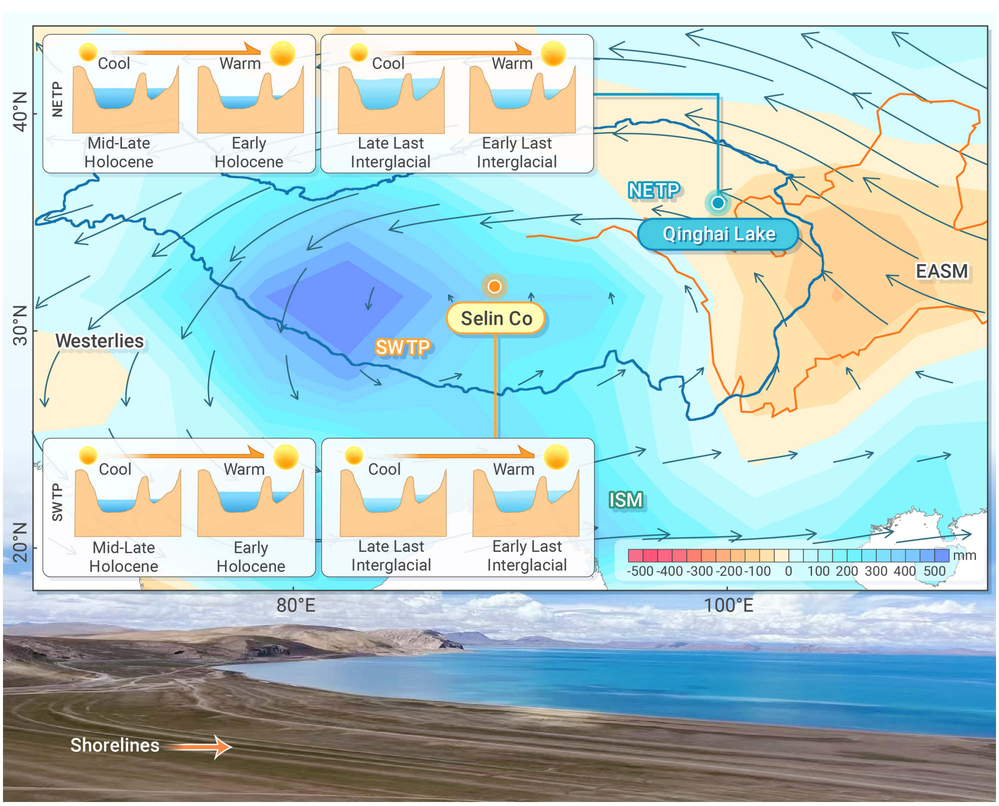

Figure 1. Spatial asymmetry of lake level changes across the TP over the past multi-timescales The upper illustrates main atmospheric circulations and summer precipitation anomalies (June-July-August) on the TP during the warm period relative to the cool period. Arrows show JJA wind vectors during the warm period relative to the cool period. The schematic diagrams represent spatial asymmetry of lake expansions (e.g., Qinghai Lake and Selin Co) across the TP on multiple timescales. The lower panel shows photograph of shoreline groups developed on the south of Selin Co. NETP = northeastern TP; SWTP = southwestern TP; EASM = East Asian summer monsoon; ISM = Indian summer monsoon.

DRIVERS FOR SPATIAL ASYMMETRY OF LAKE-LEVEL CHANGES

Precipitation likely plays a key role in influencing lake level fluctuations on the TP. Climatic conditions over the TP are primarily influenced by large-scale atmospheric circulation, particularly the interaction between the mid-latitude Westerlies and the low-latitude ISM.[2] Recent studies have increasingly highlighted the influence of anthropogenic aerosols emissions on atmospheric circulation over the TP on interdecadal timescale. Differences in aerosol emissions between Europe and Asia have reduced the meridional temperature gradient in Asia, weakening the westerly jet stream. This has caused anomalous ascending air over the northern TP and descending air over the southern TP, forming a north-south dipole pattern in interdecadal precipitation variations.[5] Recent findings from the two largest lakes on the TP have elucidated a possible mechanism behind out-of-phase hydroclimatic changes between the northern and southern plateau during the two recent interglacial periods (Figure 1).[3] During these periods, higher summer insolation increased atmospheric humidity, wind circulation, and land-sea thermal gradients, ultimately strengthening summer monsoons. Specifically, mean surface temperature increased more significantly over warmer land on the TP than that over colder ocean in the tropical Indian Ocean, leading to a stronger ISM circulation over the southern TP and bringing more precipitation into the southern TP. In contrast, an anomalous downward motion prevailed on the northern plateau during this interval. The enhancing descending motion could depress the formation of precipitation and cause relatively dry conditions in the northern TP. During the low insolation, the Westerlies shifted southward and intensified over the northern TP. The main summer precipitation belt in the northern TP consistently stayed south of the Westerlies, in response to intense monsoon convection. Hence, the southern migration of the Westerlies resulted in enhanced precipitation over the northern TP by enhancing regional convection. Overall, strengthened ISM drove increased precipitation and higher lake-levels in the central and southern plateau, while the enhanced and southward-shifting Westerlies contributed to wetter conditions in the northern TP on the millennial and orbital timescales.

Future Directions

Understanding climate change on a centennial scale is critical for its profound societal, economic, and environmental impacts, and it can provide reference data for future projections. Although paleoshorelines provide direct evidence of past hydrological changes, they often have low resolution and may be discontinuous due to preservation issues. Furthermore, there is a scarcity of interdecadal to centennial-scale shoreline studies. Recently, several water-level proxies have been developed and applied to TP lakes. Proxies such as archaeal glycerol dialkyl tetraethers, grain size, pollen, ostracod assemblages, and leaf wax long-chain n-alkanes offer higher resolution and more continuous deposition records. Combining shoreline data with these proxies from sediment cores could provide more detailed insights into past lake level fluctuations.

Given the significant impact of lake expansion on local communities, infrastructure, and ecological security, understanding future changes in surface area and water storage over the TP is essential. Currently, lake models are frequently employed to predict future lake level fluctuations, often focusing on specific large individual lakes or specific case studies. These models primarily consider hydroclimatic factors such as precipitation, evapotranspiration, and wind speed, but they may overlook catchment characteristics like vegetation type and soil composition. Meanwhile, machine learning approaches have gained traction for predicting lake variations based on climatic and hydrological variables. Therefore, integrating these two methods-physical models and machine learning —could enhance the accuracy of future lake level projections.

Since lake levels are closely tied to changes in precipitation, understanding precipitation patterns is key to predicting lake fluctuations. Projections indicate an overall increase in precipitation across the entire TP, including in the southern regions, which showed the decreasing precipitation trend observed over the past 40 years.[5] However, paleoclimate studies reveal that out-of-phase precipitation patterns have historically persisted across the TP, suggesting that different regions may experience distinct trends.[3] These findings suggest the complexity and regional heterogeneity in the response of the TP to climate change, highlighting the need to consider local factors and dynamics when predicting future precipitation patterns. Additionally, the driving factors behind early Holocene precipitation patterns differ from those shaping current conditions. During the early Holocene, precipitation increases were driven by high solar insolation, while today, rising CO_2 levels are the primary factor. These different forces —solar insolation and CO_2—likely contribute to the spatial and temporal variability in precipitation across the TP.

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DECLARATION OF INTERESTS

The authors declare no competing interests.