



Short Communication

The advanced South Asian monsoon onset accelerates lake expansion over the Tibetan Plateau

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The rapid expansion of lake area in the Tibetan Plateau (TP) has attracted a considerable amount of concern in recent decades. Limited evidence has suggested that climate warming and the cryosphere change are the most prominent contributors to lake expansion. The widespread changes in lake area result from a combination of increased precipitation, melting glaciers, permafrost degradation, and changes in other components of terrestrial water. However, debate remains as to whether melting glaciers or increased precipitation have a greater impact on lake expansion. Varied topography and limited datasets hinder the ability to perform extensive research, and there is currently no definitive conclusion on the issue. Recently, some studies revealed that increased net precipitation could be responsible for the majority of water supplying the Inner Tibetan Plateau (ITP) lake volume, whereas melting glaciers play a secondary role in lake expansion [1]. The remarkable impacts of precipitation on lake variations indicate that climate change-induced precipitation may be dominant in lake expansion, thus raising the question as to which time of year contributes the most increased precipitation and how lakes have responded to climate change in recent decades [1,2].

It is evident that monsoon circulation provides favorable water vapor conditions for rainfall on the TP [3]. The plateau acts as a sensible heat-driven air pump, bringing abundant water vapor from the ocean to the continent's interior [4]. Previous studies have identified a significant increase in the amount of TP precipitation in May, which might be attributed to the advanced South Asian summer monsoon (SAM) onset [5]. Subsequently, some evidence suggests that the SAM, originating from different marginal seas, has an individual impact on low-troposphere circulation, and can

cause differences in precipitation [6]. Although it is well understood that atmospheric internal variability and external forcing can exert great influences on the SAM onset [7–9], there is little knowledge regarding whether the advanced SAM onset can contribute to changes in lake volume throughout the TP, and then exert great impacts on lake area variations. Although there are substantial efforts devoted to exploring the phenomenon and causes of lake variations, scant studies have investigated the climate dynamic mechanism associated with lake expansion on the TP. In this study, we investigate the source of the increased precipitation and examine the impact of the advanced SAM onset on lake variations.

Climate change is considered to be one of the major threats to lakes [10], but empirical knowledge regarding the TP's lake responses remains fragmented. To address this issue, the distribution uniformity of the ITP's lake area variations is clarified, and the results indicate that the ITP has experienced rapid lake expansion in recent decades. However, in the southern TP, some lakes exhibit the opposite condition, which is characterized by reduction in lake size (Fig. 1a). Great heterogeneity in lake area trends might be related to the diverse climatic and geomorphic features across the TP. However, the total lake area is characterized by a significant decadal variation, with a slight descending trend before the mid-late 1990s and then a rapid increasing period. Previous studies have highlighted the remarkable impacts of the change in annual precipitation on lake variations throughout the TP [1,11]. However, changes on an annual scale can obscure some important information, such that the contributions of seasonal or monthly precipitation cannot be accurately quantified. Figure 1b presents the proportion of climatological monthly accumulated precipitation to the total annual amount, as well as the monthly trends in precipitation. It is evident that summer precipitation contributes the

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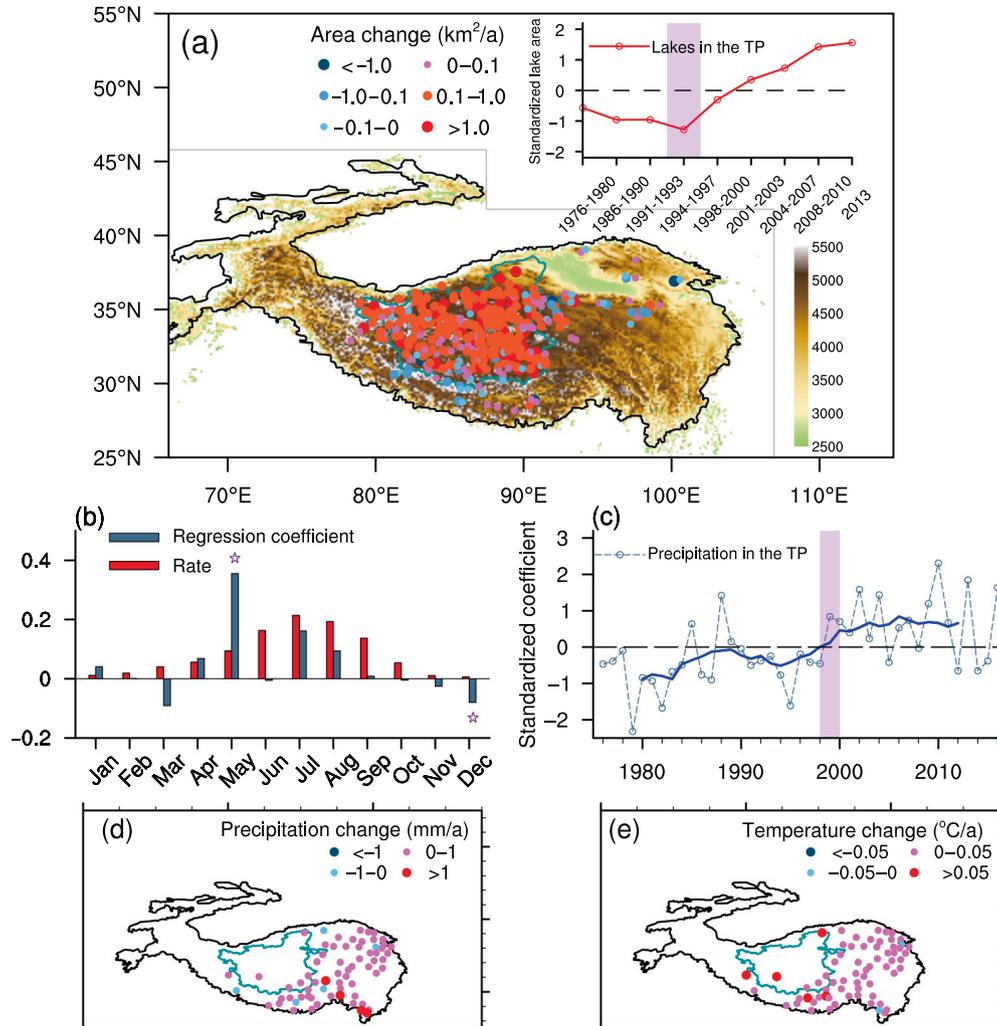


Fig. 1. The changing characteristics of lake area and meteorological variables over the Tibetan Plateau (TP). (a) The spatial pattern of linear trends of 364 lakes with area surface covering more than 10 km². The diagram in the top right corner depicts the temporal variation of total lake area averaged over 364 lakes. The shading plot depicts the elevation of the TP. (b) The histogram indicates the proportion of climatological monthly accumulated precipitation to the annual amount (red), and the linear trend of monthly accumulated precipitation (blue) during the period of 1976–2016. The five-pointed star indicates the linear trend is significant at the 99% confidence level. (c) Time series of the accumulated precipitation in May, and the blue curve indicates the result of a nine-point sliding average. The spatial distribution of linear trends of (d) accumulated precipitation and (e) surface air temperature (SST) in May over the TP using *in-situ* daily meteorological observation, respectively.

majority of the TP's total annual precipitation (57%); however, the most significant increase in precipitation primarily occurs in May. Furthermore, it is evident that precipitation in May also exhibits a significant interdecadal increasing characteristic, which is in accordance with the decadal transition of lake areas in approximately the late 1990s (Fig. 1c and Figs. S1–S3 online). In addition, the changes in precipitation and SAT in May are rather spatially homogeneous, and most meteorological sites present an increasing trend. A rising SAT can accelerate ice melt and then promote the water cycle. Consequently, the wetting and greening plateau in the early summer exerts great influences on the surrounding hydrological cycle and ecological system [5], which eventually may lead to changes in the cumulative lake area.

We further reexamined the overall mass balance and lake volume budget across the ITP. The high proportion of lake volume to terrestrial water and the remarkable contribution of net increased precipitation to lake volume (Fig. S4 online) indicate that precipitation may be dominant in modulating the lake volume variations, and glacier meltwater acts as an additional lake water source [1]. The quantitative estimation of the lake water budget provides clear evidence to distinguish the contribution of increased

precipitation from glaciers and permafrost. Nevertheless, scant research has been performed to investigate the causal attribution of increased annual precipitation, which may be the result of seasonal or monthly precipitation changes. Fig. S4 (online) also shows the proportion of increased precipitation in May to the annual increased precipitation throughout the TP from 1976 to 2016. The pattern agrees with the aforementioned assumption, presenting direct evidence to illustrate that the increased precipitation in May contributes a large proportion (approximately 50%) of the annual increased precipitation across the eastern ITP. Apart from the arid zone with rare precipitation on the western TP, the highest precipitation rates on the TP are cases where monsoon precipitation prevails. It should be noted that the majority of large lakes across the TP are located in the eastern ITP. The abnormal increment of precipitation across the southeastern TP and eastern ITP is responsible for the endorheic lake expansion. Thus, the change in precipitation in May is a vital indicator of lake expansion on the TP.

The onset of the South Asian summer monsoon exerts great influences on the total precipitation throughout India and the TP [4]. The abundant precipitation due to the monsoon circulation

provides an adequate supply of terrestrial water. Previous studies have indicated that the SAM onset has advanced remarkably because of the change in heat contrast between the continent and tropical Indian Ocean [7]. The interdecadal variation of the SAM onset may be attributed to Pacific sea surface temperature (SST) variations and the increased presence of anthropogenic aerosols [8,9]. All of the aforementioned analyses lead to speculation as to whether the increased precipitation over the TP is related to the advanced SAM onset. Fig. 2 presents the time series of three individual monsoon onset indices obtained using the U850 average over the Arabian Sea (Ars; 5°–15°N, 50°–75°E), Bay of Bengal (Bob; 5°–15°N, 80°–100°E) and Indian Ocean (Ind; 5°–15°N, 50°–100°E) [8]. All three indices exhibit the characteristics of significant decadal shift, which is in accordance with the decadal trend of the TP precipitation in May. High consistency with the SAM and TP precipitation, especially for the Arabian Sea SAM onset, whose correlation coefficient reaches 0.68 at the 0.01 significance level, indicates that the advanced SAM onset may have contributed the most to the increased precipitation across the TP in recent decades.

Fig. S5 (online) presents the regression patterns of atmospheric circulation anomalies with regard to the SAM onset index over each individual marginal sea. The anomalous cyclonic circulation dominates the entirety of the Arabian Sea and Bay of Bengal, and then directs the cross-equatorial flows towards India and the southeastern TP. Although similar atmospheric circulation fields exist during each individual marginal sea monsoon onset, visible

differences can nevertheless be found in the lower and middle troposphere. Specifically, an anomalous cyclonic circulation extends eastward during the Bengal monsoon circulation onset, which is in accordance with the atmospheric pattern at the 500 hPa geopotential fields (Fig. S6 online). Consequently, the cross-equatorial flows seem to promote zonal propagation, whereas during the Arabian and Indian Ocean monsoon onset, and a warm and moist flow is then transported northward along the eastern side of the cyclone to the TP. Simultaneously, the water vapor flux transportation also exhibits a spatial pattern similar to the circulation in the lower troposphere. The enhanced northward airflow strengthens the ascending motion due to topographic lifting. Correspondingly, a strong ascending motion associated with the SAM onset occurs across the southern TP (averaged by the winds over 80°–100°E). Thus, the enhanced water vapor transportation, accompanied by the significant ascending motion during the early monsoon circulation, is favorable to increased precipitation, which is also evident in Fig. S5 (online), as validated by CRU datasets (Fig. S6 online).

In conclusion, minimally affected by humans, the TP is one of the most sensitive regions to climate change, and the plateau lakes have been regarded as direct and robust indicators of climate warming [12–15]. This study investigates the possible impact of increased precipitation in May on the variations in TP lake areas, and further explores the response to an advanced SAM onset. The high consistency of decadal shifts as a result of variances in the SAM onset, TP precipitation and lake areas indicates that an advanced SAM onset would play an important role in modulating lake variations. Enhanced water vapor transportation and strengthened ascending motion in May over the southern TP results in increased precipitation. Consequently, increased precipitation in May explains approximately 50% of the annual precipitation increase across the eastern ITP, resulting in an ample water supply increase and subsequent lake expansion. Additionally, the summer monsoon onset over the Arabian Sea produces more precipitation compared to the Bengal monsoon, and may be a potential predictor for lake area variations throughout the TP.

Conflict of interest

The authors declare that they have no conflict of interest.

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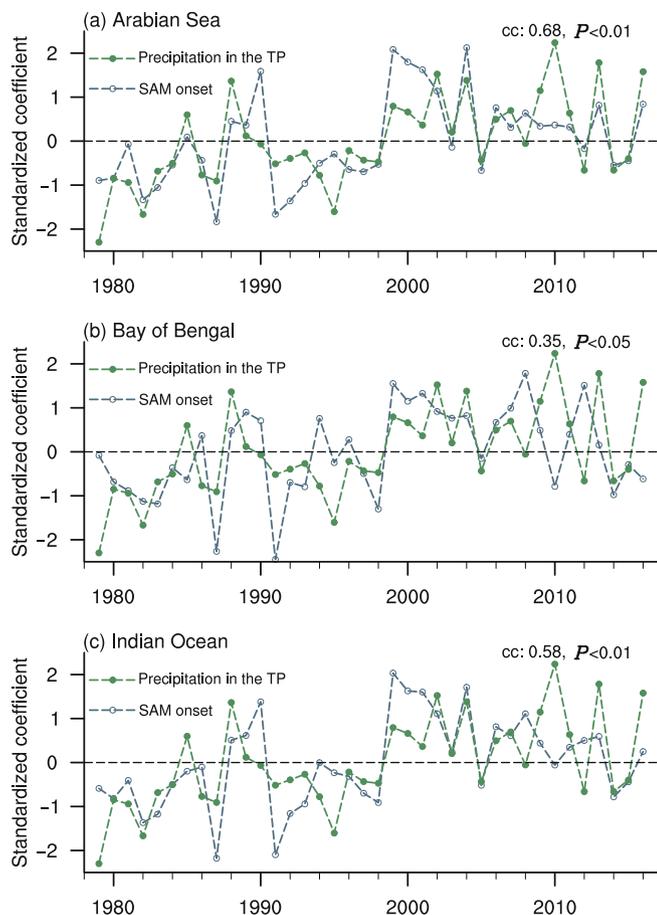


Fig. 2. (Color online) Time series of TP precipitation in May (average by monthly precipitation observed from 66 meteorological stations) and three individual monsoon onset indices obtained by using U850 averaged over each marginal sea. (a) Arabian Sea (Ars; 5°–15°N, 50°–75°E); (b) Bay of Bengal (Bob; 5°–15°N, 80°–100°E); (c) Indian Ocean (Ind; 5°–15°N, 50°–100°E).

Author contributions

Y. Liu and H. Chen designed research; Y. Liu performed research; Y. Liu and G. Zhang analyzed data; and Y. Liu, H. Chen, G. Zhang, J. Sun, and H. Wang wrote the paper.

Appendix A. Supplementary material

Supplementary material to this article can be found online at <https://doi.org/10.1016/j.scib.2019.08.011>.

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