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Short Communication

Strengthened Indian summer monsoon brought more rainfall to the western Tibetan Plateau during the early Holocene

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The Tibetan Plateau (TP) is considered to be the "Third Pole" of the earth because of its huge area (5 million km^2), its high elevation (>4000 m average altitude), and the presence of more than 100,000 km^2 of glaciers in this northern mid-latitude region. As a result of these factors, the TP influences both short-term regional and large-scale atmospheric circulation and long-term climate change [1]. More than ten large rivers originate from the TP and constitute an essential water supply for nearly one sixth of the global population. Hence the TP is often referred to as "the water tower of Asia" [1,2]. Variations of summer rainfall over the TP greatly impact inland closed lakes, river discharge, glaciers, plant phenology, and natural hazards [2].

As the precipitation over the TP peaks in summer, it exhibits a southeast-northwest decreasing gradient [3,4] (Fig. 1), and it has often been assumed this moisture is carried by the Indian summer monsoon (ISM) circulation and spreads into the interior TP via a moisture corridor that extends from east to west along the Yarlung Zangbo River [2]. However, this assumption has yet to be tested. If the hypothesis is correct, it would result in enhanced precipitation in the eastern and central TP relative to the western TP due to the orographic effects of the high elevations in those areas.

Recently, Conroy and Overpeck [5] used empirical orthogonal function analysis to divide the modern climate in the TP into three regions with distinct precipitation variability (Fig. 1). All three regions have summer season precipitation maxima. The north sub-region (region ②) is likely to have a westerly moisture source, the west sub-region (region ③) precipitation is correlated with the ISM, and the east sub-region (region ①) precipitation is negatively correlated with precipitation of the Western North Pacific monsoon, exhibits a feature of East Asian summer monsoon (EASM) [5]. Some think the precipitation in the east sub-region (region ①) may be jointly influenced by the ISM and EASM [3]. Satellite observations indicate moisture flow between the Arabian Sea and the western TP [6]. Warm and wet airflow moves north and upward along the Indus River valley and is divided into two branches caused by the terrain bifurcation. The southern branch spreads into the western TP and transports moisture to the arid area of the western TP, while the northern branch reaches the West Kunlun Mountains and falls as snow [6]. Dong et al. [2,7] report an "up-and-over" moisture transport route from central-eastern India (CEI) to the southwestern TP (SWTP) in spite of the high Himalayas topographic separation. Abundant moisture is lifted up by convective storms over CEI and the Himalayan foothills and then swept into the SWTP by favorable mid-tropospheric flows, rather than by inefficient upslope flow over the Himalayas [7]. More than 60% of summer rainfall over the SWTP is directly related to monsoon low pressure systems (LPSs) via this "up-and-over" transport pattern [7]. LPSs are influential in extending the northern boundary of the ISM system across the Himalayas into the interior of the SWTP. From this it is evident that the major modern summer moisture transport pathways are different for the western and eastern TP, even though they both have peak precipitation during the summer season. Whether these differences in moisture sources and transport pathways between eastern and western TP persisted during the Holocene remains to be answered. Further exploration

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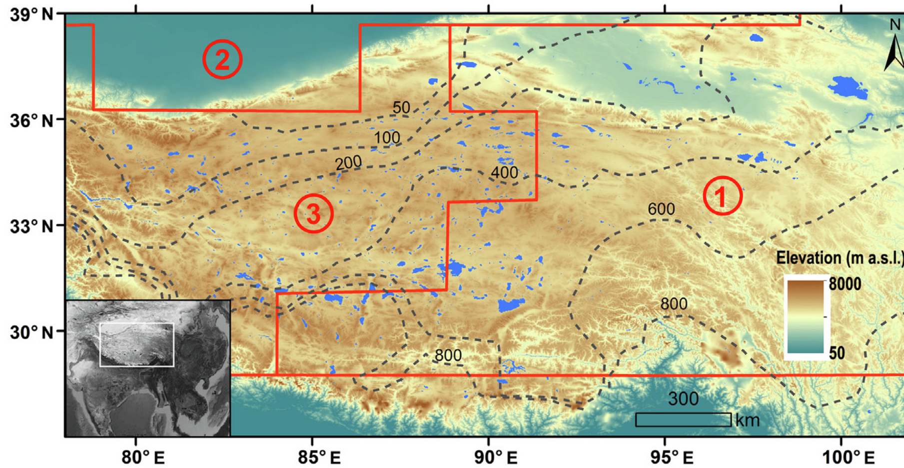

Fig. 1. Modern closed-basin lakes on the Tibetan Plateau (blue patches). Regional Tibetan Plateau precipitation zones defined by an empirical orthogonal function are shown by thick red lines (modified from Conroy and Overpeck [5]). Dashed black lines are modern annual total precipitation (mm) contours obtained from a monthly 1900–2014 global gridded precipitation data set [4].

is needed because it is critical in understanding and interpreting the asynchronous evolution of the lakes and diverging palaeoenvironmental proxies derived from lacustrine sediments between these two parts of the TP.

There are hundreds of closed-basin lakes with conspicuous palaeoshorelines scattered over the central and western TP which indicate past high lake stands [3,8]. These closed-basin lake systems provide valuable palaeohydrologic information because lake surface areas (or lake levels) were mainly constrained by the trade-off between precipitation run-off and evaporation. Palaeoshorelines are thus good indicators of past lake area (or lake level) variations and are useful proxies of the magnitude of past precipitation change [3]. Meltwater from glaciers may have flowed into some of the plateau lakes during the last deglaciation, but to what extent this contributed to Holocene lake level highstands remains unclear. In general, a consensus exists that Holocene lake-level fluctuations for closed lakes on the TP were primarily controlled by the Asian summer monsoon [3,8–10]. Several recent studies which have dated palaeoshorelines found that the highest lake levels in the central and western TP occurred during the early Holocene (between 9.5 and 8 ka) [3,8,9]. Although lake level fluctuations can reflect palaeo-rainfall variations over the TP, Hudson and Quade [3] propose that the lake area/basin area ratio, hereafter *Aw* (*Aw* = lake area: total basin area), is a better indicator of rainfall change because it normalizes lake systems according to size. Using correlation analysis, they argue that glacial meltwater, differing evaporation rates, and differing lake area/lake volume ratios resulted in very limited impacts on early Holocene lake expansions. By comparing the palaeo-*Aw* ratio to the modern *Aw* ratio, they then attribute the larger lake expansions in the western TP to increased monsoon rainfall there during the early Holocene and to a strengthened ISM [3].

We analyzed 101 lakes across the TP for their highest Holocene lake levels and highstand *Aw* to modern *Aw* ratios using the methods of Hudson and Quade [3] and Liu et al. [8]. The spatial distribution of these lakes is presented using ArcGIS 10.0 software. Both variables (lake levels above present and highstand *Aw* to modern *Aw* ratios for the highest Holocene lake level stage) decrease toward the eastern TP with a tongue-like shape (Fig. 2a, b), implying increased precipitation associated with an enhanced ISM diminished toward the east. A previous study has already demonstrated that the highstand *Aw* during the early Holocene is 3.2–8.6 times that of the modern *Aw* over the western TP, but was reduced to 1.1–2.4 times over the eastern part of TP [3]. This west-east Palaeo-*Aw* to modern *Aw* contrast potentially implies that increased monsoonal rainfall is the main contributor to the differential lake expansions and that this regional precipitation gradient is the primary cause of the west-east asymmetry of the lake expansions. The enhanced lake expansion region (tongue-shaped area in Fig. 2a and b) is roughly similar in extent to the modern ISM influenced region over the western TP (region ③ in Fig. 1), indicating that these divisions in the modern climate were an enduring feature over the plateau during the Holocene epoch.

We further simulated the early Holocene summer rainfall changes over TP and its surrounding areas using the Kiel Climate Model (KCM) [11], a non-flux-corrected coupled general circulation model. This climate simulation holds the greenhouse gas concentrations constant at pre-industrial levels, but adjusts orbital precession during the period from 9.5 to 0 ka with a ten times acceleration scheme. Detailed descriptions of the KCM model can be found in Jin et al. [11]. Our simulation result shows that summer rainfall increased more in the western TP than the east, and also indicates that summer rainfall over the western and central TP derived from the western and southwestern plateau boundary (Fig. 2c). Summer rainfall over the western TP (west of ~88° E) increased by more than 80% during the early Holocene (9.5–8.5 ka) relative to the present, featuring a tongue-like shape that pinched out toward the east (Fig. 2c). Regions with the greatest increase in precipitation overlap with regions that have higher early Holocene lake levels and higher palaeo-*Aw* to modern *Aw* ratio values (Fig. 2). Modeled percentage changes in summer rainfall verify the assertion that the ratio of palaeo-*Aw* to modern *Aw* is actually a reflection of summer rainfall variability. More summer rainfall fell over the western TP during the early Holocene, and the amplification of rainfall decreased eastward, causing lakes in the western TP to expand more drastically than those in the eastern TP relative to their present size.

During the early Holocene, northern hemisphere summer solar insolation increased, causing warmer northern middle and high latitudes and a northward migration of the Intertropical Convergence Zone (ITCZ) toward 30° N (its present summer position is located at ~20° N in the Indian subcontinent) [11]. Hence, the rain belts (i.e., the ITCZ) reached the southern and western flanks of the TP during the early Holocene. The Himalayas are sufficiently high

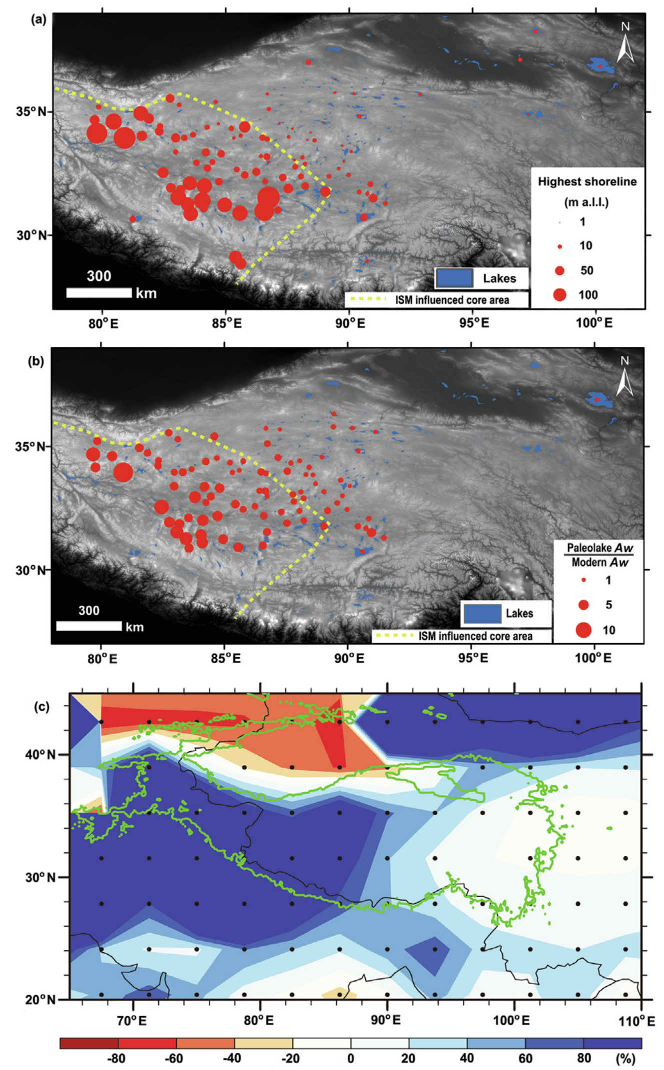

Fig. 2. Early Holocene highest shorelines above present lake levels (a.l.l.) (a) and Palaeolake *Aw* (lake area: total basin area) versus modern *Aw* ratios of Holocene highest lake level stage (b) for lakes in Tibetan Plateau. (c) Percentage changes of summer precipitation (%) during the early Holocene (9.5–8.5 ka) relative to the late Holocene (1–0 ka) over the Tibetan Plateau and its surrounding areas from KCM simulations.

that condensation removes most of the moisture within the upslope flow, leaving little moisture available for precipitation in the TP interior [2,7]. Thus, moisture may have been transported to the TP from the west and southwest sides through the "up-and-over" moisture route during the early Holocene when the ISM was enhanced and there may have been more active LPSs (Fig. 2c). Zhang and Jin [12] proposed that north-south migrations of the South Asian High in response to orbital precession-driven insolation changes can partly explain variations in the spatial distribution of summer precipitation in Asia. A northward displacement of the South Asian High during the early Holocene was associated with enhanced precipitation in northern East Asia, northern India, Mongolia and the western TP, but reduced precipitation in Central and southwestern China, eastern TP and the Indochina Peninsula [12]. Hence, although the ITCZ migrated northward during the early Holocene, the accompanied northward displacement of the South Asian High generated anomalous cyclones over the Arabian Sea. This simultaneously produced anomalous easterly winds in the northern middle and low latitudes. This resulted in increased rainfall over northern India, but a decline in water vapor input from the Bay of Bengal, leading to a greater increase in precipitation for the western TP rather than the eastern TP. A recent study proposed that during the early middle Holocene (~7.5 ka ago) monsoonal moisture did not penetrate onto the plateau significantly more than at present, but that rainfall events were more frequent and more intense, with the average annual precipitation in western TP (Bangong Lake) likely several times higher than modern [13]. This study is consistent with shoreline-based precipitation variability estimations and our KCM model simulation results. In the future, more lacustrine sediment-based investigations and better climate simulations are needed to parse the long-term east-west asymmetry of monsoon rainfall over the TP, and to investigate the potential influence of variations in this long-term rainfall pattern for future precipitation oscillations over the TP in a warming climate.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

X.J. Liu designed the research and wrote the original draft. X.J. Zhang and L.Y. Jin conducted the KCM model data analysis and prepared Fig. 2c, and also involved in writing the original draft. Y.L. Lin and F.H. Chen contributed to the interpretation of results and the writing of the original draft.

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