Special Topic: The Tibetan Plateau

Multispherical interactions and their effects on the Tibetan Plateau’s earth system: a review of the recent researches

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ABSTRACT

The Tibetan Plateau (TP) is a regional Earth system showing very strong interactions among its lithosphere, hydrosphere, cryosphere, biosphere, atmosphere, and anthroposphere. These interactions manifest TP’s impact on surrounding regions and reflect TP’s response to the global change. Quantifying the multispherical interactions is critically important to understand the TP environment. Our recent years researches including the ongoing program entitled ‘Tibetan Multi-Spheres Interactions and Their Resource-Environment Significance (TIMI)’, the completed program entitled ‘Paleo-Altitudes of Tibetan Plateau and Environment (PATE)’, as well as the other relating projects have focused on multidisciplinary research approaches and emphasized on three major pathways: Eurasia-Indian plates collision on deep-Earth dynamics, uplift impact on Earth’s mantle–crust dynamics, and contemporary interface on land surface and atmospheric dynamics. Our researches have taken in situ measurement as priority and developed several platforms of data acquisition and analysis, including the platforms of water-phase transformations, and ecosystem observations. Our field investigations have been conducted to obtain data about stratum, paleontology, paleoenvironment, genetic differentiation of animals and plants. We have developed conceptual and mathematical models for crust uplift formation, paleoclimate, glacial melt, water–air interface flux, vegetation climate, and soil erosion. We have also assessed the anthropogenic impacts on environment. Our researches have achieved new and reliable redating of the mantle–crust interaction and initial formation of the TP, found the interaction between tectonics and uplift of the TP and resultant paleoaltitude acting as a spreading source; discovered the interaction between the westerlies and Indian monsoon acting as a control chain that dominates the TP’s contemporary environment. The scientific results can play fundamental roles in supporting the TP’s resource exploration and societal sustainable development.

Keywords: Tibetan Plateau, multispherical interactions, effects

INTRODUCTION

The Tibetan Plateau (TP) is the world’s largest and highest Cenozoic plateau. Its Cenozoic magmatic rocks were produced by the interaction between mantle and crust on the TP after the onset of the collision of the Indian and Eurasian plates [1,2]. TP surface uplift processes differ from classic plate tectonic processes [3]. The TP’s ongoing surface uplift has changed, and continues to change Asian topographical features and river systems, which themselves play an important role in global climate and environmental change [2,4–6]. The TP’s unique land surface processes have responded sensitively to global climate change. Its processes have been accompanied by an integrated interaction between the Earth’s surfaces (upper crust, atmosphere,
Figure 1. The TP is the only region on the earth where the most intensive multispherical interactions are taking place, impacting on the largest population in the world.

Figure 2. A multidisciplinary research approach emphasizing on three major pathways of the interactions between multispherical interactions on the TP.
interactions and their relevant data and comprehensively review researches of the multispherical interactions of the TP earth system with interdisciplinary approaches in recent years.

**MANTLE–CRUST INTERACTIONS AND THE INITIAL FORMATION OF THE TP**

Based on field and laboratory studies, Kang et al. [7] we proposed that: (i) the Neo-Tethys opened prior to the Middle Triassic and began to be consumed beneath the Lhasa Terrane during the Early Jurassic, causing the formation of porphyry Cu-Au deposits; (ii) the Indian-Eurasian collision occurred between 65 Ma and 62 Ma in the central part of the Yarlung Zangpo Suture Zone (YZSZ) much earlier than the well-accepted '55 Ma' [8] (iii) the transition from oceanic to continental subduction occurred during the Early Tertiary, with the front of the Indian continental lithosphere subducting beneath the southern Qiangtang Plateau in the north of the TP [9,10]; (iv) a slab-tearing and/or breakoff model with different subduction angles vis-à-vis the Indian lithosphere might feasibly explain the north–south rift and the 15–12 Ma porphyry Cu-Au deposits [11]; and (v) the Gangdese magmatic arc attained an elevation of 4500 ± 400 m above sea level (asl) during the India–Eurasia collision [12,13]. Therefore, the TP is a perfect region for the study of multilayer interactions within the lithosphere.

**The seismic structure of the subducted Indian lithospheric slab beneath the Gangdese Arc**

Previous seismological studies have already provided us with a comprehensive map of the subduction of the Indian lithospheric slab beneath Tibet. However, there are some W–E trending differential changes in the subducting direction and the leading position of the Indian lithospheric slab; the details of these changes and their accommodating mechanisms remain unclear. The W–E trending TIBET-31 N linear seismic array deployed in the central Lhasa Block provides us with a good opportunity to trace lateral variations in the geometry and the nature of the underthrusting Indian lithosphere (Fig. 3). In order to enhance lateral resolution and minimize errors in measurement, only the SKS phases triggered by the events with an narrow range of back-azimuths and distances were detected, using three simultaneous measurement-splitting methods. Along the profile, the delay generally increased from east to west between 0.2 and 1.0 s, with its variation correlating spatially with the N–S oriented rifts found in southern Tibet. The SKS wave arrived 1.0–2.0 s later at stations in the eastern part of the profile than in the west. All these first-order features would suggest that the geometry of the underthrusting Indian lithospheric slab in the Himalayan-Tibetan Collision Zone beneath southern Tibet is characterized by systematic lateral variations. Ding et al. [10] thus proposed a slab-tearing and/or breakoff model for the Indian lithosphere, with...
Interaction between crust and mantle beneath the Gangdese Arc

The TP was mainly created by convergence processes involving oceanic lithosphere subduction, followed by continental collision and lithosphere subduction between the Indian and Eurasian continents. However, any understanding of the detailed processes associated with the transition from oceanic to continental lithosphere subduction in the Gangdese of the southern Lhasa Block, southern Tibet, has remained limited. Based on detailed petrological, geochronological and geochemical studies of Late Cretaceous-Early Oligocene (~100–30 Ma) mafic-felsic intrusive rocks in the Lhasa-Nyingchi area immediately north of the YZSZ, a record of the transition from oceanic to continental lithospheric subduction in the southern Lhasa Block has now been well established, thus: (i) 100–70 Ma, the presence of intrusive rocks mainly consisting of subducted oceanic crust-derived adakites and minor subarc mantle-derived gabbros, norites and hornblendites with depleted mantle-like $\varepsilon$Nd(t) values, all of which are devoid of any Indian continental component; (ii) ~62–40 Ma, the presence of intrusive rocks consisting principally of thickened lower crust-derived adakites with slightly positive $\varepsilon$Nd(t) values, and ~62 Ma adakites in the southernmost part of the Lhasa Block containing a minor Indian continental component; and (iii) ~35–30 Ma, the presence of intrusive rocks mainly consisting of subducted continental crust-derived adakites and minor enriched mantle-derived gabbros, all of which exhibit negative $\varepsilon$Nd(t) values and contain Indian continental components. This part of the Gangdese underwent a tectonodynamic transition from oceanic subduction to continental subduction before 35 Ma (Fig. 4) [10].

Plate subduction continuously transports crustal materials with high $\delta^{18}$O values down to the mantle wedge, where mantle peridotites are projected to exhibit $\delta^{18}$O-rich features. Increased $\delta^{18}$O values relative to the upper mantle value have been reported for magmas from some subduction zones. However, peridotites with $\delta^{18}$O values significantly higher than the well-defined upper mantle values have never been observed in modern subduction zones. Here, we present in situ oxygen isotope data from...
olivine crystals found in Sailipu mantle xenoliths from southern Tibet, which were subjected to a long history of Tethyan subduction prior to the India–Eurasia collision. Our data identified for the first time a metasomatized mantle that, interpreted as a subarc lithospheric mantle, shows anomalously enriched oxygen isotopes ($\delta^{18}O = 8.03^{\pm}0.28$‰) (Fig. 5) [15]. Such a $\delta^{18}O$-rich mantle commonly does not contribute significantly to typical island arc basalts. However, partial melting or contamination of such a $\delta^{18}O$-rich mantle may feasibly account for $\delta^{18}O$-rich signatures in arc basalts.

**Figure 5.** Pyroxene $\delta^{18}O$ in Sailipu mantle xenoliths [15].

**Figure 6.** Reconstructions of the Lhasa and Qiangtang terranes on the TP. During the Eocene, the southern margins of the Lhasa Terrane were uplifted to $\sim 4500$ m asl and formed two high mountain ranges (the Qiangtang and Gangdese mountains), with the low-elevation Lunpola-Nima Basin sandwiched between them [12].

**Uplift of the Gangdese**

Paleoelevation reconstruction using oxygen isotopes can make significant contributions toward understanding the Cenozoic uplift of the Himalaya and the TP. Ding et al. [12] presents results on new oxygen and carbon isotopic compositions from well-dated Tertiary paleosols, lacustrine calcareous carbonates, and marls from the Nianbo (60–54 Ma) and Upper Pana formations (51–48 Ma) of the Linzizong Group, in the Linzhou (Penbo) Basin. The sediments of the Nianbo Formation, which are $>180$ m thick, were deposited in alluvial fans, braided rivers, fan deltas and on nearshore to offshore lacustrine settings, whereas those of the Upper Pana Formation are $>100$ m thick and are comprised predominantly of proximal alluvial fan and braided river deposits. Correlations between their lithofacies and stable isotopic compositions suggest that the Basin was principally a hydrologically open environment. It needs to be stressed that the $\delta^{18}O_C$ and $\delta^{13}C_C$ values from the Nianbo and Upper Pana formations have not yet been reset using late-stage diagenesis based on petrographic examination, fossil ostracode oxygen isotopes and stratigraphic tectonic deformation. Paleoelevations were reconstructed using corrected, mostly negative paleosurface water $\delta^{18}O_{paw}$ values. These imply that the Linzhou Basin attained an elevation of $4500 \pm 400$ m asl during the India–Eurasia collision, i.e. it achieved a near present elevation, and may have formed an Andean-type mountain range stretching across the Gangdese prior to that collision. These Gangdese mountains probably maintained a high elevation from at least the Paleocene onward, and could have played a crucial role in climate change in the TP interior during the Early Cenozoic. A paleogeomorphicscenario for Eocene Tibet proposes the existence of two $>4500$ m-high mountain ranges sandwiching a low-elevation basin (Fig. 6) [12,13].

**INTERACTION BETWEEN TECTONICS AND UPLIFT AND THE RESULTANT PALEOELEVATIONS AS MULTISPERHRICAL INTERACTION SPREADERS**

The paleoelevations of the TP

The uplift of the TP was an important factor in global climate change during the Late Cenozoic and strongly influenced the development of the Asian Monsoon system [16–18]. However, there has been much debate about the evolution and processes of TP uplift, especially regarding paleoaltimetry during the geological past.
To date, several Cenozoic basins on the TP have been well studied not only for chronology, paleoenvironment and paleontology, but also for paleoalitimetry. These include the Lunpola, Hoh Xil and Zanda basins.

The Lunpola Basin (Fig. 7) is a Tertiary rift basin situated along the central part of the Bangong–Nujiang Suture Zone (BNSZ). It extends east–west for a distance of ~220 km and has a width of 15–20 km. The present elevations of this basin vary between 4600 and 5040 m asl. For this basin, Rowley and Currie used oxygen-isotope-based estimates of the paleoalitimetry of the Dingqing Formation (Fm) to suggest that the Lunpola Basin reached at least 4000 m asl as early as 35 Ma [19]. However, discovery of the rhinocerotid fossil would suggest that the upper part of the Dingqing Fm was deposited during the Neogene. Adjusting a paleoecosystem reconstruction model to paleotemperatures prevalent during the Early Miocene, it becomes apparent that the Lunpola Basin’s paleoelevation was closer to 3000 m asl during this time [20]. Moreover, by applying the coexistence approach to the fossil pollen records of the Dingqing Fm, after calibrating the effects of temperature difference and the lapse rate, a maximum paleoelevation of 3200 m asl was estimated for the Lunpola Basin during the very Late Oligocene–very Early Miocene [21]. Recently, carbon and hydrogen isotopic compositions of leaf wax n-alkanes have also been used to estimate the paleoelevation of the Lunpola Basin; both proxies from the Dingqing Fm have indicated a paleoelevation of ~3000 m asl. Evidence from mammalian fossils, pollen and the carbon and hydrogen isotopic compositions of leaf wax n-alkanes all suggest that the paleoelevation of central Tibet was ~3000 m asl during the Late Oligocene to Early Miocene, in other words at least 1000–1500 m lower than the paleoelevation proposed by Rowley and Currie [19].

In the Hoh Xil Basin (Fig. 8), barberry (*Berberis*) leaf fossils were discovered in the Early Miocene Wudaoliang Group in northern Tibet at a present elevation of 4611 m asl. Considering the fossil and its nearest living species probably occupied a similar or identical environmental niche, the paleoelevation of the fossils’ locality, corrected for Miocene global temperature differences, is estimated to have been between 1395 and 2931 m asl during the Early Miocene. Our findings therefore contradict hypotheses that suggest that northern Tibet had reached, or exceeded, its present elevation prior to the Miocene; rather, they were <3000 m asl.

The Zanda Basin (Fig. 9) is a Late Cenozoic sedimentary basin. The Sutlej River has incised into the basement, clearly exposing Late Cenozoic strata.
Figure 9. Temporal variations in (a) bulk enamel-$\delta^{13}$C, (b) $\delta^{18}$O values of herbivores and (c) $\delta^{18}$O of local water, estimated from the enamel-$\delta^{18}$O values of large mammals (horses, rhinoceroses, bovidae and cows) in the Zanda Basin since $\sim$4.2 Ma [23].

The Zanda Basin affords an opportunity to evaluate the biological response to environmental change at high elevations. Abundant, well-preserved fossil mammals and fish from an 800 m continuous section of fine- to coarse-grained sediments open a rare window into a past biological world. Wang et al. documented the detailed mammalian biostratigraphy, chronology and paleozoogeography of the area based on Zanda Basin fossil mammals [23] (Fig. 9). Their high-resolution biostratigraphy and biochronology offer, for the first time, independent constraints that both support and modify recent magnetostratigraphic correlations. Using characteristic Pliocene and Pleistocene mammals, particularly the small mammal assemblages in the lower part of the section, and monodactylid Equus from the upper section, they proposed a correlation from C1n to C3An.1r, with an age range of $\sim$400 Ka to 6.4 Ma.

Wang et al. reported the results from isotopic analyses of fauna and of modern herbivores and waters, as well as paleotemperature estimates, from the Zanda Basin [23] (Fig. 9). The $\delta^{13}$C values of enamel samples from modern wild Tibetan asses and domesticated horses, cows and goats in the area were $-9.4%_\circ \pm 1.8%_\circ$, indicating a diet primarily composed of $C_3$ plants consistent with the current dominance of $C_3$ vegetation in the region. The enamel-$\delta^{13}$C values of the fossil horses, rhinoceroses, deer and bovidae were $-9.6%_\circ \pm 0.8%_\circ$, indicating that these ancient mammals, like modern herbivores in the area, also fed primarily on $C_3$ vegetation and lived in an environment dominated by $C_3$ plants. The lack of significant $C_4$ plants in the Basin suggests that the area had reached high elevations ($>2500$ m asl) by at least the mid-Pliocene. Considered in combination with changes in the historic $\delta^{13}$C values of atmospheric CO$_2$, the enamel-$\delta^{13}$C values suggest that the average modern-equivalent $\delta^{13}$C value of $C_3$ vegetation in the Zanda Basin in the mid-Pliocene was $\sim 1%_\circ$–2%$_\circ$ lower than that of the $C_3$ biomass in the Basin today. This would imply a reduction in mean annual precipitation of $\sim$ 200–400 mm in the area since then (assuming that the modern $C_3$ $\delta^{13}$C–precipitation relation is equally applicable to the past). Consistent with this inference from the $\delta^{13}$C data, the enamel-$\delta^{18}$O data show a significant shift to higher values after the mid-Pliocene, which also suggests a shift in climate to much drier conditions after $\sim$4–3 Ma. Paleotemperature estimates derived from a fossil bone-based oxygen isotope temperature proxy as well as the carbonate clumped isotope thermometer for the mid-Pliocene Zanda Basin are higher than the present-day mean annual temperature observed in the area. After accounting for Late Cenozoic global cooling, these paleotemperature estimates suggest that the paleoelevation of the Zanda Basin in the mid-Pliocene was similar to, or slightly less than $\sim$1 km, lower than its present-day elevation, consistent with the inference from the $\delta^{13}$C data.

These new isotopic paleoelevation findings are consistent with previous paleoaltimetry estimates based on the discovery of an ancestral woolly rhinoceros from the Zanda Basin. The suggestion that Coelodonta thibetana was the precursor of its Late Pleistocene megafaunal descendants has stimulated the ‘out of Tibet’ hypothesis, which suggests that the high TP was a Pliocene cradle for Ice Age cold adaptations [24]. Other independent paleoaltimetry evidence for the Zanda Basin has been obtained from a well-preserved skeleton of a 4.6 Ma old three-toed horse (Hipparion zandaense) from the Zanda Basin. Morphological features indicate that the Zanda horse was a cursorial horse that lived in alpine steppe habitats. Because this open landscape would have been situated above the
The uplift of the TP as an originator of cryophilic animals

The high elevation of the Zanda Basin during the Pliocene greatly influenced the ecosystem in this area. Tseng et al. [26] described a new species of the cursorial hyaenid Chasmaporthetes, *C. gangsriensis*, from the Zanda Basin (Fig. 10). Chasmaporthetes *gangsriensis* is smaller than other Plio-Pleistocene Eurasian records of the genus and retains relatively wide premolars that are underdifferentiated in size. Metatarsal and phalangeal elements attributed to *C. gangsriensis* are long and gracile, indicating cursorial abilities typical of Chasmaporthetes. Dated to the Early Pliocene (4.89–4.08 Ma), *C. gangsriensis* is morphologically the most basal Pliocene Chasmaporthetes in China and is consistent with the ‘out of Tibet’ hypothesis for certain Pleistocene megafauna.

Pantherine felids (‘big cats’) include the largest living cats, apex predators in their respective ecosystems. Although the oldest pantherine fossils occur in Africa, molecular phylogenies point to Asia as their origin region. This paradox cannot be reconciled using current knowledge, primarily because early big cat fossils are exceedingly rare and fragmentary. Tseng et al. [27] reported the discovery of a fossil pantherine *Panthera blytheae* from the Zanda Basin, with an age of Late Miocene–Early Pliocene, replacing African records as the oldest pantherine identified (Fig. 11). A ‘total evidence’ phylogenetic analysis of pantherines indicates that the new cat was closely related to the snow leopard, exhibiting intermediate characteristics on the evolutionary line to the largest cats. Historical biogeographic models provide robust support for the Asian origin of pantherines. Combined analyses indicate that 75% of the divergence events in the pantherine lineage extend back to the Miocene, up to 7 Ma earlier than previously estimated. The earlier evolutionary origin of big cats revealed by the new fossils and analyses indicate a close association between TP uplift and the diversification of the earliest living cats.

The ‘Third Pole’ of the world is a fitting metaphor for the Himalaya–TP region, in allusion to its vast
frozen terrain, which rivals the Arctic and Antarctic, but which is located at high elevations and low latitudes. Extant Tibetan and arctic mammals share biological adaptations to freezing temperatures such as long and thick winter fur in the Arctic muskox and Tibetan yak, and, for carnivores, a more predatory niche. In this research program, our scientists identified the first evolutionary link between an Early Pliocene (3.60–5.08 Ma) fox, *Vulpes qiuzhudingi*, from the Himalaya (Zanda Basin) and Kunlun Mountains (Kunlun Pass Basin) and the modern arctic fox *Vulpes lagopus* in the polar region [28]. A highly hypercarnivorous dentition of the new fox bears a striking resemblance to that of *V. lagopus* and substantially predates the previous oldest records of the Arctic fox by 3–4 Ma. The low-latitude, high-elevation TP is separated from the nearest part of the geographical range of the modern Arctic fox by at least 2000 km. The apparent connection between an ancestral high-elevation species and its modern polar descendant is consistent with our ‘out of Tibet’ hypothesis, postulating that high-elevation Tibet was a training ground for cold-environment adaptations well before the start of the Ice Age (Fig. 12).
TP uplift and its far-reaching effects on the environment

A nearly complete and partially articulated skeleton of a primitive haplorhine primate has been identified in the Jingzhou area of Hubei Province [29]. The fossil was dated to the Early Eocene, ∼55 Ma ago. It is the oldest fossil primate of this quality ever recovered. Coupled with a detailed morphological examination using propagation phase contrast X-ray synchrotron microtomography (Fig. 13), our phylogenetic analysis indicated that this fossil is the most basal known member of the tarsiiform clade. In addition to further support for an early dichotomy between the strepsirrhine and haplorhine clades, this new primate, Archicebus achilles (Fig. 14), provides clues about the paleoenvironment of the Jianghan Plain at the Paleocene-Eocene (P/E) boundary, as A. achilles had adapted to live in forests under a warm-temperate climate. This finding further supports the idea that the climate of this area during the P/E boundary period was much warmer than at present.

The Eocene–Oligocene Boundary (EOB; ∼34 Ma) marks one of the largest extinctions of marine invertebrates in the world’s oceans, and of mammalian fauna in Europe and Asia, during the Cenozoic Era. A shift to a cooler climate across this boundary has been suggested as the cause of this extinction in the marine environment, but there is no manifold evidence for a synchronous turnover of flora, fauna and climate at the EOB in a single terrestrial site in Asia to support this hypothesis. New magnetostratigraphic data, together with mammalian fossils, demonstrate that the EOB occurs in Paleogene sediments in the Junggar Basin (Fig. 15; Sun et al., 2014). Mammalian fossils indicate a turnover marked by a change from a large-size perissodactyl-dominant fauna to a small rodent/lagomorph-dominant fauna [30] (Fig. 16). Pollen results reveal an abrupt shift from warm-humid forest in the Late Eocene to dry-temperate forest-steppe in the Early Oligocene. Climatic proxy parameters also indicate climatic cooling at, and after, the end of the Eocene. The results therefore show that climate change forced a turnover of flora and fauna.

The TP uplift and the global climatic cooling on the paleo-environmental shift at EOB have tremendous impact on TP environmental shift during EOB. Although TP uplift was responsible for aridification in central Asia by creating a rain shadow, the timing of the uplift may have been diachronous. The oblique subduction of the Indian lithosphere beneath Tibet accounts for the stepwise rise of different parts of the TP, ranging from 55 Ma in the southwest, to the
latest uplift of its northeastern margin in the past few million years. To date, evidence of a dramatic uplift of Tibet at 34 Ma is lacking. Therefore, there is some uncertainty that the growth of the Plateau could have reached a threshold elevation that could trigger a change in atmospheric circulation and climatic patterns.

**TP uplift and its far-reaching effect on the birth of the Yangtze River**

The development of fluvial systems in East Asia can be closely linked to the evolving topography following the India–Eurasia collision (Fig. 17). Nevertheless, the age of the Yangtze River system
Figure 16. Lithology and magnetostratigraphy of the Keziletuogayi Section. (a) The lithology of the section, (b) Photograph showing the boundary (indicated by the red arrow) between Late Eocene and Early Oligocene strata, (c) Magnetostratigraphy and mammalian fossil zones (A1–3) of the Keziletuogayi Section [30].

has been a debated issue, with estimates ranging from 40 to 45 Ma, down to a more recent initiation during the Pleistocene. To understand better how and when the Yangtze River began to transport sediments from the TP to the eastern lowland basins, and by inference, the establishment of the eastward throughflow river system, Zheng et al. [31] collected basalts interbedded within fluvial sediments from the lower reaches of the Yangtze and dated them using 40Ar/39Ar. Provenance investigations, including mineralogy, geochemistry and detrital zircon U–Pb ages from sand grains within these sediments have suggested that a river containing sediments indistinguishable from those of the modern river was established before ~23 Ma [31]. The argument that the progress of the Yangtze River through the Three Gorges must have postdated 36.5 Ma because of evaporate and lacustrine sedimentation in the Jianghan Basin before that time does not support the existence of a large river with a comparable size to the Yangtze running through the Basin. Zheng et al. [31] therefore propose that the present Yangtze River system formed in response to regional extension throughout eastern China, synchronous with the start of strike–slip tectonism and surface uplift in eastern Tibet, and fed by strengthened rains caused by the newly intensified summer monsoon.
THE CHAIN IMPACTS ON THE TP’S MODERN ENVIRONMENT OF THE INTERACTION BETWEEN THE WESTERLIES AND INDIAN MONSOON

The three modes of interaction between the westerlies and the Indian monsoon

The westerlies and the Indian monsoon are the primary atmospheric circulations impacting climate and environmental change on the TP [32]. Their influence on moisture transportation by these two atmospheric circulations is a key factor for understanding spatial changes in glaciers, lakes and rivers, and an important scientific basis for explaining the implications of ice core, tree ring and lake core studies [33].

The oxygen stable isotope in precipitation (precipitation $\delta^{18}O$) on the TP reveals a close relation with the dominant influence of the westerlies and the Indian monsoon [34–38]. We estimated the spatial and temporal relationships between precipitation $\delta^{18}O$ and the two dominate atmospheric circulations on the TP by analyzing precipitation isotopic data from 24 observation stations (Fig. 18) over ten years, combined with simulations from three high-resolution isotopic GCM models (LMDZiso, REMOiso and ECHAM5iso) and modern meteorological datasets [37]. These investigations found three distinct models (the westerlies model; the transitional model; and the monsoonal model) that characterized by the differently spatial and temporal patterns of precipitation $\delta^{18}O$ and their relations with temperature and precipitation amount (Fig. 19) [37].

Temporally, in the westerlies model domain, the seasonal cycle of precipitation $\delta^{18}O$ is parallel with that of temperature, reaching a maximum in summer and a minimum in winter (Fig. 19a). In the monsoonal model domain, seasonal mean $\delta^{18}O$ is maximum in spring and minimum in summer (Fig. 19g), and the shift of the moisture sources between the Bay of Bengal and the southern Indian Ocean presents the most strongly depleted precipitation $\delta^{18}O$ values in summer. In the transitional model domain, there were no extreme $\delta^{18}O$ values in summer due to the location of the interactive impact region. More significant temperature effect exists when either the westerlies, or the Indian monsoon, were the sole dominant atmospheric process. The lapse rate in the westerlies model domain is larger than that in the monsoonal model domain when the seasonality is considered. The Global Climate Model (GCM) accurately represented the spatial and seasonal patterns of precipitation $\delta^{18}O$, precipitation amount and temperature in the three models (Fig. 19), and they all capture the transformed influence of the westerlies and the Indian monsoon on seasonal precipitation $\delta^{18}O$, further confirm the mechanism that influences of atmospheric circulations on the precipitation $\delta^{18}O$ over the TP [37].

Spatially, the summer (from June to September) southern TP is controlled by the strong southerly and southwesterly winds at 500 hPa south of $30^\circ$N, and gradually weakens from $30^\circ$N to $35^\circ$N, then the westerlies prevail north of $35^\circ$N, together with the gradual decrease of precipitation amount from south to north (Fig. 20a), meanwhile the horizontal water vapor transports via the monsoon flow from the southern Oceans (i.e. the Arabian Sea, the Bay of Bengal and the southern Indian Ocean). However,
the westerlies dominate the moisture transport on the whole TP in winter (from December to February) (Fig. 20b). These seasonal changes are also fingerprinted in precipitation $\delta^{18}$O. Precipitation $\delta^{18}$O clearly increases northward in summer (Fig. 20c), just the reverse in winter (Fig. 20d). This enhances the interaction between the westerlies and the Indian monsoon on the spatial distribution of precipitation $\delta^{18}$O on the TP [37].

The modern impacts on glaciers and lakes of the interaction between the westerlies and Indian monsoon circulations

The weakening Indian monsoon and strengthening westerlies are possibly reducing and increasing precipitation in their respective domains, influencing changes on glaciers and lakes on the TP.

Based on the investigation of the glacier retreat of 82 glaciers, area reduction of 7090 glaciers and mass balance change of 15 glaciers, our study has shown that different atmospheric circulations can influence precipitation spatial patterns, and consequently glaciers and lakes, on the TP. We found three main patterns of glacial change on the TP which corresponded to three types of interaction between the westerlies and the Indian monsoon: greatest glacial retreat along the margins of the southeastern TP where is markedly influenced by the Indian monsoon; less glacial retreat toward which is characterized with the interplay of both the Indian monsoon and the westerlies circulation; but stable, or even increasing, glacial volumes in certain areas in the northwest TP, particularly in the Pamir/West Kunlun region, where the westerlies is dominating (Fig. 22) [33].

One of the TP's most prominent features is the large number and area of inland lakes widely distributed on the TP. The water balance of inland lakes on the TP involves complex hydrological processes; their dynamics over recent decades is a good

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**Figure 18.** Sketch map of locations of monitoring stations and the moisture transport by the westerlies and the Indian monsoon over the TP. Red triangles depict locations of $\delta^{18}$O monitoring stations. 1-Urumqi, 2-Zhangye, 3-Taxkorgen, 4-Delingha, 5-Hetian, 6-Lanzhou, 7-Kabul, 8-Tuotuohe, 9-Yushu, 10-Shiquanhe, 11-Gaize, 12-Nagqu, 13-Yangcun, 14-Bomi, 15-Lulang, 16-Lhasa, 17-Nuxia, 18-Baidi, 19-Larzi, 20-Wengguo, 21-Dingri, 22-Dui, 23-Nyalam, 24-Zhangmu. Up triangles stand for Global Network of Isotopes in Precipitation (GNIP) stations and down triangles stand for our monitoring stations [37].
Figure 19. Seasonal patterns in precipitation $\delta^{18}$O, precipitation amount and temperature from observational data (black), zoomed LMDZiso (red), REMOiso (green) and ECHAM5wiso (blue) in different TP domains. (a) Weighted monthly $\delta^{18}$O (%), (b) precipitation amount (mm/month) and (c) temperature ($^\circ$C) averaged over seven stations in the westerlies domain. (d–f) As a–c, but for the transitional domain, averaged over four stations. (g–i) As a–c but for the monsoonal domain, averaged over 13 stations [37].

Figure 20. Spatial patterns of summer winds (arrows) together with precipitation amount (shading) over the TP and surrounding regions (a) and precipitation $\delta^{18}$O (triangles) at monitoring stations (c). (b) and (d) same as (a) and (c), but stands for winter [37].

indicator of changes in water cycle under rapid global warming. Based on satellite images and extensive field investigations, we demonstrate that closed lakes on the TP interior varied heterogeneously during 1976–1999, but expanded coherently and significantly in both lake area and water depth during 1999–2010 [40]. As shown in Fig. 23, the total lake area of the 99 selected lakes on the TPI decreased slightly by 2.3% from 1976 to 1990, but increased by 5.7% from 1990 to 1999. Since 1999, the selected lakes showed an overall expansion, with a significant increase in total area by 18.2%. The average rate of lake area increase from 1999 to 2010 was about three times that from 1990 to 1999. In the Himalayas region, on the other hand, lakes showed shrinkage trend during the period 1976–2010. Generally, there is a contrast in lake dynamics on the TP interior and Himalayas in the last decades. Therefore, there was a widespread reduction in lake area in the southern Yarlung-Zangbo catchment, but a general expansion of the two on the northern Qiangtang Plateau (Fig. 23).
Figure 21. Comparisons between the environmental proxies of sediment Core NC 08/01 on the central TP for the past 24 ka. There is a clear shift before and after 16.5 ka, indicating a shift in dominance from westerlies to the Indian summer monsoon. Stage II-1 (corresponding to H1) was cold and humid, reflected by lower total organic carbon (TOC), Ca, Artemisia and higher Cyperaceae values. Stage II-2 (corresponding to the B/A interstadial) was warm and humid, reflected by higher TOC, Cyperaceae and lower Ca. Stage II-3 (corresponding to the Younger Dryas event) was cold and dry, reflected by lower TOC, Cyperaceae and higher Artemisia and Ca. Temperature appeared to be warmer during the Early Holocene (Stage III-1), reflected by higher TOC, Fe/Mn and lower Ca [39].

The modern impact on ecosystem of the interaction between the westerlies and Indian monsoon

Phenological data can reveal the response of vegetation growth to climate change. Global warming, and especially the presence of warmer spring water, will continuously advance the green-up date. The TP green-up dates and their relation to vegetation biomass and husbandry production are important topics of research vis-à-vis the agricultural sector. The quality of phenological information obtained from vegetation indices according to remote sensing technology may be questioned because of the presence of a snow cover in early spring; this dispute is continuing.

The increase in spring temperatures was as much as 0.10°C/yr during 2000 and 2011. However, on a regional scale, green-up dates did not significantly change in response to the temperature increase, based on the comparative analyses of four data resources, and on five methods which removed the spring ice cover interference factor (Fig. 24) [41]. Further study showed that the reason for this phenomenon was the mutually counteracting effect of delay in green-up dates on the southwestern Plateau and an advance in green-up dates on the northeast TP [41]. Such spatial variations in green-up dates are consistent with changes in precipitation, suggesting precipitation plays a significant role in regulating spring phenology on the Plateau [42]. Spring precipitation declined in the southwestern area, but increased on the northeastern TP.

In addition to this inconspicuous response of vegetation to temperature change, further analyses of the relations between temperature and vegetation growth in the Northern Hemisphere over the past 30 years illustrate that the positive correlation between temperature and the satellite-derived Normalized Difference Vegetation Index (NDVI) decreased, suggesting that the acceleration in vegetation growth caused by global warming is growing weaker [44]. This trend was obvious in the temperate and arctic zones of the Northern Hemisphere (Fig. 25). In temperate regions, the decline in the correlation between vegetation and temperature change was mainly related to increased drought, while plant acclimation to global warming explains...
Figure 22. Spatial and temporal patterns in glacier status on the TP and its surroundings. (a) Glacial retreat for 82 glaciers, (b) area reduction for 7,090 glaciers and (c) mass balance for 15 glaciers. Glaciers are categorized into seven regions and marked clockwise using Roman numerals in a–c. (d) Cumulative mass balance for 11 glaciers, 2006–10. (e) Cumulative mass balance for the three longest glacier mass-balance time series along Transect 1 [33].

the trend in arctic ecosystems. This study implies that there is necessity to modify the traditional view that vegetation growth in the Northern Hemisphere is primarily limited by temperature and that vegetation growth benefits from global warming.

On the other hand, changes in vegetation regulate climate through altering the water cycle and any energy exchanges between the terrestrial ecosystem and the atmosphere. It has been pointed out that in the Arctic rising temperatures enhance vegetation activity, which, in turn, leads to a positive feedback on temperature due to a reduced albedo. Based on a combination of in situ observations, satellite-measured vegetation greenness and gridded evapotranspiration estimates, Shen et al. [45] found that in contrast to arctic regions, increased vegetation activity on the TP tended to attenuate daytime warming (Fig. 26). Further analysis suggests that this negative feedback is mainly related to the enhanced ET resulting from the positive trend of vegetation greenness. These results provide a new perspective for the understanding of land-surface biophysical feedbacks on climate in this region.

CONCLUSIONS

Our researches have focused on the multispherical interactions of the TP earth system and found the key roles of three major pathways including the Eurasia-Indian plates collision linking the deep parts of the earth system, uplift impact linking the uplift and its long-reaching effect, and contemporary interface linking the land surface processes. We have found multilayer interactions of the deep lithosphere within the TP and more reliable redating of the initial formation of the TP, the interaction between tectonics and uplift and resultant paleoaltitude acting as a spreading source biospherically, hydrospherically and atmospherically, such as the pre-Miocene birth of the Yangtze River, the synchronous turnover of flora, fauna, and climate at the
Figure 23. Changes in lake area on the TP interior and Himalayas, 1976–2010 [40].

Figure 24. (a) A schematic diagram indicating that increases in non-growing season NDVI lead to artificial advances in green-up dates. (b) Annual SPOT NDVI curve averaged for the earliest (2000–2), and for the latest (2009–11), three years. (c) As for B, but for MODIS NDVI. (d) Temporal changes in the difference between SPOT and MODIS NDVI between May and April (NDVI May—NDVI Apr) [41,43].
Figure 25. Spatial distribution of the partial correlation coefficient of vegetation productivity and climate. (a) Partial correlation coefficient (RNDVI-GT) between growing season (GS) NDVI (NDVIGS) and GS temperature (GT) and (b) partial correlation coefficient (RNPP-GT) between estimated average GS net primary productivity (NPPGS) and GT for ten models [44].

Figure 26. Spatial relation of the growing season NDVI trend to Tmean, Tmax and Tmin trends recorded by the 55 meteorological stations on the TP. In each of the panels (a–o), the period for calculating the temporal trends and NDVI datasets are given in the top of the figure. Each point is for one station. R is the correlation coefficient between the growing season NDVI trend and the temperature trend. RP indicates the partial correlation coefficients for the growing season NDVI trend vis-à-vis the Tmax (or Tmin) trend through controlling Tmin (or Tmax). Tmean, Tmax and Tmin refer to daily mean, daytime maximum and nighttime minimum temperatures, respectively. ***P < 0.01; *P < 0.10. Correlations with no asterisk are not significant (P > 0.10) [45].
EOB in Asia with the TP representing a training ground for cold-environment adaptations and then going ‘out of Tibet’ well before the start of the Ice Age, and the three modes of the interactions between the westerlies and the Indian monsoon represented by precipitation δ18O, and the chain effects of the three modes of the westerlies and Indian monsoon on cryosphere, hydrosphere and ecosystem. The achievement implies that the TP is a self-driving system which works through major internal pathways among multispherical interactions, that the TP is also an out-driving system which works through external effects. It is, therefore, important to pay attention to far-reaching effects when studying the multispherical interactions of the TP earth system.

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