Interaction Between the Indian Monsoon and Westerlies Produces Cascading Environmental Effects on the Modern Tibetan Plateau: Postprint

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Abstract

The westerlies and Indian monsoon, as the two major atmospheric circulation systems, are the decisive factors controlling climate and environmental changes on the Tibetan Plateau. Research demonstrates that the influence scope and magnitude of these two circulation systems exhibit significant spatial differentiation: based on precipitation stable isotope measurements and model simulations, the interaction characteristics between modern westerlies and Indian monsoon on the Tibetan Plateau manifest as three modes, namely the Indian monsoon mode, westerly mode, and transitional mode. Analysis based on lake sediment records reveals that the dominant ranges of these three modes have continuously varied during historical periods. The three modes generate cascading environmental effects on the modern Tibetan Plateau environment, resulting in distinct regional characteristics in glacier, lake, and ecosystem changes in this region. Specifically, glaciers in the Indian monsoon mode exhibit strong retreat, with lakes tending to shrink; glaciers in the westerly mode tend to stabilize or even partially advance, with lakes tending to expand; and glaciers in the transitional mode show diminished retreat, with lakes exhibiting insignificant changes. The vegetation green-up period in the westerly mode advances, while that in the Indian monsoon mode is delayed, and vegetation processes in the transitional mode are relatively complex.

Full Text

Chained Impacts on Modern Environment of Interaction between Westerlies and Indian Monsoon on Tibetan Plateau

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Abstract

The westerlies and the Indian monsoon are the primary atmospheric circulations impacting climate and environmental changes on the Tibetan Plateau. Our results reveal that both the intensity and extent influenced by these two circulations display distinct spatial and temporal patterns. Based on both the in-situ oxygen stable isotope in precipitation and simulation from high resolution isotopic GCM models, three modes of interaction between the westerlies and the Indian monsoon (the westerlies model; the transitional model; and the monsoonal model) were founded on the Tibetan Plateau. The lake sediment further evidence that the extents of three model domains display the temporally change. We also found three distinct change patterns of glaciers, lakes, and ecosystem on the Tibetan Plateau which corresponded to three models of interaction between the westerlies and the Indian monsoon. In the monsoon domain, it is characterized with greatest glacial retreat, widespread reduction in lake area, and the delay in green-up dates; in contrast, the stable or even increasing glacial volumes, significant lake expansion, and an advance in green-up dates were found in the westerlies domain; the relative complex process of glaciers, lakes, and ecosystem occurs in the transitional domain.

Keywords: westerlies, Indian monsoon, Tibetan Plateau, environmental impact

Introduction

The Tibetan Plateau represents the highest-altitude geographical unit on Earth and constitutes the main body of the "Third Pole" beyond the polar regions [1]. Its extreme elevation transforms precipitation into alpine glaciers, while cold climatic conditions foster extensive permafrost development, together forming the largest cryosphere in Earth' s mid- and low-latitude regions. Simultaneously, the Tibetan Plateau hosts one of Asia' s densest lake distributions, with glacier meltwater and numerous lakes providing sustained and stable water sources for river development. More than ten major rivers originating from the Tibetan Plateau supply essential domestic and agricultural water to East and South Asian populations accounting for one-third of the world' s total [2]. As the convergence zone of the westerlies and Indian monsoon circulation systems, changes in the plateau not only alter regional climatic conditions but also influence climate variability across East and South Asia on a larger scale. Against the backdrop of the plateau' s unique climate, hydrology, and soil development, typical ecosystems have formed that exhibit fragile ecological balance. Consequently, the Tibetan Plateau represents one of the most complex and sensitive regions responding to global climate change.

The Tibetan Plateau' s response to global climate change—including glacier retreat, permafrost thawing, runoff alteration, ecological environment modification, and intensified natural disasters—has attracted widespread attention from the international academic community. In fact, the westerlies and Indian monsoon serve as the dominant drivers of these modern climatic and environmental changes. Variations in these two major circulation systems influence the thermal and dynamic conditions of the Tibetan Plateau [3], subsequently affecting changes in other Earth spheres. Therefore, clarifying the interaction between westerlies and Indian monsoon and their environmental effects constitutes a core issue for assessing and predicting the magnitude of future climate change impacts on the environment. This research holds significant theoretical importance for Earth system science and benefits socioeconomic development in the Third Pole region while serving deeper national interests.

Stable Isotopes as Atmospheric Tracers

Stable isotopes (^{1} O and D), known as the "fingerprint" of water, provide important indicators for moisture transport and water cycling processes of the Indian monsoon and westerlies. Numerous studies have demonstrated that westerly and Indian monsoon moisture transport closely correlates with precipitation ^{1} O variations on the Tibetan Plateau [4-8]. Based on ten years of precipitation ^{1} O observations from 24 stations across the Tibetan Plateau, combined with simulation results from three state-of-the-art high-resolution isotopic atmospheric general circulation models (LMDZiso, REMOiso, and ECHAM5wiso) and modern meteorological station data [7], we conducted a comprehensive analysis of the spatiotemporal patterns of precipitation ^{1} O on the plateau (Figure 1). The study revealed that spatiotemporal distribution patterns of precipitation ^{1} O exhibit correlations with air temperature and precipitation amount across different temporal and spatial scales. Consequently, precipitation ^{1} O on the Tibetan Plateau can be classified into three distinct modes: the Indian monsoon mode, the westerlies mode, and the transitional mode.

Temporally, the westerlies mode exhibits precipitation oxygen stable isotopes following the same seasonal pattern as air temperature, with high values in summer and low values in winter (Figure 2a). The Indian monsoon mode shows precipitation oxygen stable isotopes reaching maximum values in spring and minimum values in summer (Figure 2g). The shift in moisture sources between the Bay of Bengal and the South Indian Ocean leads to significant ¹ O depletion during summer. The transitional mode, located at the intersection of westerly and Indian monsoon influences, lacks obvious seasonal extremes in precipitation oxygen stable isotopes. When the region is controlled by a single dominant atmospheric circulation, the temperature effect becomes relatively more significant. Considering seasonality, the westerlies mode exhibits a greater temperature lapse rate than the monsoon mode. Isotopic atmospheric circulation models accurately capture the spatial and seasonal variations of precipitation ¹ O, precipitation amount, and temperature across the three modes (Figure 2 [Figure 2: see original paper]). This confirms the influence of westerlies and Indian monsoon on seasonal precipitation ¹ O and clarifies the mechanisms through which atmospheric circulation affects precipitation ¹ O on the Tibetan Plateau [7].

Spatial Patterns of Atmospheric Circulation

Spatially, during summer (June–September each year), southerly and southwesterly winds prevail at the 500 hPa level south of 30°N on the Tibetan Plateau, gradually weakening between 30°N and 35°N, while westerly winds dominate north of 35°N. Precipitation decreases progressively from south to north (Figure 3a [Figure 3: see original paper]). The Indian monsoon transports moisture from southern oceans (the Arabian Sea, Bay of Bengal, and South Indian Ocean) to the plateau. During winter (December–February each year), westerlies dominate moisture transport across the entire Tibetan Plateau (Figure 3b). These seasonal variations can be traced through precipitation ¹ O values, which increase distinctly northward during summer (Figure 3c) and show the opposite pattern in winter (Figure 3d). This further demonstrates how interactions between westerlies and Indian monsoon influence the spatial distribution of precipitation ¹ O on the Tibetan Plateau [7].

Historical Records from Lake Sediments

The westerlies and Indian monsoon at mid- and low-latitudes have undergone historical changes, which must have profoundly impacted surface water-heat combinations and thermal effects on the Tibetan Plateau. However, current research has yet to adequately describe this transformation process. Using modern pollen from Nam Co Lake in the westerly/Indian monsoon transitional zone of the Tibetan Plateau, we established discriminant indicators for response characteristics under different atmospheric circulation controls. Combining these indicators with other elements, we analyzed continuous lake records from Nam Co spanning the past 24,000 years. The findings reveal that climate records from central Tibet respond to environmental changes in the high-latitude North Atlantic region, though the linkage mechanisms differ under various climatic conditions [9]. During the Last Glacial Maximum and deglaciation period (24,000-16,500 years ago), the region was primarily controlled by westerlies spanning the Eurasian continent, after which it came under significant Indian monsoon influence. In the early Holocene, enhanced solar radiation at mid- and low-latitudes created uniquely favorable water-heat conditions in the Tibetan Plateau region (Figure 4 [Figure 4: see original paper]). Following the last deglaciation (around 16,500 years ago), the Tibetan Plateau shifted from westerlies mode control to Indian monsoon mode control, endowing the plateau' s climate and environmental changes with different response mechanisms to global change.

Impacts on Modern Glaciers and Lakes

Modern changes in the Indian monsoon and westerlies alter precipitation patterns in their respective control regions, thereby affecting glacier and lake variations on the Tibetan Plateau. We comprehensively analyzed remote sensing data of area changes for 7,090 glaciers across seven representative regions on the Tibetan Plateau over the past 30 years, combined with terminus variations of 82 glaciers and in-situ mass balance observations from 15 typical glaciers. From three perspectives—glacier area change, terminus advance/retreat, and ice volume loss—we examined the spatiotemporal patterns of glacier variations on the plateau (Figure 5). The results demonstrate that the Himalayas and southeastern Tibetan Plateau under Indian monsoon influence exhibit the most intense glacier retreat, characterized by strong terminus retreat, rapid area reduction, and strongly negative mass balance. The degree of glacier retreat decreases progressively from the Himalayas toward the interior plateau where westerly-monsoon interaction occurs, reaching minimal retreat in the Pamir Plateau under westerlies control, where glaciers show less length retreat, smaller area reduction, and slightly positive mass balance [10]. Temporally, Tibetan Plateau glaciers have shown an accelerating loss trend since the 1990s (Figures 5d [Figure 5: see original paper] and 5e). The Xiaodongkemadi Glacier, which has the longest and most continuous monitoring record on the plateau, exhibited a mean mass balance of -0.24 m/year from 1989-2010, with the average mass loss from 2000-2010 being three times that of the 1989-1999 average.

Another prominent feature of the Tibetan Plateau is its extensive distribution of numerous large inland lakes. The water balance of these inland lakes involves complex hydrological processes, and their dynamics over recent decades can effectively reflect water cycle changes under global warming conditions. Combining satellite imagery with field surveys, we confirmed that while closed inland lakes on the Tibetan Plateau showed diverse changes from 1976-1999, both their area and depth increased significantly from 1999-2010 [11]. As shown in Figure 6 [Figure 6: see original paper], the total area of 99 selected Tibetan Plateau lakes decreased slightly by 2.3% from 1976-1990, increased by 5.7% from 1990-1999, and exhibited overall expansion with an 18.2% total area increase since 1999. The average lake area growth rate from 1999-2010 was three times that of the 1990-1999 period. Spatially, inland lakes on the Tibetan Plateau and those in the Himalayan region have shown opposite north-south changes in recent years: lakes in the southern Yarlung Tsangpo River basin under Indian monsoon influence have generally shrunk, while lakes in the northern Qiangtang Plateau under westerlies control have experienced strong expansion (Figure 6).

Impacts on Ecosystem Phenology

Phenological changes represent the most sensitive indicator of ecosystem responses to climate change. Numerous domestic and international studies have shown that global warming, particularly spring temperature increases, significantly advances green-up onset in temperate and frigid zones. On the Tibetan Plateau, vegetation green-up changes affect forage yield and consequently livestock production. Current phenological change information for the plateau is primarily extracted from vegetation indices obtained through remote sensing technology. Over the past decade, spring temperatures on the Tibetan Plateau have risen extensively, but the widespread presence of spring snow and ice in this region easily compromises vegetation index data quality. Consequently, the scientific community remains divided on whether vegetation green-up onset on the Tibetan Plateau has advanced. We collected four sets of remote sensing data, rigorously corrected for adverse effects from snow, ice, and clouds, and applied five internationally recognized methods to extract green-up onset from the remote sensing data. Combined with meteorological observations, we systematically analyzed green-up onset changes on the Tibetan Plateau over the past decade. The results indicate that while spring temperatures on the plateau rose by 0.10°C/year from 2000–2011, no significant trend in vegetation green-up onset emerged at the regional scale (Figure 7 [Figure 7: see original paper]) [10]. Further research shows this phenomenon occurs because green-up onset has been delayed in southwestern Tibet while advancing in northeastern Tibet, with the two trends offsetting each other (Figure 8 [Figure 8: see original paper]) [12]. Spatial differences in green-up onset coincide with precipitation changes, demonstrating that precipitation plays an important role in regulating spring phenology on the Tibetan Plateau [13]. Overall, spring precipitation has decreased in southwestern Tibet in recent years while increasing in northeastern Tibet.

Beyond the insignificant response of Tibetan Plateau vegetation phenology to temperature changes, further analysis of the relationship between Northern Hemisphere temperature and vegetation growth reveals that the correlation between vegetation productivity and temperature has significantly weakened from 1982–2011. While climate warming notably enhanced Northern Hemisphere vegetation productivity during the 1980s and mid-1990s, this relationship has become insignificant in the most recent 15 years (Figure 9 [Figure 9: see original paper]). Model simulation results indicate that climate change constitutes the primary cause of the declining vegetation productivity-temperature relationship, with factors such as rising atmospheric CO concentration contributing relatively less [15]. However, in the Tibetan Plateau region—the Earth' s "Third Pole"

—vegetation growth responses to temperature changes over the past 30 years have not shown obvious dynamic patterns, differing from vegetation responses in high-latitude Northern Hemisphere regions. Based on Tibetan Plateau field observations, satellite-measured vegetation greenness data, and gridded evapotranspiration, combined with regional climate modeling, we found that contrary to the Arctic region, enhanced vegetation activity on the Tibetan Plateau dampens daytime warming during the growing season (Figure 10 [Figure 10: see original paper]). This negative feedback primarily results from increased vegetation greenness enhancing transpiration, which has a cooling effect [16]. These studies provide new perspectives for understanding the biophysical feedback of the Tibetan Plateau surface to climate.

Conclusion

Understanding how the westerlies and Indian monsoon—two major atmospheric circulations—affect moisture transport processes on the Tibetan Plateau can reveal the driving mechanisms behind spatial variation differences in glaciers, lakes, rivers, and ecosystems across the region. Research has found that spatiotemporal distribution patterns of precipitation stable oxygen isotopes on the Tibetan Plateau can be divided into three distinct modes: the westerlies mode, the Indian monsoon mode, and the transitional mode. This precipitation mode significantly influences regional water phase transitions. Regarding glacier changes, variations in glacier length, area, and ice volume all indicate significant retreat along the Himalayas and southeastern plateau under Indian monsoon mode control, reduced retreat in the transitional mode region of central Tibet (Tanggula Mountains-Qiangtang Plateau), and minimal changes or even partial advances in the northwestern plateau and Kunlun Mountains under westerlies mode control. In terms of lake changes, lakes in the southern plateau under Indian monsoon mode influence have experienced decreasing area and water volume, while lakes in the northern Qiangtang Plateau under westerlies mode control have shown significant expansion. Regional remote sensing retrievals and typical field observations across the area have both identified precipitation as exerting clear control over vegetation green-up onset, with increased spring temperature and precipitation in northeastern Tibet advancing green-up, while decreased precipitation in southwestern Tibet delays it.

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Author Biography

Yao Tandong is an elected member of the Chinese Academy of Sciences (CAS) and Director of the Institute of Tibetan Plateau Research, CAS. Having spent years studying Third Pole glaciers and environment, he initiated and promoted the international Third Pole Environment (TPE) program and spearheaded research on Chinese mountain ice cores and Tibetan Plateau Earth System science. He identified three modes of westerly-monsoon interaction using Tibetan Plateau precipitation stable isotopes, revealing their direct effects on current glacier and lake changes on the plateau. Prof. Yao' s findings have been published in reputable international journals and rank among the 0.01% most highly cited papers. His research group is among the top teams in the ten major geoscience frontiers listed by Thomson Reuters in 2015 and 2016. He has received the Ho Leung Ho Lee Foundation Award and multiple National Natural Science Awards. In 2017, Prof. Yao was awarded the Vega Medal for his contributions to glacier and environmental research on the Tibetan Plateau.
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