Reviews of Geophysics

COMMISSIONED MANUSCRIPT

10.1029/2022RG000771

Key Points:

- We summarize recent advances in climate change research and observations of the land–atmosphere coupling processes over the Tibetan Plateau (TP)
- We highlight the impact of the TP on the global climate, including atmospheric species transport, circulation, and air-sea interactions
- We conclude projected future climate changes over the TP and discuss future research directives for assessing the TP's global climate impact

Correspondence to:

J. Huang and G. Wu,
hjp@lzu.edu.cn;
gxwu@lasg.iap.ac.cn

Citation:

Huang, J., Zhou, X., Wu, G., Xu, X., Zhao, Q., Liu, Y., et al. (2023). Global climate impacts of land-surface and atmospheric processes over the Tibetan Plateau. *Reviews of Geophysics*, *61*, e2022RG000771. https://doi.org/10.1029/2022RG000771

Received 13 FEB 2022
Accepted 14 OCT 2022

Global Climate Impacts of Land-Surface and Atmospheric Processes Over the Tibetan Plateau

Jianping Huang[1,2], Xiuji Zhou[3], Guoxiong Wu[4,5], Xiangde Xu[3], Qingyun Zhao[1], Yimin Liu[4,5], Anmin Duan[4,6], Yongkun Xie[1], Yaoming Ma[2,5,7,8], Ping Zhao[3], Song Yang[9,10], Kun Yang[11], Haijun Yang[12], Jianchun Bian[4,5,13], Yunfei Fu[14], Jinming Ge[1], Yuzhi Liu[1], Qigang Wu[15], Haipeng Yu[16], Binbin Wang[2], Qing Bao[4,5], and Kai Qie[1]

[1]Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou, China, [2]Land–Atmosphere Interaction and Its Climatic Effects Group, State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, CAS, Beijing, China, [3]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China, [4]State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS), Beijing, China, [5]College of Earth and Planetary Science, University of Chinese Academy of Sciences, Beijing, China, [6]State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, [7]National Observation and Research Station for Qomolangma Special Atmospheric Processes and Environmental Changes, Dingri, China, [8]Kathmandu Center of Research and Education, CAS, Beijing, China, [9]School of Atmospheric Sciences and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, China, [10]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China, [11]Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing, China, [12]Department of Atmospheric and Oceanic Sciences and Institute of Atmospheric Science, CMA-FDU Joint Laboratory of Marine Meteorology, Fudan University, Shanghai, China, [13]Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, CAS, Beijing, China, [14]School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China, [15]Department of Atmospheric and Oceanic Sciences and Institute of Atmospheric Sciences, Fudan University, Shanghai, China, [16]Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Northwest Institute of Eco-Environment and Resources, CAS, Lanzhou, China

Abstract The Tibetan Plateau (TP) impacts local and remote atmospheric circulations, wherein it mechanically and thermally affects air masses or airflows. Moreover, the TP provides a key channel for substance transport between the troposphere and the stratosphere. This study reviews recent advances in research regarding land–atmosphere coupling processes over the TP. The TP experiences climate warming and wetting. Climate warming has caused glacier retreat, permafrost degradation, and a general increase in vegetation density, while climate wetting has led to a significant increase in the number of major lakes, primarily through increased precipitation. Local and regional climates are affected by interactions between the land and the atmosphere. Namely, the TP drives surface pollutants to the upper troposphere in an Asian summer monsoon (ASM) anticyclone circulation, before spreading to the lower stratosphere. Further, the thermal forcing of the TP plays an essential role in the ASM. TP forcing can modulate hemispheric-scale atmospheric circulations across all seasons. The TP interacts with remote oceans through a forced atmospheric response and is substantially affected by the evolution of the Earth's climate via promoting Atlantic meridional overturning circulation and eliminating Pacific meridional overturning circulation. The extensive influence of the TP is facilitated by its coupling with the ASM in the summer; whereas its winter influence on climate mainly occurs through Rossby waves. The observed increasing trends of temperature and precipitation over the TP are projected to continue throughout the 21st century.

Plain Language Summary The impact of the Tibetan Plateau on atmospheric circulation and the climate has been of great interest to the scientific community. Here, we review the literature on the mechanisms of its climate effects, to provide an overview of recent progress in the field and directives for future research.

1. Introduction

The Tibetan Plateau (TP) is located in the subtropics of the eastern Afro-Eurasian supercontinent, spanning an area of approximately 2.5 million km^2 and an average elevation of 4 km. Qomolangma reaches an altitude of over 8.8 km and extends into the upper troposphere. Given its significant size and elevation, the plateau exerts a substantial influence on global atmospheric and oceanic circulation.

The TP is known for its vast glaciers, snow cover, and permafrost, and is often referred to as the "Third Pole" (Qiu, 2008; T. Yao et al., 2012). The lake area and snow/ice storage of the TP account for 52% and 80% of China's total, respectively. The TP is also the headwaters of multiple major rivers across Asia, such as the Yangtze, Yellow, Indus, Mekong, and Ganges Rivers, providing water to nearly 40% of the global population, and supporting their daily lives and agricultural and industrial activities. As the "Asian water tower" (Kitoh & Arakawa, 2016; C. Lu et al., 2005; Qiu, 2008; X. Xu et al., 2008, 2014; T. Yao et al., 2019), the TP exerts a profound influence on the global natural environment and climate through land-ocean-atmosphere interactions (An et al., 2001; Kitoh, 2004; M. Lu et al., 2018, 2021; Wu, 1984; Wu et al., 2007, 2012c, 2015a; X. Xu et al., 2002). Accordingly, the hydrological cycle of the TP has long been an important focus of governments and scientific research.

The TP is also a hotspot for indicating global climate change patterns. The plateau has a full range of transitional vegetation belts, from tropical and subtropical broad-leaved forests, to mountainous tundra, having been regarded as the "botanical garden" or "kingdom of plants." The TP has diverse landscapes, with significant differences in soil property, soil moisture, vegetation dynamics, surface heterogeneity, and many other surface statuses (Ma et al., 2006, 2008; B. Wang et al., 2015). Correspondingly, land surface processes, with distinct surface parameters over different landscapes, play dominant roles in the growth of the atmospheric boundary layer (ABL) and the formation of precipitation/clouds (Duan et al., 2011; Ma et al., 2006; X. Sun et al., 2021; X. Xu et al., 2002; P. Zhao et al., 2018a). In summer, dominant mesoscale convective activities and larger-scale cumulonimbus clouds over the plateau exert a "chimney effect" on air mass transport into the upper atmosphere (Bian et al., 2011; Flohn, 1968; P. Zhao et al., 2018b; Zhou et al., 1995, 2004). In addition, substance exchange and transport between the troposphere and stratosphere over the plateau affect the atmospheric composition, its spatial distribution, and ultimately, the ozone layer, as well as the regional and global climate through processes involving atmospheric chemistry, microphysics, radiation, etc. Thus, as the planet's climate continues to change, ongoing shifts over the plateau are of global concern (Oku et al., 2006; Rangwala & Miller, 2012; B. Wang et al., 2008; T. Yao et al., 2019; You et al., 2020a).

To this end, the TP's influence on weather and climate has been investigated for well over a century. Blanford (1884) suggested that the extent and thickness of the Himalayan snow cover can influence the climatic conditions of the Indian plains, and is associated with increased winter snow cover in the northwest Himalayas, with decreased rainfall over the plains of western India. Walker (1910) extended these results, having found a negative correlation between the total accumulated snow depth at the end of May, and summer monsoon rainfall levels in India from 1876 to 1908. Following these early studies, meteorologists developed a theoretical basis for how the mechanical forcings of the TP influenced East Asian atmospheric circulation regimes (Bolin, 1950; Flohn, 1957; Z. Gu, 1951; Queney, 1948; Yeh, 1950), which themselves spawned substantial research interest over the following decades (e.g., Abe et al., 2013; England & Houseman, 1988; Hahn & Manabe, 1975; Jiang et al., 2016; Kitoh et al., 2013; Molnar et al., 1993; Wu, 1984; Wu et al., 2015a; Yanai & Wu, 2006). The TP exerts a significant mechanical effect on the westerlies during winter, as two distinct westerly jet streams form to the north and south of the plateau, converge in the east, and together create the world's strongest westerly jet stream over EA, significantly affecting Asian-Pacific weather and climate (e.g., S. Yang et al., 2002). The TP is also a large heat source in the summer, producing a lower-tropospheric cyclonic circulation that surrounds the plateau, and a strong upper-tropospheric anticyclonic circulation (Z. Gu, 1951; Tao & Chen, 1957; Ye et al., 1957; Yeh, 1950). Yeh (1954) proposed that the dynamic and thermodynamic effects caused by the TP are equally important for atmospheric circulation variability. This was later confirmed by the theoretical atmospheric circulation models put forth by B. Zhu (1957). This finding initiated a new era of investigations in plateau meteorology, as evidenced by the book Qinghai-Tibetan Plateau Meteorology (Ye & Gao, 1979) which summarized numerous related achievements from previous studies. In the 1980s, Wu (1984) elucidated the nonlinearity of the interaction between mechanical and thermal effects, while demonstrating the crucial role of thermal forcing in determining the observed atmospheric circulation. Since these pioneering works on TP meteorology, the region's climatic effects have been an enduring topic of scientific research (J. Huang et al., 2019; Y. Liu et al., 2020c; Wu et al., 2015a; T. Yao et al., 2019; Zhou et al., 2009).

The present understanding of TP climate dynamics has substantially advanced with new observational data and improved numerical models. Based on various theories, observations, and simulations, Wu et al. (2007) proposed that a wintertime asymmetric dipole circulation is induced by the mechanical forcing of the TP on westerly airflow. A secondary important finding is the key role of the TP's thermal effects on the formation and onset of the Asian summer monsoon (ASM). The ASM includes several interlinked components, namely: the East Asian summer monsoon (EASM), South Asian summer monsoon (SASM), and TP summer monsoon. The mechanism called the TP sensible heat-driven air pump (TP-SHAP, Wu et al., 1997, 2007) is also essential for the formation of the EASM and eastern SASM (Wu & Zhang, 1998; Wu et al., 2012a, 2012b). More recently, M. Lu et al. (2021) quantitatively demonstrated that TP thermal effects cause a larger change in the EASM than in the SASM, and that its impact on Southeast Asian precipitation is the inverse of that on South China and India.

In addition to the influence on the adjacent ASM region, advances have been made in understanding the impacts of the TP on the climate of remote regions. For example, anomalies in the heat source of the TP can affect remote atmospheric circulation in the mid-to-high latitudes of the Northern Hemisphere, as TP thermal forcing can excite Rossby wave trains that affect downstream regions, spanning the eastern Eurasian continent, the Pacific, and even into North America (Lee et al., 2013; W. Li et al., 2021; X. Liu et al., 2002; Y. Liu et al., 2007; M. Lu et al., 2021; Y. Zhang et al., 2004; P. Zhang et al., 2005; P. Zhao & Chen, 2001; P. Zhao et al., 2018b; Zhou et al., 2009; C. Zhu et al., 2018). Coupled with the Iranian Plateau, the TP can affect the climate of upstream regions, from West Asia to the North Atlantic, through both zonally overturning atmospheric circulation and Rossby wave trains (J. Liu & Chen, 2017; M. Lu et al., 2018, 2019; Nan et al., 2019, 2021; Wu & Liu, 2016; Wu et al., 2012c; Zhou et al., 2009). Furthermore, our current understanding of the TP's role in atmospheric substance exchange between the lower troposphere and stratosphere has expanded (Bian et al., 2020; Zhou et al., 1995, 2004).

A further important advance concerns recent findings regarding TP dynamics on the formation of the Atlantic and Pacific meridional overturning circulations (Wen & Yang, 2020; H. Yang & Wen, 2020), and on the variability in the El Niño-Southern Oscillation (ENSO; Miyakoda et al., 2003; Nan et al., 2009; Wen et al., 2020). The influences of the TP on air-sea interactions over the Pacific, Atlantic, and Indian Oceans have also advanced recently (B. He, Liu, et al., 2019; C. He, Wang, et al., 2019; M. Lu et al., 2019; R. Sun et al., 2019).

The present review aims to address the recent advancements in observations and climate changes over the TP, to highlight the TP's impacts on the global climate via mechanisms concerning land surface, atmosphere boundary layer, troposphere, stratosphere, the ocean, and their interactions. First, the enhanced observations and land–atmosphere interactions are discussed in Section 2. Section 3 introduces the observed changes in the climate system over the TP. The effects of the TP on atmospheric composition transport are discussed in Section 4. Section 5 focuses on the thermodynamic and dynamic forcing of the region. The modulation of global climate by the TP is summarized in Section 6. Section 7 highlights the projected changes in the TP climate and forcings. Conclusions are drawn in Section 8 based on the available research, in addition to consideration of future outlooks.

2. Enhanced Observations and Land–Atmosphere Interactions

The dynamic and thermodynamic effects of the TP on the upper atmosphere function gradually through the surface layer and ABL. Experimental and field investigations of hydrometeorology and land–atmosphere interactions over the TP, have a long history and can provide a basis for studying land surface processes and identifying the TP's effects on local, regional, and global climate change (Duan et al., 2011; Ma et al., 2006; X. Xu et al., 2002; P. Zhao et al., 2018a). For this purpose, considerable effort has been devoted to constructing observational networks, culminating in the Tibetan Observation and Research Platform (Ma et al., 2008), and comprehensive three-dimensional observation networks for measuring land–atmosphere interactions and ABL processes (Ma et al., 2022). These data have greatly improved our understanding of climate characteristics, climate system variation, and land–atmosphere interactions over the TP. For example, the plateau-scale surface and atmospheric heating are important for maintaining the South Asian high (i.e., ASM anticyclone in the upper troposphere and stratosphere) and the SASM (K. Yang et al., 2004). Namely, surface evaporation is a key component of water and energy cycles over the TP (Curio et al., 2015; Gao et al., 2020; K. Yang et al., 2022). Substantial progress has been made through studies of local/regional land–atmosphere interactions, where it is now known that including bedrock-atmosphere interactions in the Weather Research and Forecasting model (WRF) can significantly reduce wet and cold biases (Yue et al., 2021). Moreover, glacial winds slow monsoonal water-vapor transport to higher elevations, thereby enhancing precipitation near the glacier front, while simultaneously decreasing snowfall at higher elevations (C. Lin et al., 2021). Lastly, momentum exchange between the lake surface and atmosphere may play an important role in downwind precipitation (X. Yao et al., 2021).

2.1. Hydro-Meteorological Observations

In the 1960s, researchers at the Chinese Academy of Sciences first investigated the variability of atmospheric radiation in the Mt. Everest region. Subsequently, research activities were expanded to assess the influence of plateau topography on weather, climate, and atmospheric circulation to understand the formation and evolution of atmospheric physical phenomena. As summarized by X. Xu and Chen (2006), in situ measurements observed extremely high values of solar radiation (even larger than the solar constant) and surface net radiation under proper cloud cover. The TP is thus a strong heat source, which can maintain a characteristic deep mixed layer, through which it influences atmospheric circulation and monsoon systems.

Subsequently, several large field experiments have been conducted (Ma et al., 2006; X. Xu et al., 2008; R. Zhang et al., 2012) across the region. During the Second TP Atmospheric Scientific Experiment (May–August 1998), measurements of land–atmosphere interactions and boundary-layer processes recorded higher turbulent layer heights over the TP than at the low-elevation plains and revealed characteristics of strong vertical movements, thermal convection bubbles, and "popcorn" cloud development in Naqu, central TP. Such frequently observed cloud structures can develop into a deep, mature eastward-moving convective cloud clusters, making the TP an important source of convective cloud system-induced floods in eastern China (X. Xu & Chen, 2006). During the Third TP Atmospheric Scientific Experiment (beginning in 2013 and lasting 8–10 years) (P. Zhao et al., 2018b), routine automatic sounding systems were set up at three stations (Shiquanhe and Gaize in the west, and central Shenzha), cloud-precipitation measurements were conducted in Naqu via multiple radars and aircraft campaigns; and tropospheric–stratospheric composition data were collected across multiple sites. Researchers have also observed macro- and micro-physical characteristics of clouds, and revealed the transition mechanisms between their different water phases.

In addition to large-scale experiments, the Tibetan Observation and Research Platform have also been constructed (Ma et al., 2008). The platform is composed of automatic weather stations, soil temperature and moisture probes, radiation budget measurements, boundary-layer towers, microwave radiometers, and radiosonde data, and has led to new recognitions of land–atmosphere interactions and boundary-layer processes (Ma et al., 2017, 2020). Moreover, soil moisture and temperature monitoring networks have been deployed in distinct climate regions of the TP (Z. Su et al., 2011; K. Yang et al., 2013), providing calibration and evaluation information for soil moisture and temperature products from satellite remote sensing, data assimilation, and hydrological modeling.

Recently, the Second TP Scientific Expedition and Research established a comprehensive, three-dimensional observation network over the TP to measure land–atmosphere interactions and ABL processes (Ma et al., 2022). This network consists of 28 ABL towers (each containing instruments to determine eddy covariance, five layers of air temperature, air humidity, wind speed, wind direction, radiation, rain gauge, five layers of soil temperature, and soil moisture, and two layers of soil heat flux), 10 microwave radiometers, 15 radiosonde systems, 10 blowing snow monitoring systems, and five wind profilers. The network covers multiple landscapes (grasslands, lakes, forests, glaciers, deserts, bare soil, and wetlands) under various climatic and environmental conditions of the TP, especially in mountainous regions. To date, network research has focused on land–atmosphere water and heat coupling over lakes, glaciers, frozen soil, and snow. Additionally, enormous resources have been applied toward integrating in situ measurements, satellite algorithms, and numerical simulations for investigating the coupling of water and heat between the land surface and ABL. In short, all of these hydro-meteorological activities have provided an abundance of data, and laid a solid foundation for land–atmosphere interaction research over the TP.

2.2. Plateau-Scale Land–Atmosphere Interactions

The TP is characterized by strong land–atmosphere interactions due to its intense solar radiation, high and complex topography, and prevalent cryosphere. Specifically, atmospheric interactions can influence the climate across different spatiotemporal scales. For example, plateau-scale surface and atmospheric heating are important for maintaining the South Asian high and SASM. Surface heating increases gradually throughout the pre-monsoon period, reaching its maximum in May, creating strong dry convection, and high ABL (K. Yang et al., 2004). With the onset of the SASM from mid-May to early June, soil moisture increases, surface latent heat exceeds sensible

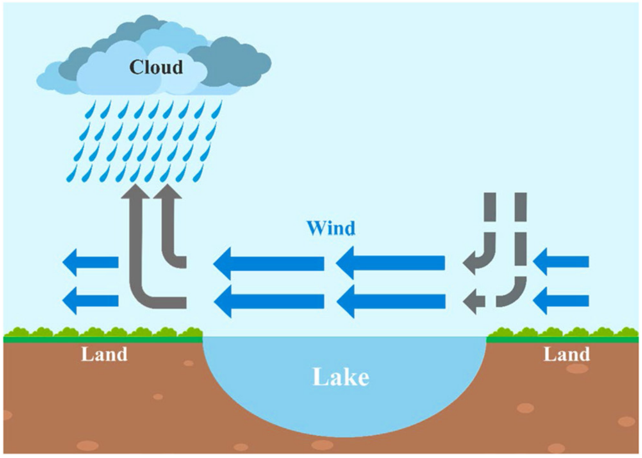

Figure 1. Schematic diagram displaying the role of easterly momentum exchange between lake and atmosphere on precipitation. Blue arrows indicate a low-level wind field, with the longer arrows portraying higher wind speeds. Solid gray arrows indicate the convergence and updraft downwind caused by the change in roughness, with dashed gray arrows displaying divergence and downdraft upwind. Source: X. Yao et al. (2021).

heat, the ABL depth decreases significantly, and cloudiness increases. Anomalies in cryospheric conditions and soil moisture across the TP during the preceding spring may weaken or enhance surface and atmospheric heat sources, driving regional hydroclimatic anomalies (Ma et al., 2017; K. Yang et al., 2014).

Large-scale surface evaporation is also important for the TP climate, with approximately two-thirds of the precipitation to the atmosphere taking place through this process (Curio et al., 2015). Moreover, evaporation in the TP is nearly equal to the precipitation (K. Yang et al., 2022); whereas the precipitation recycling ratio over the TP can reach 30%–40% in the summer (Gao et al., 2020). Accordingly, surface evaporation is a key component of the water and energy cycles over the TP.

2.3. Local/Regional Land–Atmosphere Interactions

Local/regional land–atmosphere interactions can modify similar-scale climates. Substantial progress has been made in recent research. For example, lithosphere–atmosphere interactions in the topographically complex southern TP (Yue et al., 2021). Here, the regional surface type is most commonly set as mineral soils in models, such as WRF, although there is a large fraction of exposed bedrock on the montane slopes, where bedrock allows little infiltration, and thus considerably enhances surface runoff. Accordingly, little water returns to the atmosphere through stony surface evaporation, resulting in less atmospheric water vapor to generate precipitation. Simultaneously, the lower heat capacity of the bedrock and minimal moisture, allows for distinct increases in surface temperatures and sensible heat, strengthening winds, and leading to intensified air descent over the valleys. While both water-vapor deficiency and enhanced mountain-valley circulation are unfavorable for the formation of precipitation, they promote increased valley temperatures. As a result, the inclusion of bedrock–atmosphere interactions in the WRF can reduce precipitation bias from 0.89 to -0.37 mm d^{-1} and air temperature bias from -1.5 to -0.8°C for a summer simulation (Yue et al., 2021).

Two recent case studies (C. Lin et al., 2021; Ren et al., 2020) explored the influence of glaciers in the southeastern TP and Nepalese Himalayas on the local climate. In the Khumbu Valley of the Nepalese Himalayas, an observation network consisting of six automatic weather stations (elevations 2,660–5,600 m asl) showed more summer precipitation in the afternoon near the glacier front, and isotopic data confirmed this association with dry katabatic glacier winds (C. Lin et al., 2021). High-resolution WRF sensitivity experiments indicated that this high afternoon precipitation is due to the local convergence caused by dry katabatic glacier winds, and moist upslope winds at the glacier front; thus, glacial winds appear to retard monsoonal water-vapor transport to higher elevations, thereby enhancing water-vapor convergence and precipitation near the glacier front, while reducing snowfall at higher elevations. Notably, glaciers' disappearance would lead to more water vapor being transported to higher elevations, causing more snowfall.

Approximately 1,400 lakes larger than 1 km^2 exist within the TP, with a total area of 50,000 km^2 (G. Zhang et al., 2019). Accordingly, the estimated annual lake evaporation in the TP is relatively large, ~51.7 ± 2.1 billion tons per year (B. Wang et al., 2020a). Studies revealed that the abundant supply of water vapor and sensible heat from the lake surface to the atmosphere may enhance downwind precipitation (Dai et al., 2018; Notaro et al., 2013); whereas a more recent study confirmed that momentum exchange between the lake surface and atmosphere may play an important role in precipitation downwind (X. Yao et al., 2021). A proposed schematic of the lake–atmosphere interactions is shown in Figure 1, where easterly winds are taken as an example. When the flow reaches the eastern lake shore, the surface type changes from land to water, and the corresponding roughness decreases. Consequently, the momentum loss on the lake surface is less than that on land, and the wind over the lake surface is accelerated, resulting in air horizontal divergence at the eastern shore. The opposite is true for the western shore of the lake, where the surface type changes from water to land, increasing roughness, and decreasing wind speed, thus facilitating air convergence, intensifying convection, and increasing precipitation downwind of the lake.

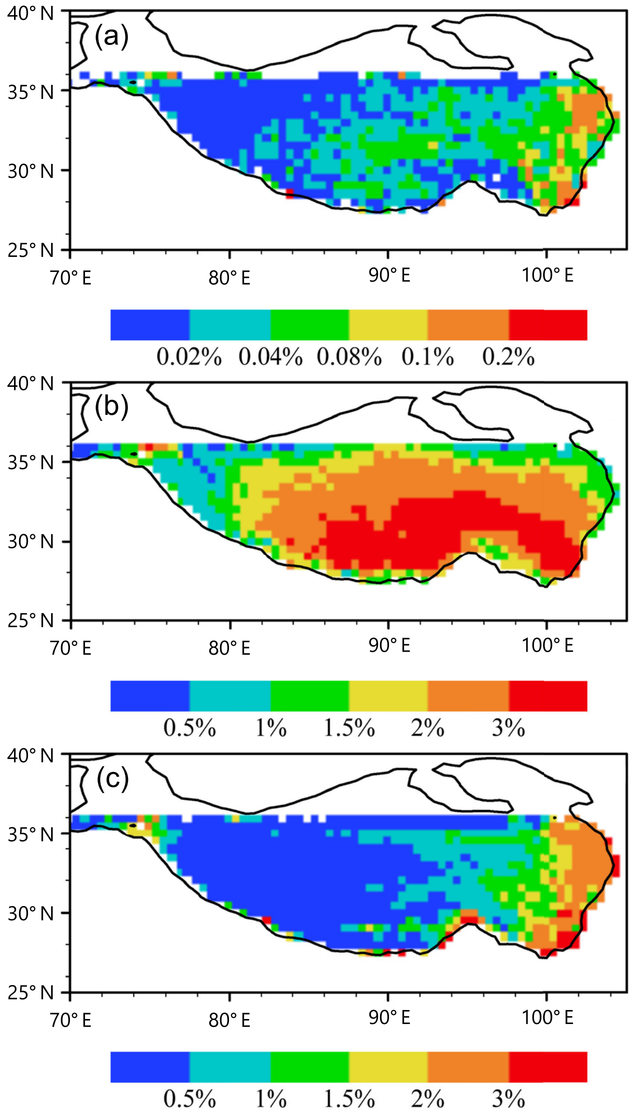

Figure 2. Frequency distributions of: (a) strong deep convection, (b) weak deep convection, and (c) shallow precipitation based on storm-top altitude over the Tibetan Plateau. Source: Fu et al. (2016).

3. Climate System Changes Over the TP

The TP climate is characterized by low air temperatures, large diurnal temperature ranges, and small seasonal temperature variations, with average annual precipitation exceeding 600 mm yr^{-1}. The region has been warming since the early 1950s due to climate change (T. Yao et al., 2019), The area and depth of major lakes have grown as well. Increased precipitation is the primary contributor to lake expansion in the central TP, along with enhanced meltwater from the cryosphere (Lei et al., 2014). Accelerated warming has caused glacier retreat, fluctuations in snow amount and cover, permafrost degradation, and thickening of the active permafrost layer (Bibi et al., 2018; X. Huang et al., 2016; Kang et al., 2010; Peng et al., 2017; T. Yao et al., 2019), and increased vegetation density (Zhong et al., 2019).

3.1. Climate Characteristics

The TP climate maintains low air temperatures, high solar radiation levels, and large diurnal and small seasonal temperature variations. The climatological temperature (1961–2010) presents a “high–low–high” distribution from southeast to northwest, corresponding to the regional topography. Annual mean temperatures are ∼12°C in the southeast and northwest, and ∼−4°C in the central TP (L. Xu et al., 2019). Across most areas, temperatures are lowest in January, and highest in July (Wei et al., 2003). The annual mean diurnal temperature range is at a maximum in winter and a minimum in summer. Average annual precipitation gradually decreases from the southeast to the central TP, and then increases toward the west (D. Li et al., 2020; F. Li et al., 2020). Precipitation is mainly concentrated during May–September in most areas due to the summer monsoon from the south and east (Wei et al., 2003). However, it peaks from December to May in the western TP due to the combined effects of westerly-driven winter storm tracks and steep topography along the western margin (D. Li et al., 2020; F. Li et al., 2020).

The climatological distribution of clouds is a unique combination of different climate zones. TP cloud characteristics are also unique. Similar to the spatial distribution of precipitation, two cloud frequency centers have been identified to the southeast and west (J. Liu & Chen, 2017). The occurrence frequencies of the middle (7–8 km asl) and low clouds (5–6 km asl) were 14% and 35%, respectively. Namely, dense cirrus, stratus, cumulus, and cumulonimbus are the four typical types over the TP (Liang et al., 2010). The seasonal variation in diurnal cloud activity shows two distinct variance maxima: one in the pre-monsoon season of March–April, and one during the monsoon season of July–August (Fujinami & Yasunari, 2001). Kurosaki and Kimura (2002) found that cloud cover is lower during the pre-monsoon period, while it is more frequently observed over the southeastern plateau in the morning during the monsoon season. Moreover, the relationship between topography and cloud distribution is not always clear when horizontal features are <100 km. In the summer, abundant mixed-phase clouds exist, leading to a strong cooling effect. The existence of supercooled water in the clouds makes shortwave, longwave, and net cloud radiative effects much stronger over the TP (Y. Yan et al., 2020, 2021). The cloud longwave radiation of the atmosphere over the TP shows a net cooling effect. Compared with the tropical oceans, the net radiative heating layer in the TP is shallower (maximum thickness, ∼3–4 km), and shows a stronger seasonal variation (Y. Yan et al., 2020).

Cloud characteristics correspond to features of deep convective precipitation over the TP (Fu et al., 2006, 2016; M. Wang et al., 2019a; L. Zhang et al., 2018). The frequency of strong deep convective precipitation is quite low, and increases from the western to eastern plateau (Figure 2). Conversely, the frequency of weak deep convective precipitation was more than ten-fold larger than that of strong deep convective precipitation. The overall relative frequencies of weak, shallow, and strong deep convective precipitation were 77%, 22%, and 1%, respectively.

Cloud droplet effective radius is ∼5–7 μm, while the cloud liquid water content remained mostly <0.2 g m^{-3}. From the surface to ∼1.2 km height (0°C layer), the cloud droplet effective radius and liquid water content increase with altitude (C. Zhao et al., 2017). Clouds with large (small) effective radii mainly occur at low (high) heights, and are likely orographic cumulus or stratocumulus (thin cirrus; C. Zhao et al., 2016).

3.2. Atmospheric Changes

The regional warming trends (Figure 3a) commencing in the early 1950s occurred approximately two decades earlier than that in the rest of the Northern Hemisphere (T. Yao et al., 2019). Notably, warming rates were substantially higher in high-altitude regions (>4,000 m; Zhong et al., 2019), but stabilized, or even decreased, at extremely high altitudes (>5,000 m; Guo et al., 2019; Qin et al., 2009). Elevation-dependent warming is highly modulated by correlated changes in snow depth (Guo et al., 2021). Since the end of the 1990s, a so-called "warming hiatus" has been observed in certain locations around the world, more significantly so over the continental Northern Hemisphere (J. Huang et al., 2017). In contrast to this cooling trend (Figure 3a), a continuous warming trend (0.25°C $decade^{-1}$) was observed over the TP during 1998–2013 (Duan & Xiao, 2015); however, changes in warm extremes were not evident (Zhong et al., 2019). Additionally, land surface temperatures increased more rapidly than near-surface air temperatures (Figure 3b), while the land–air temperature difference also increased with atmospheric warming (Y. Liu et al., 2012). Several studies have indicated that the enhancement of downward clear-sky longwave radiative flux and surface albedo feedback are crucial to the accelerated surface warming observed across the TP over recent decades (Gao et al., 2019; J. Su et al., 2017). G. Wu et al. (2020) assessed the contributions of various dynamic radiative processes to long-term surface warming over the TP based on the coupled surface–air feedback response analysis method. Long-term changes in near-surface air temperatures over the TP were attributed to external forcing and internal climate processes. Over the eastern and central TP, moistening of the atmosphere favors increases in near-surface air temperature via trapping more longwave radiation, which overwhelms the negative effect of moisture convergence-induced cloud increase. Meanwhile, this increased near-surface air temperature further leads to a reduction of surface sensible heat flux, and thus an increase in land surface temperature. In the western TP, the most important contributors to surface warming are the increasing surface latent heat flux, as well as the decreasing surface albedo and cloud cover.

Precipitation generally increased throughout the TP (Figure 3c), significantly so at 15 (21.74%) of the 69 stations; whereas 40 stations (57.97%) also experienced increased precipitation, albeit insignificant (Zhong et al., 2019). Notably, precipitation trends vary across the TP and its surrounding regions, depending upon the selection of target regions (Y. Su et al., 2020). For instance, decreasing precipitation dominated the upper Indus Basin, including high-elevation areas (>1,300 m; Latif et al., 2018), as well as eastern Nepal at an alarming rate of −20 mm yr^{-1} from 1997 to 2016 (Subba et al., 2019). Alternatively, the southern TP exhibits decadal oscillations of precipitation during July–September (Yue et al., 2021).

3.3. Hydrospheric Changes

The effect of the inland lake water balance on TP dynamics over recent decades has been a good indicator of hydrological patterns under climate change. Both satellite imagery and extensive field investigations have indicated that the major lakes in the central and western TP have expanded significantly in terms of both area and depth (Figure 4); whereas numerous lakes along the margins of the southern and eastern TP have shrunk since the mid-1990s (Lei et al., 2014). While increased precipitation and meltwater are the main drivers of lake expansion in the central TP, reduced precipitation has caused lake shrinkage in the Himalayas (Lei et al., 2014; Sheng & Li, 2011). The vast majority of TP lakes (70%) have shown warming trends, and the remaining (30%) have cooled. This contrast is likely a result of different recharge sources, where lake cooling is dominant in the northern Qiangtang Plateau, with an increased proportion of recharge water coming from glacial and permafrost meltwater, and lake warming is observed across all other regions (Guo et al., 2021; Wan et al., 2018; G. Zhang et al., 2014a).

3.4. Cryospheric Changes

Climatic warming has caused remarkable changes in the TP cryosphere (Bibi et al., 2018; X. Huang et al., 2016; Kang et al., 2010; Peng et al., 2017; T. Yao et al., 2019). Similar to most other glaciers worldwide, glaciers

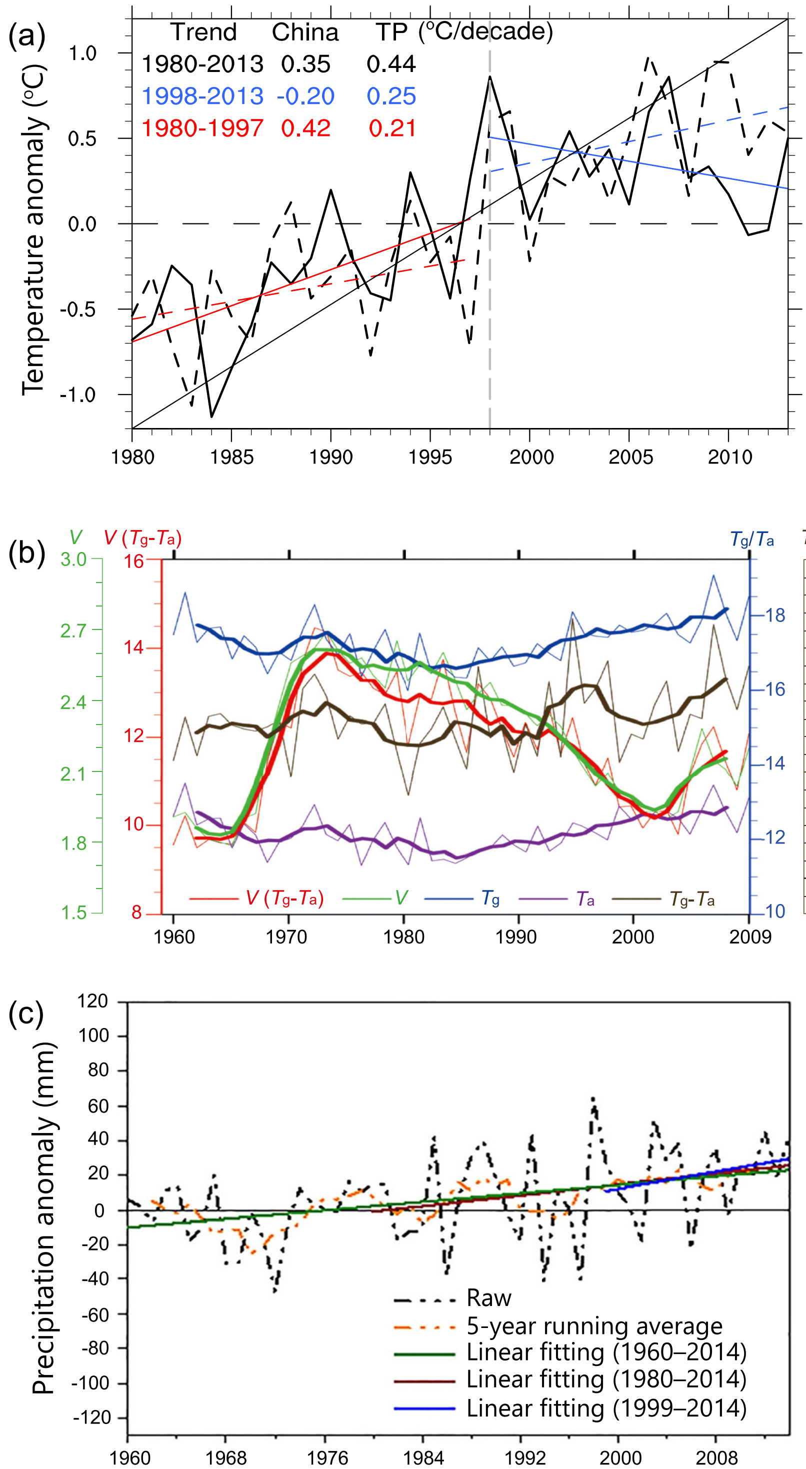

Figure 3. (a) Annual mean near-surface air temperature anomalies for China (solid) and the Tibetan Plateau (TP) (dashed) during 1980–2013 relative to 1981–2010 means; (b) Time series of JJA mean land surface (T_g; °C), and near-surface air temperatures (T_a; °C), as well as land–air temperature differences ($T_g - T_a$), near-surface wind speed (V; m s^{-1}), and a part of surface sensible heat flux $V\,(T_g - T_a)$. (c) Annual precipitation anomaly relative to 1960–1990 means over the TP (black dashed). The orange dashed curve indicates the 5-year running mean. The green, brown, and blue curves indicate the linear fitting of the three time periods. Source: Duan and Xiao (2015), Y. Liu et al. (2012), and Zhong et al. (2019).

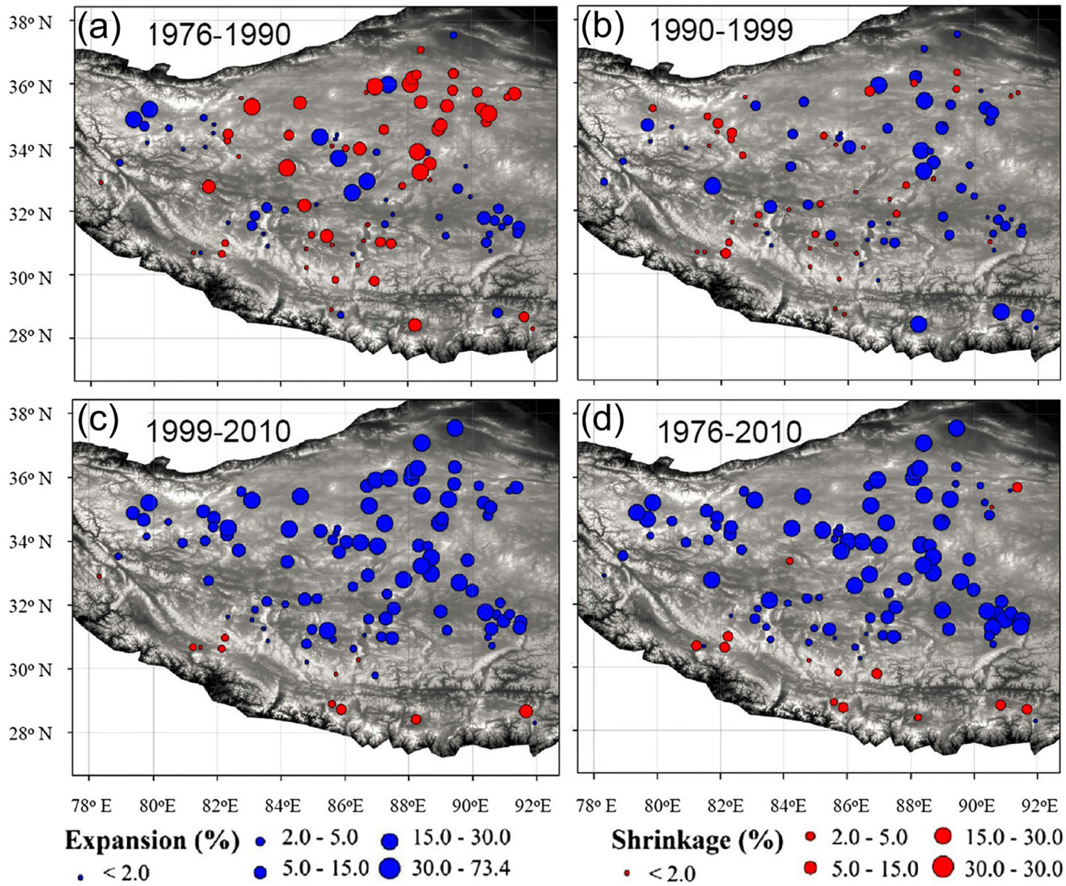

Figure 4. Lake area changes in the Tibetan Plateau interior and Himalayas during: (a) 1976–1990, (b) 1990–1999, (c) 1999–2010, and (d) 1976–2010. Source: Lei et al. (2014).

on the TP have experienced extraordinary shrinking, as shown by the reduction in glacial length, area, and mass; however, these patterns are not homogeneous across the TP. For example, the areal reduction is strongest in the Himalayas, and weakens toward the continental interior, reaching a minimum in eastern Pamir (T. Yao et al., 2012). The annual average snow depth across the TP decreased continuously (Figure 5a), albeit slightly during 1980–2017, with notably larger interannual fluctuations before 2000 than after. Spatially, annual snow depth exhibited a slight increase in the northwestern TP, and a slight decrease in the southeast (Che et al., 2019).

Permafrost covers approximately 45% of the TP (1.1×10^6 km^2; Cao et al., 2019; Ran et al., 2021). Notably, decreasing maximum freezing depth (i.e., the maximum frozen depth of soil across a year) has been observed across the entire TP, except in some southern regions (Figure 5b). Similarly, the freeze start, freeze end, and freeze duration have undergone delayed, advanced, and shortened trends, respectively (Guo & Wang, 2013; X. Li et al., 2008; Peng et al., 2017); whereas the permafrost altitudinal limit increased by 25 m in the northern TP, and by 50–80 m in the south. Active permafrost layer thickness has also increased by 0.15–0.50 m (G. Cheng & Wu, 2007).

3.5. Soil and Vegetation Changes

Soil moisture is a key variable in land–atmosphere energy and water exchange processes. Based on in situ measurements of observation networks, as well as multi-source satellite products and reanalysis data, increasing soil moisture has been documented across the western, central, and northeastern TP during 1979–2018, notably consistent with the overall trend of increasing TP precipitation (M. Cheng et al., 2019).

Namely, the alpine ecosystem underlain by permafrost is considered one of the most vulnerable ecosystems to disturbance, especially the alpine grassland on the TP with an altitude above 4,000 m. Warming alters the

10.1029/2022RG000771

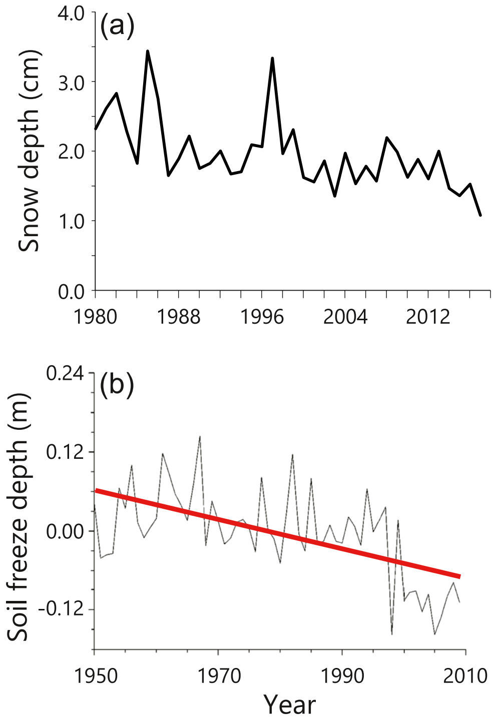

Figure 5. (a) Annual mean snow depth during 1980/1981–2017/2018; and (b) Maximum soil freeze depth during 1950–2010, in comparison with the 1971–2000 mean. Sources: Che et al. (2019), Peng et al. (2017).

surface soil (0–10 cm) organic matter composition despite unchanged carbon stocks in the TP permafrost ecosystem (D. Li et al., 2020; F. Li et al., 2020). The vegetation density shows a general increasing trend along with warming on the TP (Zhong et al., 2019), and the areas with significant increases accounted for 7.63% of the total land of the TP. Different vegetation types exhibit remarkably different responses to climate change. Grasslands in semi-arid regions, which account for 41.9% of the territory of the TP, have been identified as very sensitive to variations in both temperature and precipitation (Zhong et al., 2019).

4. TP Impacts on Atmospheric Species Transport

In situ measurements, satellite products, and model simulations have shown that the ASM anticyclonic circulation system is a key pathway for stratospheric entry of tropospheric pollutants and water vapor, with the TP's elevated topography playing an important role in this process (Bian et al., 2012, 2020; P. Yu et al., 2017). Surface pollutants are transported to the upper troposphere via ASM anticyclone circulation, and spread throughout the entire lower stratosphere of the Northern Hemisphere (Bian et al., 2020; P. Yu et al., 2017). Troposphere-to-stratosphere transport is important for controlling chemical constituent concentrations in the upper troposphere and lower stratosphere (e.g., ozone and aerosols), with the chemical, microphysical, and radiative processes involved in transport potentially having critical effects on global climate (Bian et al., 2020; R. Jia et al., 2018; Y. Liu et al., 2014).

4.1. Troposphere-To-Stratosphere Transport

The ASM anticyclone, or the South Asian high, is a dominant feature of summer circulation in the upper troposphere and lower stratosphere. Regarding the importance of ASM anticyclonic circulation on stratospheric entry, the density of tropopause crossing points, defined as the number of points where tropospheric air parcels cross the tropopause into the stratosphere, was calculated from a trajectory model for many summers, revealing two main pathways: diabatic upwelling and eddy shedding (Figure 6; Bian et al., 2020; Fan et al., 2017a). In diabatic upwelling, air rises across an isentropic surface and into the tropical stratosphere, carried by a slow diabatic upward motion, balancing radiative heating in the process. This pathway is the most dominant, occurring mainly over the southeastern part of the ASM anticyclone (Fan et al., 2017b; Garny & Randel, 2016; Pan et al., 2016) and Himalayan foothills, where heavy precipitation usually occurs (Fu et al., 2018). Indeed, forward trajectory calculations have shown that approximately two-thirds of the air crosses the tropopause via this pathway (Fan et al., 2017b). The greatest uncertainty in this mechanism comes from calculating the diabatic ascent rate based on limited data on key atmospheric species and clouds, especially the cirrus fraction and its vertical distribution in the upper troposphere. Alternatively, convective overshooting (deep convection penetrating the tropopause) is also an efficient mechanism to transport chemical species into the tropopause transition layer within the ASM anticyclone (Dessler & Sherwood, 2004), even though the frequency of this process is relatively low (N. Liu & Liu, 2016). Currently, it remains challenging to use a direct method to quantify its effects on transport over the ASM region.

Alternatively, the eddy shedding pathway involves air entering the mid-latitude stratosphere along an isentropic surface (Fan et al., 2017b; Pan et al., 2016). The subtropical westerly jet stream to the north of the ASM anticyclone is generally considered a barrier for air exchange between the anticyclonic interior and mid-latitude stratosphere; however, wave shedding caused by circulation and Rossby-wave interactions can take the interior air away from the anticyclone. Although this pathway maintains a smaller contribution to air mass transport, it is important for compositional changes in the stratosphere, as the horizontal gradient of the composition is substantially larger.

As estimated by Gettelman et al. (2004) in a detailed analysis of modeled water vapor flux, the troposphere-stratosphere exchange of water vapor in the tropics is supported by the ASM circulation from July–September. Changes in stratospheric water vapor concentration act to significantly slow down or enhance the

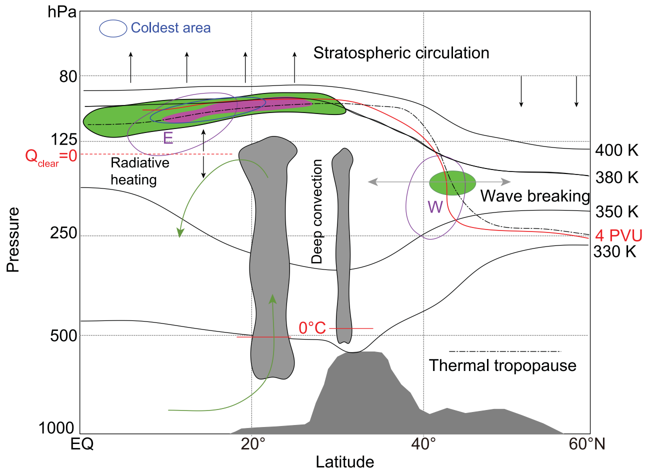

Figure 6. Schematic of the pathways for troposphere-to-stratosphere transport within the Asian summer monsoon anticyclone. At the mean temperature lapse rate tropopause (black dashed line), the density of crossing points is denoted by green and purple shadings, depicting lower, and higher densities, respectively. The coldest region (blue circle) is overlaid on the color-shaded area. Vertical motion in the upper troposphere and lower stratosphere is denoted by solid black vertical arrows; whereas the neutral radiative heating level on the tropical side is denoted by a dashed red line, and the isentropic surfaces from 330 to 400 K are represented by solid black lines. The 4-potential vorticity unit is depicted as a solid red line, while the stratosphere–troposphere exchange due to eddy shedding to the north of the anticyclone is denoted by the gray arrows along the isentropic surface. Deep monsoon convections are displayed as the two Gy cloud towers: one for bulky convection over South Asia, and the other for thinner convection over the Tibetan Plateau; whereas the freezing levels are displayed by solid red lines. The vertical monsoon circulation is denoted by green arrows, while the westerly and easterly jets in the upper troposphere are denoted as pink circles. Source: Bian et al. (2020).

rate of global surface temperature change (Solomon et al., 2010). As shown by modeled simulations, transport processes associated with the ASM also bring more hydrochloric acid into contact with liquid sulfate aerosols in the cold lowermost stratosphere of the tropics, leading to heterogeneous chemical activation of chlorine species. These processes impact the local ozone budget and decrease ozone abundances in regions 16–19 km from the Earth's surface (Solomon et al., 2016).

Despite its low frequency, deep convective transport is the most efficient exchange mechanism, and a prerequisite for the boundary-layer air mass to enter the stratosphere. For example, deep convection can transport air masses quickly from the ABL to the main deep outflow level (~360 K) within tens of minutes (Bian et al., 2020). Although pollutant aerosol transportation is primarily affected by convection, surface CO emissions are relatively high in the ASM region, and can serve as an appropriate tracer for air pollutant emissions, including aerosols. It has been shown that surface air with high CO over India is transported directly to the upper troposphere, and then confined within the ASM anticyclone, leading to maximum concentrations in the upper troposphere and lower stratosphere (R. Yan & Bian, 2015). Further, nitrate aerosols are of secondary importance near the surface, but are the most dominant aerosol species in the upper troposphere and lower stratosphere. Namely, the mechanisms leading to the accumulation of nitrate in these regions over the TP/southern ASM include vertical transport, and the gas-to-aerosol conversion of HNO_3 to form nitrate, where the high relative humidity and low temperature associated with deep convection over the upper troposphere and lower stratosphere favor the latter (Y. Gu et al., 2016); however, significant amounts of gas-phase ammonia within the ASM anticyclone (as measured by satellite observations—Höpfner et al., 2016) are believed to favor new particle formation due to its alkalinity. Further, satellite observations and high-altitude aircraft measurements have shown solid ammonium nitrate particles within the ASM anticyclone as well (Höpfner et al., 2019). Thus, deep convection over the Indian subcontinent transports pollutants from the Asian tropopause aerosol layer into the upper troposphere and lower stratosphere; whereas secondary aerosol formation and growth in cold, moist, convective environments may also play an important role in the formation of the Asian tropopause aerosol layer (Vernier et al., 2015).

4.2. Ozone Transport

The ozone acts as an important greenhouse gas in the regional radiative budget, in addition to protecting TP biodiversity by shielding flora and fauna from ultraviolet radiation. A marked TP ozone valley has been observed in the summer (Zhou et al., 1995), while the total column ozone has been decreasing since 1979, especially in the lower stratosphere (J. Zhang et al., 2014b), a pattern largely attributed to anthropogenic activities coupled with atmospheric circulation. Balloon-borne measurements of ozone in Lhasa from August 2013 verified two main causes of TP ozone variation (D. Li et al., 2018): (a) upward transport of polluted air from the boundary layer, or downward from the stratosphere; and (b) photochemical production induced by solar radiation, other chemical reactions involving lighting-produced nitrogen oxides, ozone precursors from biomass burning, and other anthropogenic pollution sources. Notably, the thermodynamic processes associated with TP warming accounted for >50% of the total column ozone decline, while the enhanced transport of ozone-poor air masses into the stratosphere and elevated tropopause due to the rapid winter warming over the TP reduces ozone concentrations in the upper troposphere and lower stratosphere, and hence lead to the deepening of the total column ozone hole (J. Zhang et al., 2014b).

The summertime total ozone column valley over the TP, as a climatological phenomenon, is caused in part by the smaller total air column (Bian et al., 2020). The TP ozone valley is also influenced by synoptic processes. Ozone transport can be decomposed into stationary and transient components related to mean flow and

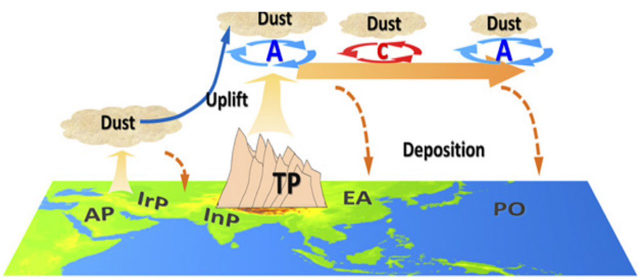

Figure 7. Schematic diagram illustrating dust belt formation during the spring over the Northern Hemisphere. A, anticyclonic circulation center; C, cyclonic circulation center; AP, Arabian Peninsula; IrP, Iranian Plateau; InP, Indian Peninsula; EA, East Asia; PO, Pacific Ocean. Source: C. Xu et al. (2018).

eddies, respectively (W. Xu et al., 2021). The zonal transport of ozone, calculated as the sum of the stationary and transient zonal components, strengthens the TP ozone valley; whereas meridional transport weakens the ozone valley. Notably, the transient transport of ozone was much weaker than stationary transport; thus, mean flow is predominant in the stationary component.

In turn, the ozone valley over the TP influences the South Asian high, and by removing this valley from numerical experiments, the South Asian high becomes stronger and colder from June to August (Z. Li et al., 2017). Increasing ozone at 200–30 hPa leads to a significant enhancement of longwave and shortwave radiative heating rates in the South Asian high region. Consequently, the radiative warming-induced enhancement of horizontal divergence strengthens the South Asian high. Colder South Asian highs are primarily caused by dynamic processes, such as adiabatic expansion and ascending movement decreasing temperatures after removing the ozone valley over the TP; however, the thermodynamic process due to radiative heating partly offsets this cooling response.

4.3. Aerosol Transport

ASM circulation influences not only the aforementioned components of atmospheric composition, but the distribution and transport of polluting and nonpolluting aerosols as well. The ASM anticyclone is also collocated with higher concentrations of pollutants emitted within the continental ABL. Air mass in the ABL (both polluted and unpolluted), converges at the intensive convection region in the lower troposphere, traverses the mid-troposphere along convective motion, and ultimately moves to the upper troposphere and lower stratosphere (Fan et al., 2017a; Feng et al., 2020). Increasing concentrations of stratospheric aerosols influence global climate change, as it has been shown that stratospheric aerosol changes caused a negative radiative forcing of ∼−0.1 W m^{-2} from 2000 to 2010, thereby reducing the warming potential that would have otherwise occurred (Solomon et al., 2011).

Dust is a major component of global atmospheric aerosols, and the most prominent aerosol type over the TP, mostly originating from the Taklimakan Desert (S. Chen et al., 2013; J. Huang et al., 2007; R. Jia et al., 2015; Y. Liu et al., 2015). The TP also experiences a high frequency of dust storms (Fang et al., 2004). Compared with other dust source areas across China, the TP is a key dust source for long-distance transport, as its high elevations cause fine particles to be readily lifted into the westerly jet stream. Dust storms are also accompanied by a strong ascending stream over the TP, enhancing dust particle concentrations of various sizes across all altitudes. Lifted coarser particles largely fall out, and accumulate as loess in the eastern TP; whereas fine particles are transported by the westerly jet stream, and subside in the northern Pacific (Fang et al., 2004; Pullen et al., 2011). A dust belt can become apparent at altitudes >6 km over the downwind direction of the TP (∼30°N–40°N), crossing the Pacific Ocean, and extending to North America in the spring (C. Xu et al., 2018). Such patterns are likely due to the influence of surface heating on local convection across the TP. Local convection in turn controls vertical aerosol exchange and pollution diffusion rates to the surrounding areas, thereby enhancing the TP as an aerosol source (Luo et al., 2020). The TP also plays a crucial role in the long-distance transport of dust, acting as a major pathway for dust transfer to the upper troposphere via convective ascent. The prevailing spring convection over the TP can cause convective overshooting that carries dust aerosols from the mid-troposphere to the upper troposphere (Figure 7), from where the dust is then transported downstream along the subtropical westerly jet. Thus, the TP acts as a transport channel from the lower atmosphere to the upper troposphere, enabling the long-range zonal transport of dust across the Northern Hemisphere (C. Xu et al., 2015, 2018).

In situ measurements from Kunming (summer of 2015) revealed a strong increase in aerosol concentrations that extended up to 2 km above the TP tropopause (P. Yu et al., 2017). Further, a climate model simulation demonstrated that abundant anthropogenic aerosol precursor emissions from Asia, coupled with rapid vertical transport associated with monsoon convection, led to significant particle formation within the ASM anticyclone in the upper troposphere. These particles subsequently spread throughout the entire Northern Hemisphere lower stratosphere, and contributed significantly (15%) to the annual stratospheric column aerosol surface area across this global area (Figure 8). These in situ observations and model simulations suggest that the ASM anticyclone is an important pathway for surface pollutants to reach the stratosphere.

10.1029/2022RG000771

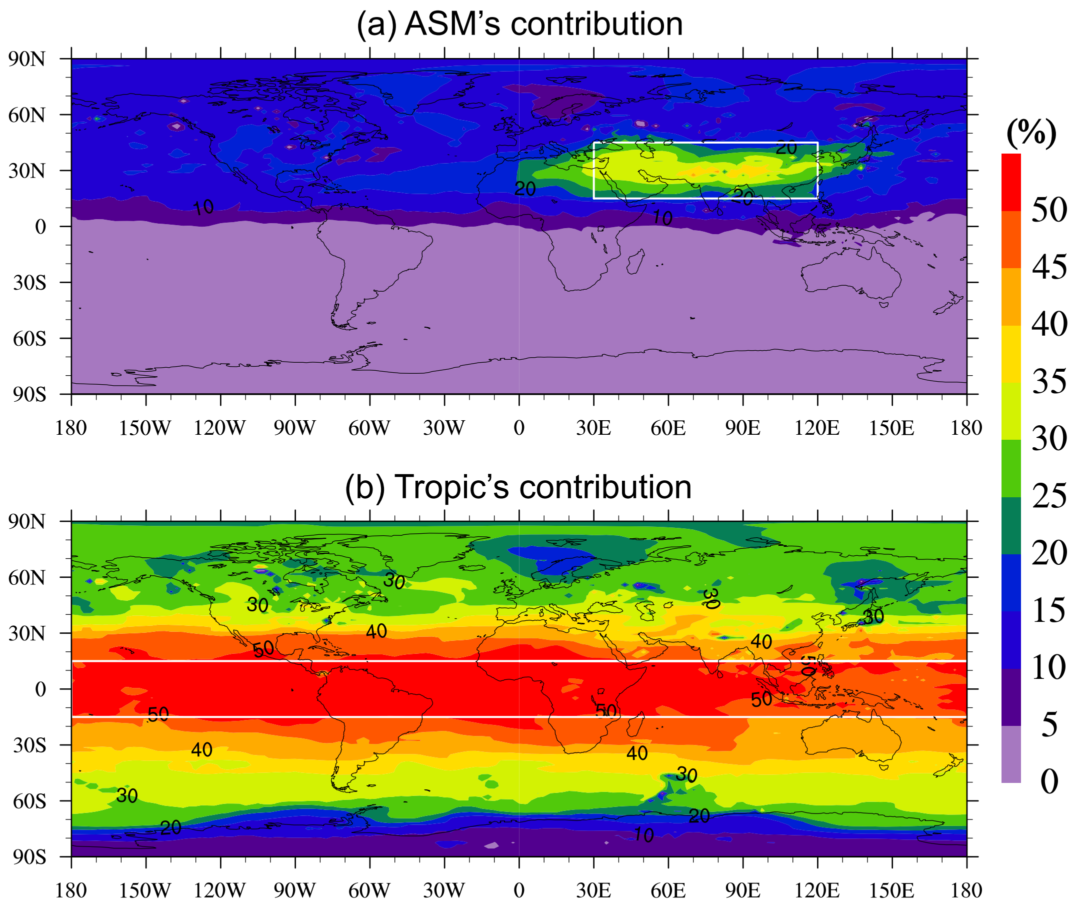

Figure 8. (a) Aerosol contribution (percent) to the annual mean particle surface area in the stratosphere that are transported through the Asian summer monsoon 3D box (30°E–120°E, 15°N–45°N; June–September). White box shows the spatial extent of the region included within the 3D box, where aerosol and aerosol precursors were eliminated. (b) Aerosol contribution to the annual mean particle surface area in the stratosphere that are transported through the tropics (180°W–180°E, 15°S–15°N; entire year). Source: P. Yu et al. (2017).

5. Thermal and Dynamical Forcing of the TP

The atmospheric heat source over the TP shows strong annual variability due to the differences in heat distribution between land and sea, as well as those between uplifted topography and air (P. Zhao & Chen, 2001). Notably, the TP atmospheric heat source significantly affects the formation and variation of ASM (B. He et al., 2019; C. He et al., 2019; Y. Liu et al., 2020c; M. Lu et al., 2021; G. Wu et al., 2015a, 2016; 2017). The thermal influence of the TP dominates the precipitation distribution over the ASM regions; whereas its mechanical influence contributes more to the winter (Y. Liu et al., 2007; M. Lu et al., 2021).

5.1. Composition of the Heat Source/Sink Over the TP

The atmospheric heat source/sink is a physical quantity reflecting the heat budget of an air column (Ye & Gao, 1979). It represents the heat gained and lost by the large air column in a given region and is the most fundamental driving force of atmospheric circulation. The atmospheric heat source/sink includes three primary, non-adiabatic heating processes: radiation exchange between the atmosphere and the land surface, turbulent heat transfer, and latent heat of condensation. Currently, the two methods used to calculate the atmospheric heat source/sink are direct and inverse, where the former is based on the radiation balance principle, using observations or reanalysis data to calculate each of the three components. Its advantage lies in its relative simplicity and its capacity to provide the spatial distributions of the three components. Alternatively, the inverse algorithm (i.e., residual diagnosis method) is based on the direct vertical integration of the thermodynamic equation of atmospheric

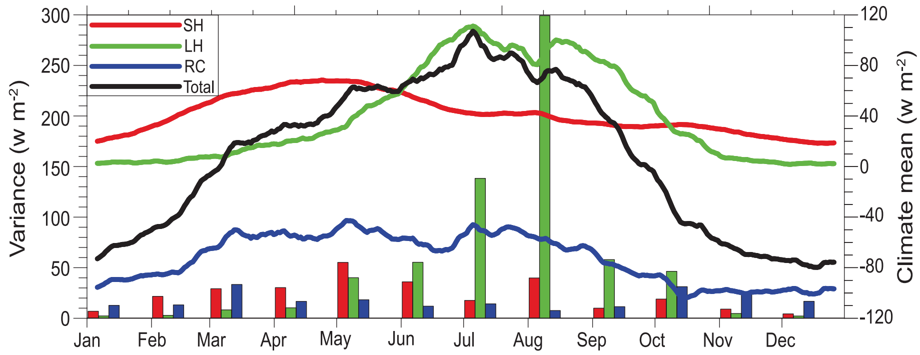

Figure 9. Climatological means (solid lines; W m^{-2}) and monthly variance (bars) of each component in the Tibetan Plateau heat source, as determined by averaging data across 73 meteorological observation stations over the TP: Red denotes sensible heating; green is latent heating; blue is net radiation flux of the air column (RC); and black is their sum. Source: Y. Zhao et al. (2018c).

energy (Yanai et al., 1992), and is capable of calculating atmospheric heat source/sink distribution and producing its vertical structure as well.

Considerable uncertainty exists when quantitatively estimating the atmospheric heat source over the TP depending on the data set used (L. Chen et al., 2019; Mazhar et al., 2021; Wu et al., 2017; J. Xie et al., 2019). Uncertainty can also arise from different observation station elevations, as such data is not valid over particularly large areas. Further, the lack of direct surface heat flux and vertical heating profile observations at most stations also contribute to this limitation (Duan et al., 2018).

For decades, studies have investigated the atmospheric heat source/sink over the TP, along with its impact on the weather and climate (Y. Liu et al., 2007; Nan et al., 2021; L. Wang et al., 2018; Wu, 1984; Wu et al., 2017; Yanai et al., 1992; Yeh, 1954; P. Zhao et al., 2019). Namely, the atmospheric heat source/sink over the TP also shows strong annual variability (P. Zhao & Chen, 2001), where surface sensible heating (SH) prevails over latent heating (LH) in the free atmosphere from March to May (before the onset of the ASM). Comparing the variance of sensible and LH (Figure 9, red and green bars, respectively), the latter is much greater in May than in March or April; thus, it is evident that May is a transitional month, during which the relative importance of SH decreases as LH gradually gains dominance (Y. Zhao et al., 2018c). From June to August (during the ASM), LH due to condensation is predominant over the southern and eastern TP; whereas sensible heat dominates to the west (P. Zhao & Chen, 2001). Further, regional LH of the ASM in the southern TP and over the northern Bay of Bengal was much stronger than the sensible heat over the remaining TP (Wu et al., 2017).

Climatological fields indicate that sensible heat flux is dominant in the western and central TP; whereas LH (due to precipitation) and radiation cooling are the primary forces in the southeastern corner of the TP (Duan et al., 2018; Flohn & Reiter, 1968; Nitta, 1983; Z. Xie & Wang, 2019; J. Xie et al., 2019). Over a seasonal timescale, latent heat is the dominant diabatic force in the free atmosphere of the summer (Y. Liu et al., 2012). In recent decades, however, the atmospheric heat source over the TP has shown a significant decreasing trend, mainly owing to changes in surface sensible heat flux (Duan et al., 2018; Y. Liu et al., 2012).

5.2. Clarification of the Climatic Effects of Mechanical and Thermal Forcing

The dynamic/orographic/mechanical effects of mountains on atmospheric circulation during winter have been examined since the late 1940s (e.g., Queney, 1948; Wu, 1984; Yeh, 1950). B. J. Hoskins and Karoly (1981) and Held (1983) discussed linear processes in orographic forcing, whereas Valdes and Hoskins (1991) emphasized nonlinear processes. Since the 1950s, investigations on the importance of thermal forcing across the TP in generating anomalous ASM have received greater attention than those exploring the role of TP mechanical forcing. Y. Liu et al. (2007) compared these two impacts on ASM circulations using a sequence of idealized experiments with a global primitive equation model, with their results indicating some similarities between the responses to the two forcings when applied separately. The upper tropospheric Tibetan anticyclone is predominantly generated by heating, with a weak contribution from orographic effects (Figure 10). Below this, both forcings tend to

10.1029/2022RG000771

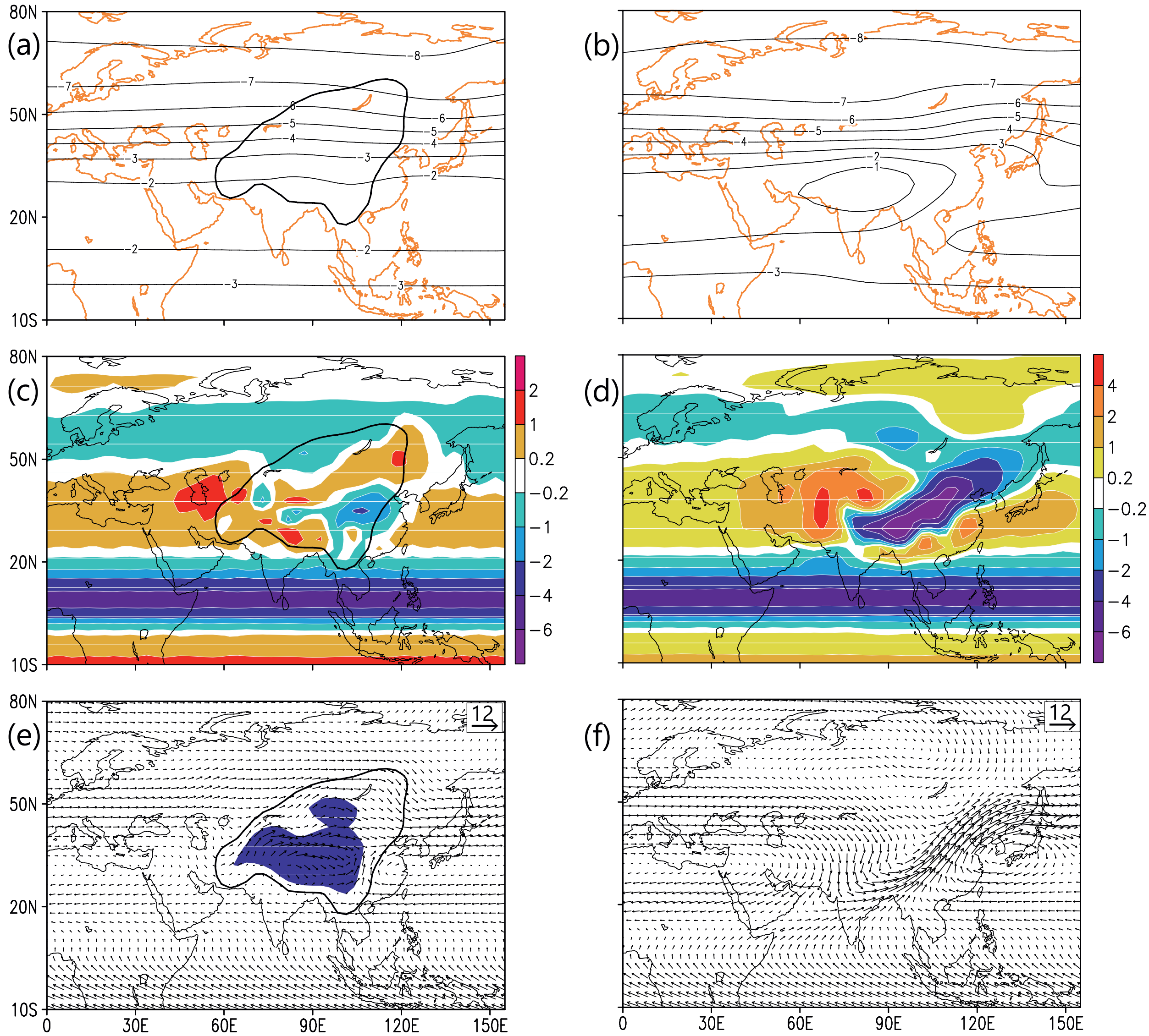

Figure 10. Comparing means of days 15–70 for the Tibetan Plateau (TP) orography only experiment (left column), and TP heating only experiment (right column) via a global primitive equation model: (a, b) 200 hPa stream function (units 10^7 m^2 s^{-1}), (c, d) 400 hPa vertical motion (units 10^{-2} Pa s^{-1}), and (e, f) wind vectors at 850 hPa (units m s^{-1}). The orographic height of 500 m is depicted by the bold contour, and the region where the 850-hPa surface is below ground is shaded in (e). Source: Y. Liu et al. (2007).

generate air descending in an equatorward anticyclonic circulation, down the isentropes to the west, and rising in a similar poleward circulation to the east; however, the heating-only response had a strong ascending southwesterly flow that was guided around the south and southeast of the orography when included. On the northern side, westerly flow over the orography gives rise to an upslope, and descent on the downslope.

Based on an Atmospheric General Circulation Model, Boos and Kuang (2010) showed that although TP heating locally enhances rainfall along its southern edge, large-scale SASM circulation is otherwise unaffected by plateau removal, provided that the narrow orography of the Himalayas and adjacent mountain ranges are preserved. These mountains produce strong monsoons by insulating warm, moist air over subcontinental India from the cold, dry extratropics. This hypothesis has stimulated a debate regarding the maintenance of the SASM (B. He et al., 2015; Y. Liu et al., 2020c; M. Lu et al., 2021; Qiu, 2013; Wu et al., 2012c, Y. Wu et al., 2020b), and subsequent numerical experiments have shown that the proposed barrier-induced blocking mechanism could not be found (e.g., G.-S. Chen et al., 2014). This is likely a result of surface SH on the southern slopes of the Himalayas (i.e., southern slopes of the TP) being retained in the experimental design of Boos and Kuang (2010). Therefore, the thermal pumping effect of the TP was included. Notably, once the surface SH on the southern slopes of the Himalayas was removed, the northern branch of the SASM and EASM disappeared (Y. Liu et al., 2020c; Wu et al., 2012c). Son et al. (2019, 2020) suggested that the Rossby waves induced by mechanical uplifting of the westerly winds accounted for ∼65% of the total EASM precipitation; however, in their "without heating" model design, the increasing albedo was assigned only to the TP areas above 2.5 km elevation. Here, surface SH over the slopes of the TP areas below 2.5 km elevation was retained. Over 85% of the water vapor contained in the atmosphere is located within 3 km above the surface. Because the thermal pumping of TP uplifted to approximately 2 km produces a primary EASM (X. Liu & Yin, 2002; G. Wu et al., 2016), the thermal impact of the upper TP on the EASM can substantially underestimate its full thermal influence. Recently, H. Sun and Liu (2021) indicated that both the mechanical and thermal effects of the TP on precipitation exhibit a more salient influence on the EASM than on the SASM region, while the effects on precipitation possess remarkable regional and seasonal dependence. In general, the consensus is that the thermal influence of the TP dominates precipitation distribution over the ASM regions in the summer; whereas its mechanical influence contributes more in the winter (Y. Liu et al., 2007; M. Lu et al., 2021).

5.3. Thermal Impact on the Asian Summer Monsoon

In the summer, the zero-westerly wind line occurs within the TP region, while TP heating has a crucial impact on the Asian monsoon and its variability. The TP generates the strongest monsoon circulation on Earth, where summer surface SH on large mountain slopes can lift the surrounding air mass and water vapor to produce surface convergent flows and rainfall (Figure 11). In winter, surface cooling over the TP slopes induces a slow downward motion and air mass outflow to the surrounding areas, thereby producing surface divergence from the TP toward other Asian regions in the lowest atmosphere. Both of these seasonal pumping processes combine to form the TP-SHAP, thereby affecting overall monsoon circulation (Wu et al., 1997, 2007).

The potential vorticity forcing induced by the TP-SHAP generates a strong, vast cyclonic circulation surrounding the plateau in the lower troposphere, which transports abundant water vapor from the sea to land for continental monsoon rainfall. TP heating also creates the minimum absolute and potential vorticities in the upper troposphere of the subtropics by altering the temperature and pressure field structures above the TP, and inducing monsoonal meridional circulation under the constraint of angular momentum conservation. This mechanism generates a favorable large-scale ascending background for monsoon development over the vast ASM region (Hsu & Plumb, 2000; Wu et al., 2016a, 2018). TP thermal forcing can also influence ASM onset over the Bay of Bengal by enhancing the warm pool at the surface, and modulating the South Asian high in the upper troposphere (Wu et al., 2012a, 2015a).

The mechanical barrier effects of the TP in winter split the westerly flow into northern and southern branches while blocking northerly flow in the lower troposphere; thus, the cold intrusion into India is deflected into a northwesterly or northeasterly flow (B. He et al., 2015; Y. Liu et al., 2007, 2020c). In spring, when the westerly winds over the southern TP remain strong, the TP triggers an early occurrence of monsoon rainfall downstream, particularly over the Bay of Bengal and South China (Park et al., 2012). Notably, when there is a positive tripole pattern of sea surface temperature anomalies in the North Atlantic during winter–spring, a stable downstream wave train forms a distinct land–air coupling configuration over the TP in May, consisting of anomalous positive precipitation, negative surface SH, and a baroclinic structure with a shallow anticyclonic circulation in the lower layer (W. Yu et al., 2021). As a result, the cross-equatorial flow is reduced, and the SASM is delayed. In summer, when the westerly winds over the southern TP nearly disappear, the strength of the ASM circulation is not significantly affected by TP isolation. Mechanically driven downstream convergence in the presence of the TP is responsible for the zonally asymmetric monsoon onset in the spring (Park et al., 2012). Further, the TP barrier effect causes the prevailing southerly flow to climb its southern slope, forming heavier precipitation when surface heating occurs on the sloped surface. In the absence of surface heating, the barrier effect would cause the impinging southerly flow to deflect around the TP; thus, no monsoon would be produced over northern India (Y. Liu et al., 2020c; Wu et al., 2012c).

Recent studies on the thermal effect of the TP and its neighboring Iranian Plateau have shown that both areas exert thermal influences on atmospheric circulation (Y. Liu et al., 2017, 2020c; Wu et al., 2016a). Moreover, surface SH over the two plateaus exerts both individual feedback influences on each other. For example, SH over the Iranian Plateau can decrease (increase) SH (LH) over the TP; whereas SH over the TP can increase surface

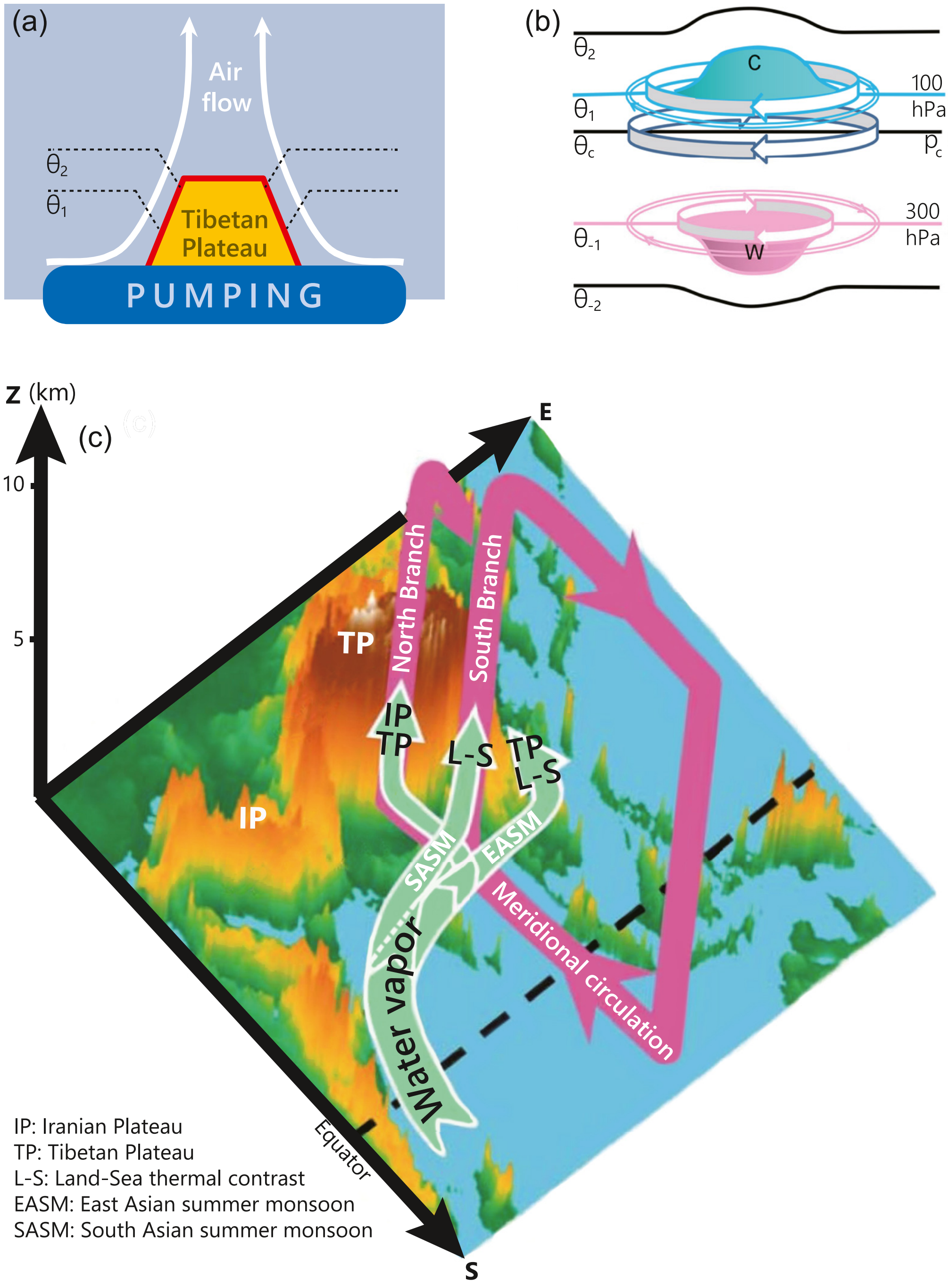

Figure 11. Schematic view of the Tibetan Plateau (TP)-sensible heat-driven air pump (Tibetan Plateau sensible heat-driven air pump, TP-SHAP) for determining the Asian summer monsoon (ASM). (a) TP-SHAP mechanism, where the yellow trapezoid and thick red line represent the plateau and its surface sensible heating, respectively. White vectors indicate the ascending air flow penetrating the isentropic surfaces from smaller surface θ_1 to larger θ_2 due to the TP-SHAP. (b) Schematic indicating the formation of the minimum potential vorticity forcing area near the tropopause due to TP thermal forcing. Vectors indicate anticyclonic circulation, where C (blue) denotes cold temperatures, and W (pink) denotes warm temperature. (c) Schematic diagram showing gross ASM structure. The southern branch of the South Asian summer monsoon is mainly due to land–sea thermal contrast in the tropics; whereas for the northern branch, water vapor is drawn northward toward the continent, and uplifted to produce heavy precipitation controlled primarily by the TP-SHAP. The remaining water vapor is transported northeastward to sustain the East Asian summer monsoon, which is controlled by the land–sea thermal contrast, as well as the thermal forcing of the TP. Source: G. Wu et al. (2007, 2012c, 2016).

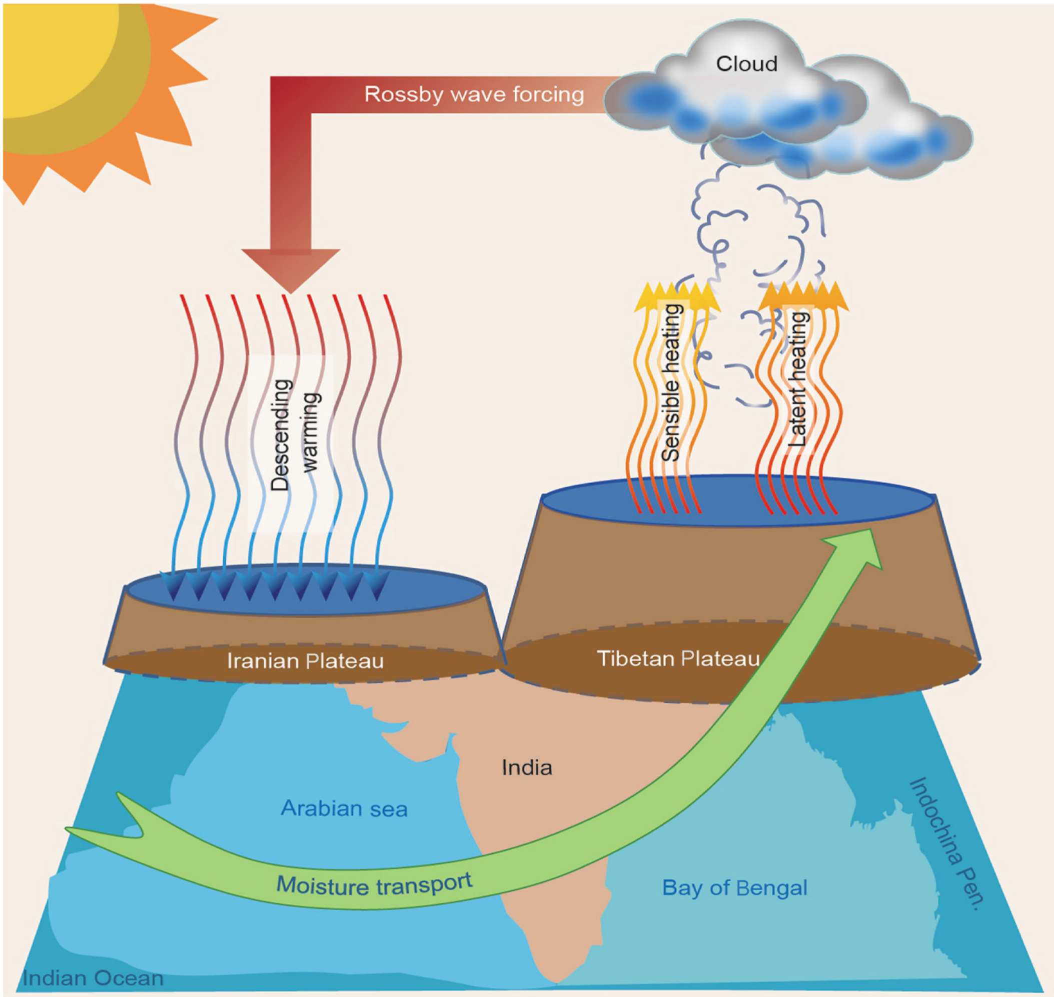

Figure 12. Schematic of a feedback coupling system composed of thermal forcing over the Tibetan Plateau, Iranian Plateau, and water-vapor transport in South Asia. Source: Y. Liu et al. (2017) and B. Zhang (2017).

heating over the Iranian Plateau, thereby reaching a quasi-equilibrium between sensible and latent heat over the TP, sensible heat over the Iranian Plateau, and vertical atmospheric motions. The heating effect of the TP–Iranian Plateau coupling system increases the upper-tropospheric temperature maximum and lifts the tropopause, thereby cooling the lower stratosphere (Figure 12; Y. Liu et al., 2017, 2020c). Furthermore, the coupling system generates a separate cyclonic circulation in the lower troposphere, which contributes to the aridity of North Africa, and heavy precipitation over the Arabian Sea and northern India, enhancing the SASM and EASM while spurring the development of a central-Asian desert (Wu et al., 2012c). Thus, within the TP–Iranian Plateau coupling system, the interaction between surface SH and LH over the TP plays a leading role.

Studies have also revealed that the TP summer monsoon is a subsystem of the ASM, independent of both the SASM and EASM (Kuo & Qian, 1981; M. Tang et al., 1979, 1984; S. Xu & Gao, 1962). Atmospheric heating drives warm temperature, low-pressure environments in the TP summer, and cold, high-pressure conditions in the winter, forming opposing prevailing wind systems between the two systems. Further studies have also supported the relative independence of the TP monsoon, its close relation to other Asian monsoon subsystems (M. Wang & Duan, 2015), and its important impacts on atmospheric circulation and climate anomalies in EA. Ge et al. (2017) revealed that the TP summer monsoon has a significant effect on summer precipitation in northern India, where stronger (weaker) TP monsoons strengthen (weaken) the south branch of the westerlies, inhibiting (benefiting) meridional flow of moist air from the Indian Ocean while causing the water vapor transport of northern India and monsoon rainfall to decrease (increase).

10.1029/2022RG000771

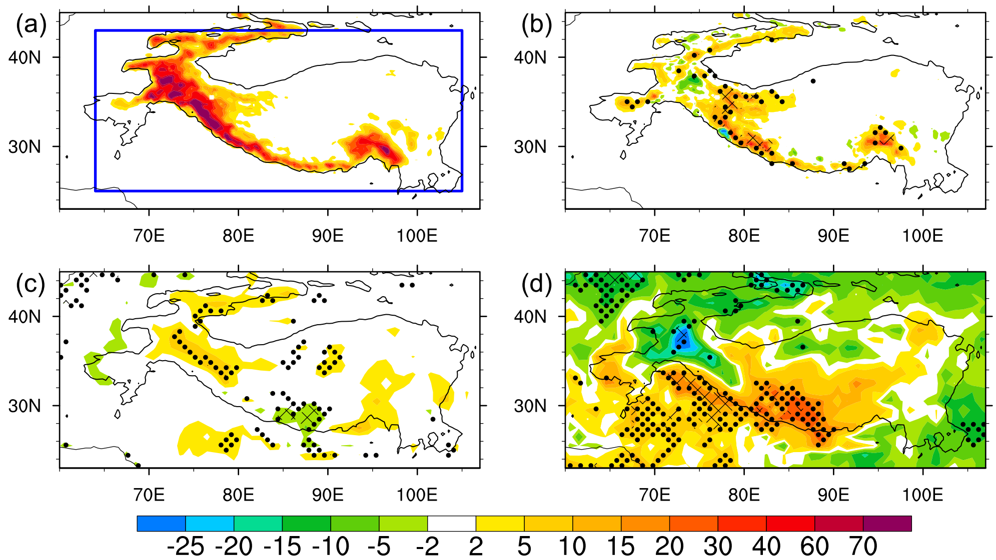

Figure 13. Climatological spatial distribution of (a) snow water equivalent (Shading, Units: mm) in May. Composite differences of (b) snow water equivalent (Shading, Units: mm), (c) surface albedo (shading, unit: %), and (d) surface net shortwave radiation (shading, Unit: W m^{-2}) between above- and below-normal Tibetan Plateau (TP) snow cover years, according to the snow cover area proportion index in May. The blue box in (a) indicates the domain used to define the snow cover area proportion index (64°E–105°E, 25°N–43°N). The dots indicate the differences are statistically significant at the 90% confidence level according to the Student's *t*-test. Black contours in each panel outline TP areas with an averaged altitude >2,000 m. Source: Xiao and Duan (2016).

5.4. Changes to Thermal Forcing

Snow cover influences the local surface energy budget and hydrological flux, which in turn affects large-scale atmospheric circulation (Che et al., 2019; Xiao & Duan, 2016). The albedo effect of heavy TP snow reduces the amount of absorbed solar radiation, cooling the surface; whereas the hydrological effect of spring snowmelt increases soil moisture, and prolongs surface cooling through soil moisture evaporation. Melting heavy snow, and subsequent wet soils in the spring reduce sensible surface and tropospheric heating above the TP. Furthermore, multiple sources of snow data analysis have demonstrated that the effects of winter or spring snow cover anomalies over the western TP and Himalayas can remain until the summer (Xiao & Duan, 2016). More snow cover in western TP may increase surface albedo, thereby decreasing the absorbed net shortwave radiation, and further intensifying western TP snow cover (Figure 13). Through such snow-albedo feedbacks, excessive western TP snow cover anomalies may strengthen and persist throughout the summer; however, the persistent effects of winter snow cover over most parts of the central and eastern TP are limited to the period from winter to spring, thus exerting little influence on the summer atmospheric heat source over the TP.

Aerosols also affect thermal forcing; for example, dust aerosols can significantly affect the radiative energy budget and thermodynamic structure of the air column over the TP, primarily through altering the shortwave radiation budget (R. Jia et al., 2018). The resulting annual and interannual variations in dust-forced radiative heating highlight their significant warming effect on atmospheric thermal structure, particularly near the surface (T. Wang et al., 2020b). Similarly, black carbon can further induce positive radiative effects, exerting pronounced warming over the TP, which can in turn further enhance the thermal pumping (Das et al., 2021; Luo et al., 2020; Sharma et al., 2021; C. Zhao et al., 2020).

Rapid warming since the 1980s, and wind stilling (i.e., weakening) since the 1970s have also caused changes in thermal forcing over the TP. K. Yang et al. (2014) and Ma et al. (2017) suggested that wind stilling would decrease the amount of heat transferred from the TP, and result in ozone depletion, enhanced greenhouse gas effects, and the enrichment of surface-water evaporation. With the rapid retreat and thinning of permafrost, large carbon pools sequestered within can be released, thereby increasing the net sources of atmospheric carbon, and creating a positive feedback loop, further accelerating warming trends. Rapid warming and wind stilling also lower the Bowen ratio, and reduce the surface sensible heat flux; whereas warming can enhance atmospheric radiative cooling through outgoing longwave radiation. Together, these processes contribute to the weakened thermal forcing over the TP (Ma et al., 2017; K. Yang et al., 2014).

6. TP Modulation on Global Climate

The large-scale orography of the TP affects the Asian climate primarily through thermal forcing in the spring and summer, and mechanical forcing in winter (Ashfaq, 2020; Held & Ting, 1990; Y. Liu et al., 2007; Wu et al., 2007, 2015a). Earlier studies extensively investigated the TP's impacts on the regional westerly jet stream, local atmospheric circulation, and ASM (Abe et al., 2013; An et al., 2001; Flohn, 1957; Hahn & Manabe, 1975; Kitoh et al., 2013; Molnar et al., 1993; Wu, 1984; Wu et al., 2012c; Yanai & Wu, 2006; Yeh, 1950; Y. Zhang et al., 2004). It has also been demonstrated that TP forcing and its variability can modulate hemispheric-scale atmospheric circulation across all seasons, with many of these effects being related to known teleconnections (M. Lu et al., 2018; Nan et al., 2019; B. Wang et al., 2008; P. Zhang et al., 2005; P. Zhao & Chen, 2001). The TP can interact with remote oceans through forced atmospheric responses, thereby regulating sea surface temperatures and oceanic currents (Baldwin et al., 2019; Fallah et al., 2016; B. He et al., 2019; C. He et al., 2019; M. Lu et al., 2019; R. Sun et al., 2019; H. Yang et al., 2020). Such interactions can play a crucial role in the global climate.

6.1. Impacts on Stationary Waves

Theoretical studies on atmospheric waves since the 1940s have considerably contributed toward historical research regarding the TP's climate effects (Bolin, 1950; Flohn, 1957; Z. Gu, 1951; Queney, 1948; Yeh, 1950). Initially, studies focused on stationary waves mechanically generated by orography (Bolin, 1950; Queney, 1948). Thereafter, Yeh (1954) initiated thermal effect studies by proposing the importance of both mechanical and thermal forcing. For pure mechanical forcing, the airflow impinging upon the TP is deflected around the high mountains, rather than climbing over them, as TP topography is higher than the critical mountain height which is between 100 and 1,000 m (Wu, 1984). Held and Ting (1990) further demonstrated that the relative magnitude of the stationary waves in response to mechanical forcing decreases with the weakening of the westerlies; whereas the wave magnitude in response to thermal forcing increases with weakening westerlies. Consequently, the impact of the TP on stationary waves is dominated by thermal forcing in the summer, and mechanical forcing in the winter (Y. Liu et al., 2007; Wu et al., 2007, 2015a).

During the winter, westerly winds are deflected by the TP topography (Figure 14a), and the resulting zonal deviation of streamlines produces an asymmetric dipole with anticyclonic circulation in the northern TP and cyclonic circulation in the south (Wu et al., 2007). The anticyclonic gyre at high latitudes transports warm air northward to the west, and cold air southward to the east; whereas the cyclonic gyre at low latitudes transports dry air southward to the Indian subcontinent, and moist air northward to the Indochina Peninsula and South China, triggering the dry season in South Asia, and the persistent rainy season in Southeast Asia and South China that precedes the onset of the ASM (Wu et al., 2007, 2015a; Wu & Liu, 2016). During the spring, a TP-dipole-type stationary circulation pattern persists, contributing to the formation of persistent rainfall in the early spring over South China (Wu et al., 2015b).

During the summer, thermal forcing promotes the convergence of the surrounding air mass in the lower troposphere toward the TP along a cyclonic pathway (Figure 14b). Simultaneously, mechanical forcing tends to generate anticyclonic circulations on both the west and east sides by deflecting the impinging westerlies in the higher latitudes to the west, and the impinging easterlies in the lower latitudes to the east. Because the climatological isentropic surfaces along the subtropics tilt sharply southward, mechanically forced anticyclonic circulations slide upward to the eastern TP, and downward to the west (B. J. Hoskins, 1991; B. Hoskins et al., 2003). Consequently, the resulting mechanically forced vertical motion is in phase with the thermal forcing (Y. Liu et al., 2007; Wu et al., 2015a); thus, although thermal forcing was dominant, mechanical forcing also favored the observed descent and ascent vertical motions in the western and eastern TP, respectively.

In addition to climatology, anomalous TP thermal forcing can influence downstream climate variability by triggering anomalous Rossby wave trains (Cui et al., 2015; Y. Liu et al., 2020c). While early studies examined the impacts of winter–spring TP snow anomalies on the ASM (Senan et al., 2016; Si & Ding, 2013; Xiao & Duan, 2016; You et al., 2020c), recent observational and modeling studies have shown that persistent TP thermal

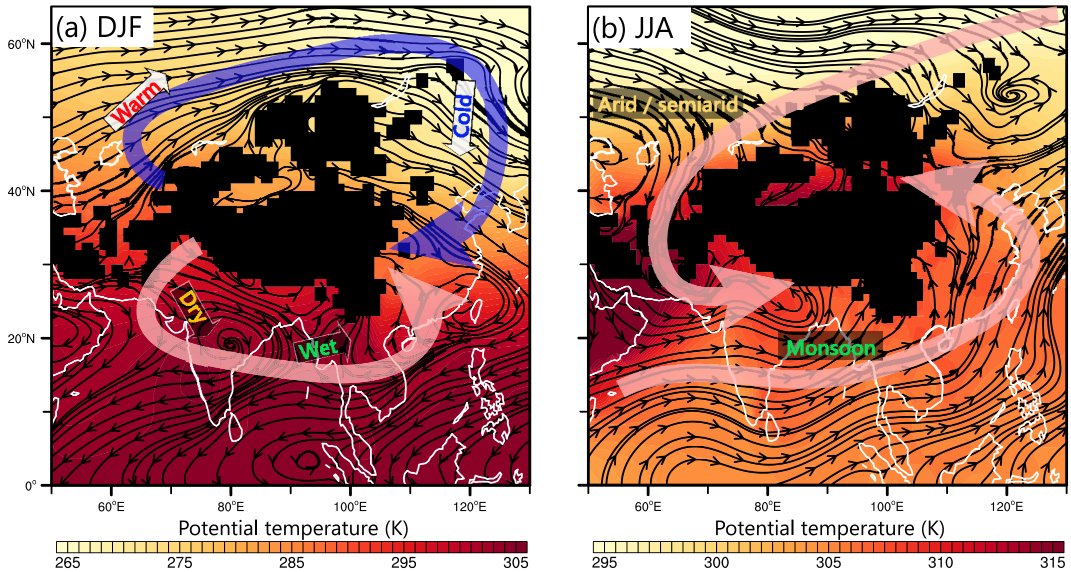

Figure 14. Distribution of 850 hPa potential temperature and stream fields (streamlines) for the means from: (a) December–February, and (b) June–August, based on ERA5 reanalysis (Hersbach et al., 2020) across 1979–2019. Blue (anticyclonic) and pink (cyclonic) curled arrows show stream fields when zonal means were removed. Source: Reproduced based on Figure 7 of Wu et al. (2007).

forcing due to snow anomalies or other changes can cause hemispheric-scale atmospheric circulation variations across all seasons (W. Li et al., 2021; Y. Liu et al., 2020b, 2020c; X. Sun et al., 2021; H. Sun & Liu, 2021).

In particular, the persistent autumn–winter TP snow anomaly affects the Pacific–North America (PNA) teleconnection response and the southward migration of the East Asian jet stream, while altering the North Pacific storm track (H. Lin & Wu, 2011; Wu et al., 2011). The PNA teleconnection response stems from the increased eastward propagation of stationary Rossby-wave energy, triggered by persistent TP snow forcing in conjunction with the transient eddy feedback mechanism (S. Liu et al., 2017). Extensive autumn TP snow cover causes the PNA teleconnection to favor warm–north and cold–south North American winters with substantial predictability (H. Lin & Wu, 2011, 2012). Moreover, the interannual variation of wintertime TP snow cover can influence convection associated with the Madden–Julian Oscillation (MJO; Han et al., 2021; Lyu et al., 2018). MJO convection tends to be stronger over the Indian Ocean when excessive winter TP snow cover is present; whereas convection is more vigorous over the western Pacific when TP snow cover is reduced in winter. The dynamical mechanism is that reduced TP snow cover can exert an anomalous upper-level anticyclone over the TP and eastern China, thus favoring westward extension and enhancement of the South Asian high over the tropical oceans; whereas the inverse is true for enhanced snow cover. Moreover, it was revealed that the zonal-vertical cells associated with the MJO were superposed with anomalous TP snow cover-induced vertical motion in the Indian and western Pacific Oceans (Lyu et al., 2018).

Springtime TP snow cover anomalies can induce an almost-global atmospheric response. Recently, S. Liu et al. (2020a) showed that significantly increased TP snow cover, and snow water equivalent induced a negative West Pacific teleconnection response, and significant tropical response (Figures 15a and 15b). Extensive spring TP snow cover causes simultaneously significant: local and remote surface cooling over most Asian areas surrounding the TP; tropospheric cooling extending from the TP into the North Pacific, and across most of North America and the North Atlantic (Figure 15e); and a southward shift in the North Pacific storm track (Figure 15f), resulting in a negative West Pacific teleconnection response induced throughout the troposphere and stratosphere (Figures 15d and 15g). In addition, extensive spring TP snow increases Pacific trade winds (Figure 15h), a strengthened intertropical convergence zone over the equatorial Pacific, and an enhanced local Hadley circulation (S. Liu et al., 2020a).

In addition to climate, snow cover can persist through summer at the highest altitudes in the western TP (Han et al., 2021; You et al., 2020c), thus affecting Eurasian continental weather patterns (Z. Wu et al., 2016b). For

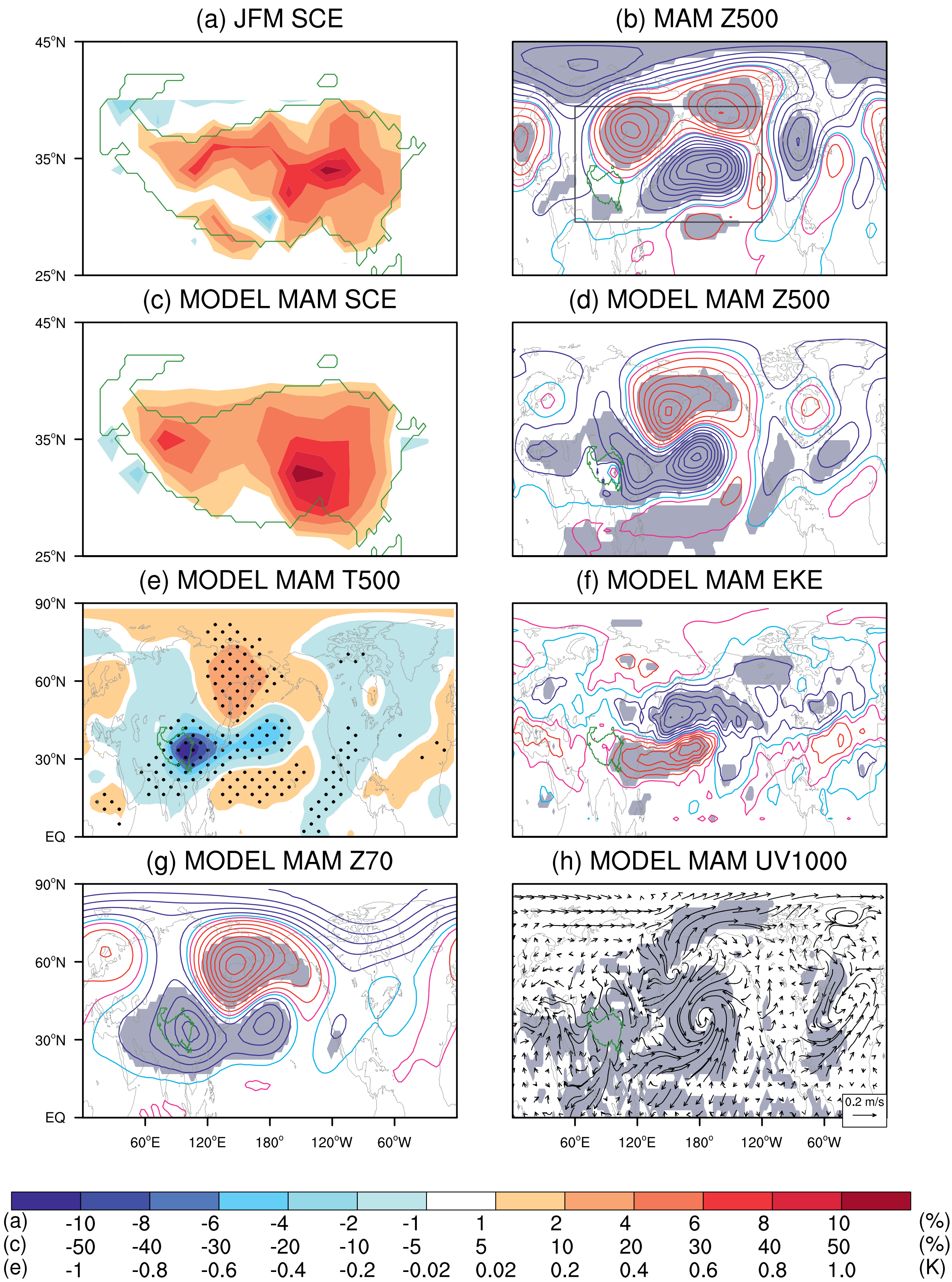
(a) JFM SCE
(b) MAM Z500
(c) MODEL MAM SCE
(d) MODEL MAM Z500
(e) MODEL MAM T500
(f) MODEL MAM EKE
(g) MODEL MAM Z70
(h) MODEL MAM UV1000
45°N
35°N
25°N
90°N
60°N
30°N
EQ
60°E
120°E
180°
120°W
60°W
0.2 m/s
(a) -10 -8 -6 -4 -2 -1 1 2 4 6 8 10 (%)
(c) -50 -40 -30 -20 -10 -5 5 10 20 30 40 50 (%)
(e) -1 -0.8 -0.6 -0.4 -0.2 -0.02 0.02 0.2 0.4 0.6 0.8 1.0 (K)

Figure 15.

instance, TP snow cover variability explains >30% of the total variance in heatwave variability in southern Europe and northeastern Asia (Z. Wu et al., 2016b). Specifically, reduced TP snow cover may induce a distinct teleconnection pattern across the Eurasian continent, with two anomalous high-pressure centers in the upper troposphere over southern Europe and northeastern Asia. In turn, these patterns can potentially lead to reduced cloud formation, increased net shortwave radiation, and stronger surface sensible heat flux, thereby resulting in a deeper, warmer, and drier ABL that would further inhibit local cloud formation. Such positive land–atmosphere feedback can further intensify local heat waves.

6.2. Impacts on Upstream Climate and Pacific Air-Sea Coupling

A prominent subtropical climate system in the upper troposphere during the summer is characterized by a large-scale South Asian high, and upper tropospheric temperature maximum. According to the temperature-vertical gradients of the diabatic heating (T-Q_z) mechanism (Wu et al., 2015b), the zonal location of these factors is jointly anchored by monsoonal convective heating in the east and radiative longwave cooling to the west. The T-Q_z mechanism depicts the response of atmospheric circulation to the zonal and vertical asymmetric distribution of diabatic heating, as derived from the potential vorticity and thermal wind balances. Furthermore, the T-Q_z relationship is significant for interannual variability (Wu et al., 2015b).

The T-Q_z mechanism provides theoretical explanations for the impacts of the TP on the upstream climate, where thermal forcing can influence the upstream climate by regulating both local and adjacent monsoonal convective heating, thus provoking zonal-vertical cells and Rossby waves related to the upper-level high pressure (Y. Liu et al., 2017; Wu et al., 2015a, Wu, He, et al., 2015, 2016b). For example, studies have revealed that TP heating can exert a significant influence on the upstream climate of the Atlantic–African–European sector in the summer (M. Lu et al., 2018, 2019). To the west of the TP, especially in West Asia, Southern Europe, North Africa, and the North Atlantic, prominent zonal-vertical cells and Rossby wave trains were observed in response to anomalous TP heating. When this TP heating is enhanced, an anomalous zonal-vertical cell appears with an ascending motion over the TP and a sinking motion over the Mediterranean Sea (M. Lu et al., 2018). Consequently, anomalous high-pressure and uniform warming appear across the entire troposphere between the ascending motion over the TP, and the descending motion over the regions to the west.

Additionally, the thermal forcing of the TP can also influence the downstream climate in the spring (Nan et al., 2009), such as over the Pacific, featuring barotropic anticyclonic circulation over the northwestern Pacific, and cyclonic circulation to the south (R. Sun et al., 2019). The mechanisms involving both atmospheric Rossby waves and air–sea interactions are summarized in Figure 16. Specifically, SH over the TP in the spring stimulates a Rossby wave train from the TP to the downstream northwestern Pacific region. The anticyclonic circulation induced by the wave train then leads to anticyclonic wind stress at the sea surface, resulting in oceanic Ekman transport and pumping. Consequently, the sea surface temperature anomaly over the North Pacific presents a horseshoe-like pattern, generated by local air-sea fluxes and oceanic meridional heat advection. This is featured by the basin-wide warm anomalies over the central North Pacific that were surrounded by cold anomalies. In addition, the equatorial low-level westerly flow at the southern edge of the cyclonic anomaly favors a warm sea surface temperature anomaly via advection across the equatorial central Pacific. The atmospheric wave response to the warm sea surface temperature anomaly can in turn enhance the atmospheric dipole anomalies over the western Pacific. Therefore, in addition to atmospheric Rossby waves, land-air-sea interactions are crucial for assessing the TP's impact on the downstream PO (Duan et al., 2017; Z. Wang et al., 2019b; Zhuo et al., 2016).

In addition to the spring, the extratropical teleconnection in response to TP heating in the summer is characterized by the Asia–Pacific Oscillation, and shows an increased tropospheric temperature, strengthened ascent motion over Asia, decreased tropospheric temperature, and strengthened sinking motion over the central-eastern North Pacific (J. Liu & Chen, 2017; P. Zhao et al., 2018b, 2019). Notably, the latter reduces in situ mid- and

Figure 15. Observed and simulated spring (MAM) atmospheric responses to Tibetan Plateau (TP) snow forcing. (a, b) Maximum covariance maps of JFM snow cover extent (SCE) and (b) MAM Z500 in the maximum covariance analysis between JFM TP SCE and MAM Z500 anomalies over East Asia to the North Pacific area (outlined in b) during 1979–2015. (c) Difference in MAM TP SCE (%), average of three light spring snow years (1984, 1985, and 1992) minus three heavy spring snow years (1981, 1983, and 1998). (d–h) Ensemble mean spring atmospheric responses to the simultaneous TP snow forcing shown in (c): (d) Z500, (e) T500, (f) 300-hPa eddy kinetic energy (EKE), (g) Z70, and (h) UV1000. The dashed light blue and solid light red contours represent −0.5 and 0.5 m in (b), (d), and (g) for Z500 and Z70, and represent −0.25 and 0.25 $m^2 s^{-2}$ in (f) for EKE to show the detail of tropical atmospheric responses. The darker blue and red contours are at the interval of 2 m for Z500 and Z70 starting with ±2 m and 1 $m^2 s^{-2}$ for EKE starting with ±1 $m^2 s^{-2}$. Source: S. Liu et al. (2020a).

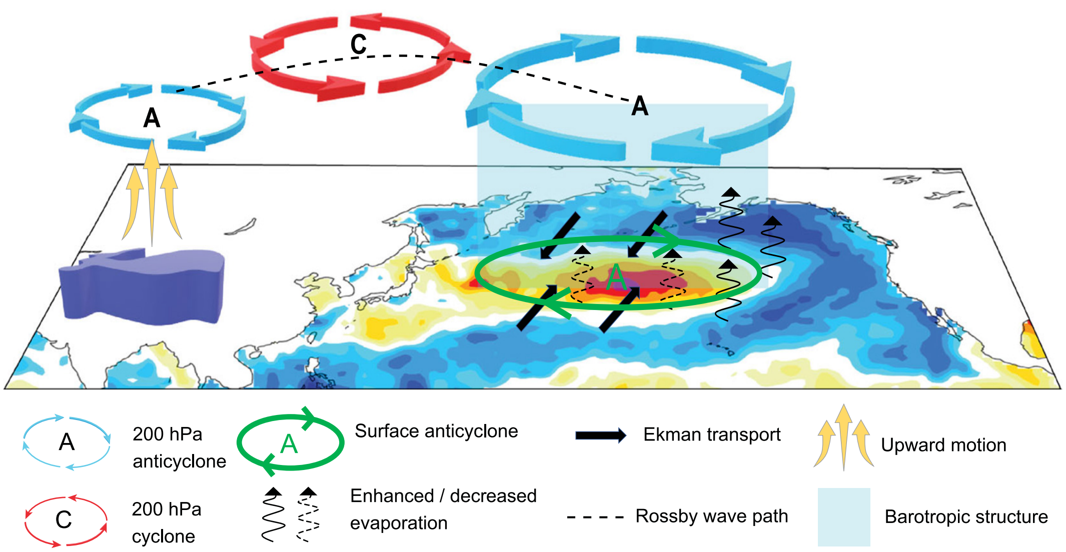

Figure 16. Schematic depicting how spring Tibetan Plateau heating modulates North Pacific air–sea interactions. Source: R. Sun et al. (2019) and Y. Liu et al. (2020c).

upper-tropospheric temperatures, primarily by modulating condensation heating from precipitation. Associated with the Asia–Pacific Oscillation are significant cyclonic anomalies over the Asia–African monsoon region, subtropical anticyclones over the North Pacific and Atlantic, and anomalous land surface temperature and rainfall patterns over Africa, South Asia, EA, and extratropical North America (P. Zhao et al., 2018b). Furthermore, the strengthened anticyclone over the North Pacific modifies local air–sea interactions and ENSO variability (Nan et al., 2009; R. Sun et al., 2019; Wen et al., 2020).

6.3. Impact on the Atlantic Meridional Overturning Circulation

The Atlantic meridional overturning circulation (AMOC) plays a fundamental role in controlling global climate through heat and freshwater transport (Figure 17). For example, the northward ocean heat transport of the AMOC is responsible for the relative warmth of the Northern Hemisphere compared to the Southern Hemisphere (Buckley & Marshall, 2016). However, using a set of numerical simulations, recent studies have suggested that the AMOC cannot persist without the TP (Fallah et al., 2016; B. Su et al., 2018; H. Yang & Wen, 2020).

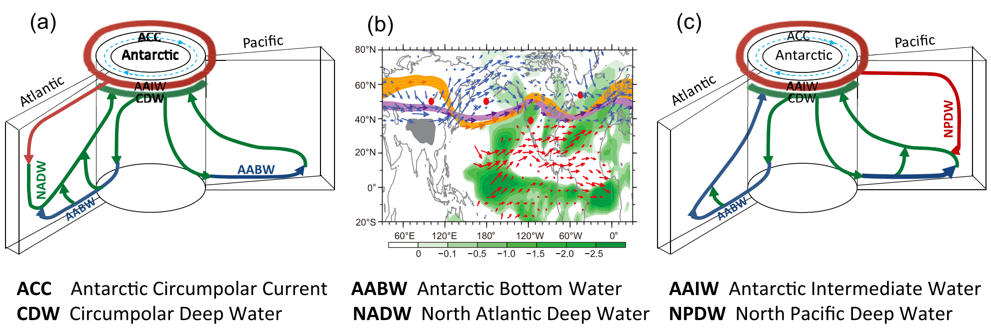

Figure 17. (a) Schematic diagram depicting global overturning circulations in their current state: strong Atlantic meridional overturning circulation (AMOC), and very weak Pacific meridional overturning circulation (PMOC). (b) Changes in wave train, westerlies, and water-vapor transport when the Tibetan Plateau (TP) (gray patch) is removed from the model. Yellow ribbon and arrows show the current stationary wave structure and corresponding winds at 850 hPa geopotential height, respectively; whereas the purple ribbon and arrows are the same as the yellow, except for the modeled world where the TP was excluded. Red dots (blue stars) represent the global high- and low-pressure centers with (without) the TP, while the blue arrows indicate the enhanced westerlies when the TP is removed. Red arrows represent changes in water-vapor transport at 850 hPa, and green shading represents changes in water-vapor convergence, with a negative value indicating the oceanic gain of freshwater from the atmosphere. (c) Schematic diagram showing global overturning circulations in a world without the TP. Notably, the AMOC shuts down, while the PMOC is established. Source: H. Yang and Wen (2020).

In addition to simulations, paleoclimatic records indicate that the time of accelerated TP uplift (∼10–8 million years ago [Ma]) is in pace with the first stage of modern AMOC formation (∼12–9 Ma) (Ferreira et al., 2018). Hence, the TP uplift may have affected the paleoclimate evolution of AMOC. Simulations also suggest an influence of TP topography on the Pacific meridional overturning circulation (PMOC) (B. Su et al., 2018; Wen & Yang, 2020). However, these simulations were performed by models with low resolution, consequently lacking robustness. Therefore, further simulations using multiple high-resolution models are needed to verify these conclusions.

The atmospheric and oceanic circulation responses to TP removal in the simulations are depicted here for reference for further research. Removing the TP topography in the simulations would enhance the mid-latitude westerlies and weaken the trade winds over the tropical Pacific (Figure 17b). Consequently, more moisture would be relocated from the tropical Pacific to the North Atlantic, thus weakening Atlantic thermohaline circulation (Fallah et al., 2016; H. Yang & Wen, 2020). For PMOC, removing the TP promotes anomalous high pressure over the North Pacific, causing anomalous Ekman downwelling, which in turn enhances the saline surface-water subduction north of 40°N. Moreover, high-salinity surface water can also be advected north- and eastward by the Kuroshio and its extensions, subducting to the deeper ocean by the enhanced Ekman downwelling, thus enabling the formation of deep water in the North Pacific and the establishment of PMOC (Figure 17c) (Wen & Yang, 2020).

In addition to TP topography, simulations changing the TP heating further only, indicate that TP heating can exert a remote influence on the climate variability of the North Atlantic (M. Lu et al., 2018, 2019). In turn, TP-induced changes in the North Atlantic sea surface temperature can further modulate the remote influence of the TP (M. Lu et al., 2019). A weakened TP-induced precipitation dipole over the eastern tropical Atlantic and West Africa is observed when the influence of Atlantic sea surface temperatures is considered, leading to the appearance of an anomalous wave train pattern with northeastward downstream influence. This pattern intensifies the northern portions of the anticyclones over the extratropical North Atlantic, and cyclones over northeastern North America and northern Europe. Accordingly, precipitation then decreases over the northwestern Atlantic, increases over northeastern North America and northern Europe, and decreases over the Sahel (M. Lu et al., 2018).

6.4. Global Climate Impact

A group of experiments by a coupled climate model has shown that the absence of the TP would result in a 4°C colder, and 10% drier Northern Hemisphere, in addition to a 2°C warmer Southern Hemisphere relative to current climates (H. Yang et al., 2020), thereby implying a possible contribution of the TP in shaping the current habitable Earth. Figure 18 schematically summarizes the role of the TP in modulating global circulation, and precisely how it affects global land surface temperatures and humidity levels.

On a paleoclimate scale, simulations have suggested that TP topography may help to shape the Earth's modern climate by promoting the establishment of the AMOC, and shutting down the PMOC (Fallah et al., 2016; B. Su et al., 2018; Wen & Yang, 2020; H. Yang et al., 2020). Consequently, the enhancement of northward ocean heat transport and atmospheric moisture transport across the equator results in a warmer and wetter (i.e., more habitable) Northern Hemisphere. Moreover, the TP's presence has influenced the tropical climate, especially by weakening the Hadley cell by 15% and enhancing Walker circulation by 40% (H. Yang & Wen, 2020). The weakened Hadley cell relates to the northward meridional displacement of the convective zone over the Indian–Asian–Pacific region, while the enhanced Walker circulation correlates to the zonal asymmetric changes in the equatorial convections, which are further related to the enhanced easterlies and the cold tongue in the eastern equatorial Pacific. Furthermore, TP uplift also weakens winter ENSO variability by inducing a westward migration of the convection zone, and a lower ocean sensitivity owing to the deeper mixed layer and stronger thermocline (Wen et al., 2020). However, these conclusions are based on limited simulations of a low-resolution model, thus bearing uncertainty.

In addition to these paleoclimatic phenomena, seasonal dynamics of TP's influence on the global climate have been summarized. In the summer (Figure 18a), the TP exerts its influence by modulating westerlies, hemispheric Rossby wave trains, zonal-vertical cells (TP-to-upstream and TP-to-downstream), and meridional-vertical cells (TP-to-Indian Ocean; Y. Liu et al., 2017, 2020c; M. Lu et al., 2018, 2019; Nan et al., 2019; R. Sun et al., 2019; H. Yang et al., 2020; P. Zhao et al., 2019; Zhou et al., 2009). These phenomena can be theoretically explained by combining mechanisms, including the stationary waves theorem (Section 6.1), TP-SHAP (Section 5.3), T-Q_z (Section 6.2), and the threshold behavior theorem of thermally forced circulation (Plumb & Hou, 1992).

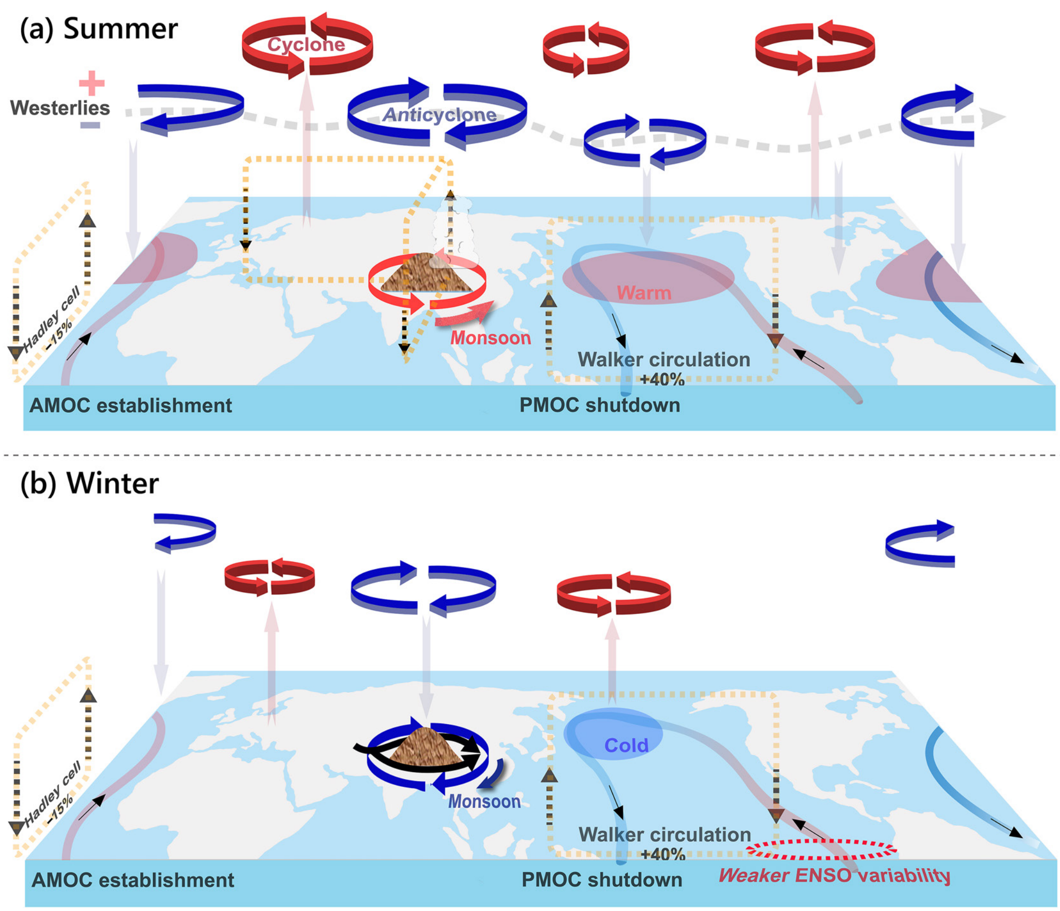

Figure 18. Schematic view of the TP-modulated global circulations in summer (a) and winter (b), summarized based on: Fallah et al. (2016), Lin and Wu (2011, 2012), Y. Liu et al. (2017, 2020c), M. Lu et al. (2018, 2019); Nan et al. (2019), R. Sun et al. (2019), Wen and Yang (2020), Wen et al. (2020), Wu et al. (2007, 2012c), H. Yang et al. (2020), J. Yu et al. (2011a, 2011b), P. Zhao et al. (2019), and Zhou et al. (2009). Illustrations of the Atlantic meridional overturning circulation, Pacific meridional overturning circulation, Hadley cell, and Walker circulation represent the annual mean climate.

A sound theoretical interpretation can thus be summarized as follows: The extensive influence of the TP is facilitated by its coupling with the Asian Monsoon. By inducing the northward extension of the SASM and northeastward migration of the EASM (Section 5.2, TP-SHAP), the TP causes strong diabatic heating within its limits and into the surrounding areas. As this diabatic heating is strong enough to break through the threshold (Plumb & Hou, 1992), angular-momentum-conserving meridional-vertical cells appear in addition to thermal equilibrium stationary waves (Section 6.1). Here, the threshold is the vanished absolute vorticity, which is contributed by the strong anticyclonic South Asian high. According to the T-Q_z mechanism, the zonal location of the South Asian high is jointly determined by that of diabatic heating, in addition to its vertical profile (Section 6.2). The motion of the meridional vertical cells further induces zonal-vertical cells. Because the TP is located in the subtropics, TP-induced upper-level circulation anomalies directly disturb the westerlies, while provoking the Rossby waves that propagate along them (Figure 18a).

Specifically, TP heating induces warming, anomalous ascent, a low-level cyclone, and an upper-level anticyclone covering the mid- and low-latitudes of Eurasia, as well as the western North Pacific (Figure 18a). Through zonal and meridional vertical cells, in addition to Rossby waves, a positive TP heating anomaly can induce decreased rainfall and warmer temperatures over the Mediterranean Sea, Indian Ocean, as well as extratropical North America and the Atlantic (M. Lu et al., 2018; Nan et al., 2019; H. Yang et al., 2020; P. Zhao et al., 2019; Zhou et al., 2009). Furthermore, such a positive anomaly can also induce decreased rainfall and warming over the Pacific through air–sea interactions (J. Liu & Chen, 2017; Nan et al., 2019; R. Sun et al., 2019), in addition to increased rainfall over the pan-Arctic areas of Northern Europe and North America (Y. Liu et al., 2020c; M. Lu et al., 2018; P. Zhao et al., 2019).

In contrast to summer, the influence of TP on winter climate is primarily mediated through Rossby waves (Figure 18b). Theoretically, this results from winter TP-related diabatic heating only having the ability to trigger a thermal equilibrium response (Plumb & Hou, 1992) in the absence of strong diabatic heating of the ASM. Climatologically, westerly winds were deflected by the TP topography (Figure 14a); whereas for Rossby wave trains, negative diabatic heating over the TP induced a quasi-barotropic anticyclonic circulation anomaly, which further modulates the wave trains (Figure 18b; J. Yu et al., 2011a, 2011b). Furthermore, anomalous winter TP snow cover can trigger a distinct PNA teleconnection pattern (see Section 6.1), thus affecting the North American winter climate (H. Lin & Wu, 2011, 2012; J. Liu & Chen, 2017; Wu et al., 2011).

7. Future Change of TP Climate and Forcings

For the remainder of the 21st century, the TP climate trends are projected to be warmer and wetter than the present, according to the Coupled Model Intercomparison Project Phase 5 (CMIP5) under Representative Concentration Pathways (RCPs) (Moss et al., 2008, 2010) scenarios, and CMIP6 models under three Shared Socioeconomic Pathways (SSPs, O'Neill et al., 2017; IPCC, 2007, 2013; D. Chen et al., 2015; R. Zhang et al., 2015; You et al., 2020b). Notably, the TP is expected to have higher warming and wetting than the other regions at the same latitude (You et al., 2020b). For temperature and precipitation, the predicted changes are related to projections of future human activities and are notably larger under RCP8.5 than under RCP4.5 (IPCC, 2013; R. Zhang et al., 2015; Zhou et al., 2021). The warming under SSPs in CMIP6 is generally stronger than that under RCPs in CMIP5 (H. Chen et al., 2020). Each of these projections, however, should be considered with caution, as their accuracy is largely dependent upon climate model reliability and the accurate design of future human activity scenarios. Accordingly, the complexities surrounding climate change, imperfect climate models, and differences in future scenarios have led to wide ranges of variability across the projected results (R. Zhang et al., 2015).

7.1. Future of TP Climate

Average annual temperatures over the TP are projected to increase by 3.2–3.5°C over the short-term (2010–2050), and 3.9–6.9°C over the long-term (2051–2100) relative to 1961–1990 averages (Figure 19a). These estimates are based on the results of 21 global climate models from the CMIP5 under RCP4.5 and RCP8.5. Spatial and seasonal warming vary greatly under different scenarios (D. Chen et al., 2015). Compared with the historical reference period (1986–2005), regionally averaged surface temperatures across the TP from the CMIP6 SSP1-2.6/SSP2-4.5/SSP5-8.5 are projected to increase by 1.2/1.3/1.4, 1.7/2/2.6, and 1.7/2.9/5.6°C over the short- (2021–2040), mid- (2041–2060), and long-term (2081–2100), respectively (You et al., 2021). Future climate projections under RCP8.5 using the Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) suggest widespread warming (ca. 5–8°C) over the Himalayan–Tibetan Highlands by the end of the 21st century (Mishra, et al., 2019).

Furthermore, annual mean precipitation over the TP is projected to increase by 10.4%–11.0% over the short-term (2010–2050), and 14.2%–21.4% over the long-term (2051–2100) under RCP4.5 and RCP8.5 relative to 1961–1990 values (Figure 19b) (R. Chen et al., 2022; Gao et al., 2018; Hu & Zhou, 2021; K. Jia et al., 2019; Lun et al., 2021; Y. Zhao et al., 2022). Specifically, the largest precipitation increases are projected to occur in the summer, and the smallest in the winter (D. Chen et al., 2015). Future climate projections using NEX-GDDP under RCP8.5 have also predicted an increase of ≤50% in monsoon and post-monsoon precipitation over the Himalayan-Tibetan Highlands by the end of the 21st century (Mishra et al., 2019); however, different models vary considerably in their projected spatial distributions of precipitation. Similarly, annual mean precipitation is projected to exhibit a 7.4%–21.6% increase by the end of the 21st century under five shared socioeconomic pathways (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSSP3-7.0, SSP5-8.5), with the largest difference relative to current conditions occurring in the northern TP (Y. Zhao et al., 2022).

Glaciers, runoff, snow cover, permafrost, and vegetation are all expected to be affected by future variations in the temperature and precipitation over the TP (W. Xu et al., 2017; M. Yang et al., 2019). From 2010 to 2100, glaciers are expected to retreat whereas the river runoff is expected to increase due to elevated levels of precipitation and glacial meltwater. Snow cover, the number of snow days, and snow water equivalent are projected to decrease. The permafrost area and the active layer thickness are expected to shrink and expand, respectively (D. Chen et al., 2015). With a rise in temperatures and precipitation, the plant growing season is expected to lengthen,

10.1029/2022RG000771

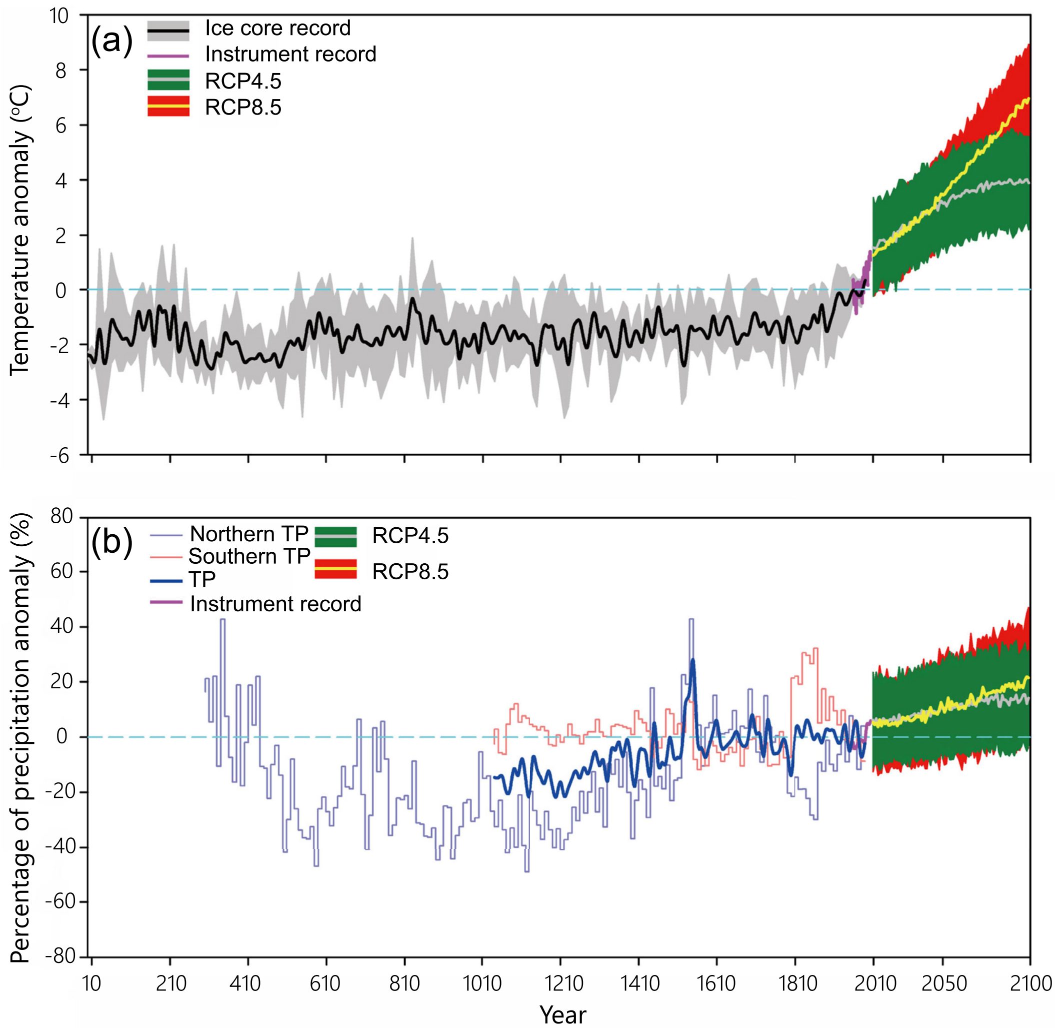

Figure 19. Variations of temperature and precipitation over the Tibetan Plateau (TP) relative to 1961–1990 mean: (a) Temperature time series derived from an integrated curve of the Dunde, Guliya, Puruogangri, and Dasuopu ice core records. Black line indicates the average value, with upper and lower shaded areas corresponding to maximum and minimum annual values. Instrument recorded temperature (purple line) is the annual average during 1960–2012 from 95 meteorological stations across the TP. Yellow line is the average of projection ensembles for TP temperatures using 21 GCMS from CMIP5 for RCP8.5; whereas the red shaded area shows one standard deviation of the projections. The gray curve is the same as the yellow curve, but for RCP4.5, with the green shaded area representing one standard deviation of projections. (b) Precipitation time series, where the thin blue curve is the average net accumulation of Guliya and Puruogangri ice cores, reflecting precipitation variation in the northern TP. Thin red line is the average net accumulation from the Dauopu ice core and reconstructed precipitation from tree-ring records in Langxian, reflecting precipitation variation in the southern TP. Blue line is the average of precipitation anomalies in both the northern and southern TP. Instrument recorded precipitation (purple line) is the average of precipitation anomalies during 1960–2012 from 95 meteorological stations across the TP. Yellow line is the average of prediction ensembles for TP precipitation using 21 GCMS from CMIP 5 for RCP8.5, with the red shaded area indicating one standard deviation. The gray curve is the same as the yellow, but for RCP4.5, with the green shaded area indicating one standard deviation. Source: D. Chen et al. (2015).

leading to an increase in the net primary productivity of the vegetation. Notably, RCP8.5 projects a greater increase than RCP4.5 (D. Chen et al., 2015; R. Zhang et al., 2015).

The ASM anticyclone is expected to change in a warmer world. D. Zhang et al. (2022) indicated that the intensity of the ASM anticyclone is projected to be weakly affected with a large spread among CMIP6 models under SSP5-8.5, suggesting that internal variability plays an important role. The intensity of the ASM anticyclone is expected to be relatively strong during 2015–2037 and 2075–2100, but weak during 2038–2074. Additionally, the position of the ASM anticyclone is projected to move equatorward, as derived from 17 CMIP5 models under RCP4.5, due to the combined effect of LH and the mean advection of stratification change (Qu & Huang, 2016). The stratosphere-troposphere exchange processes and the associated atmospheric composition in the upper troposphere are expected to undergo significant changes due to the changed ASM anticyclone (Gettelman et al., 2004, 2011).

In addition to the average climate, extreme weather conditions over the TP are also predicted to change in the future. Under RCP4.5 and RCP8.5, extreme temperatures and extreme precipitation are expected by coupled climate models to increase compared with 1986–2005 values (D. Chen et al., 2015). Furthermore, extreme temperature indices (coldest/warmest night, coldest/warmest day) all exhibited significant increasing trends under SSP2-4.5 and SSP5-8.5 scenarios (B. Tang et al., 2022).

7.2. Future of TP Thermal Forcing

Spring SH over the TP functions as a large air pump that significantly influences the ASM. However, shortly before 2000, SH began to decrease, with a rapid recovery occurring thereafter. Importantly, it is projected to increase and continue, becoming stronger with higher radiative forcing under SSP1-2.6 to SSP5-8.5 of CMIP6. Additionally, a mechanism analysis indicated that the previous decrease in SH was mainly caused by a decline in the 10 m wind speeds, while the difference in rising ground–air temperature was responsible for recent and projected increases (M. Wang et al., 2019a).

Under the medium-emission scenario (SSP2-4.5), the TP's future summer precipitation is expected to increase; whereas its thermal forcing effects are expected to weaken. Future enhancements in vertical moisture transport and surface evaporation are the primary factors behind the anticipated increase in precipitation. However, greenhouse gas-induced top-heavy heating is expected to help stabilize the atmosphere and diminish the thermal forcing effects of the TP. Hence, SH in the summer is expected to remain unchanged, as the surface wind speeds largely remain unchanged (Z. Xie & Wang, 2021).

It should be noted that current global climate system models have some biases in simulating TP climate and weather. For example, for the state-of-the-art climate models, there are common biases of cold temperature and overestimated precipitation over the TP, which are related to unrealistic model physic processes and the use of the lower topography in the coarse resolution over the TP (X. Chen et al., 2017). Therefore, with the rapid development and application of the supercomputing power, the higher resolution models with more realistic physical parameterizations are expected to be used to investigate the role of TP thermal forcing in the next Coupled Model Intercomparison Project.

8. Conclusions and Outlook

Recent advances have significantly improved the scientific understanding of land–surface and atmospheric interactions over the TP, as well as their impacts on the global climate, which can be summarized as follows:

1. Scientists have been performing experiments and field investigations within the TP for over half a century, culminating in the establishment of a comprehensive observation network that includes the Tibetan Observation and Research Platform. As a result, it has been empirically shown that land–atmosphere interactions influence the climate across different spatiotemporal scales. Furthermore, plateau-scale surface and atmospheric heating are critical for maintaining the South Asian high and SASM. Indeed, anomalies in cryospheric and soil moisture conditions during the spring may either weaken or enhance surface and atmospheric heat sources, resulting in regional hydroclimate variability. An additional important finding relates to the key role of surface evaporation in the water and energy cycles over the TP. Lastly, the available research clarifies that local and regional climates are affected by interactions between land (lithosphere, glacier, and hydrosphere) and the atmosphere.
2. The TP is becoming warmer and wetter; however, precipitation trends differ across the TP and the surrounding regions. Notably, major lakes in the central and western TP have expanded significantly in terms of both area and depth over recent decades; whereas lakes along the southern and eastern TP have shrunk. Similarly, while accelerated warming has driven glacier retreat, shrinkage was not homogeneous across the plateau. Higher temperatures have also degraded permafrost, thickened the active layer, decreased the average annual snow depth, and increased vegetation density.

3. In situ measurements have confirmed that the ASM anticyclonic circulation system surrounding the TP is a major pathway of tropospheric pollution and water vapor vertical transport, through which surface pollutants are transported to the upper troposphere and spread throughout the lower stratosphere. Moreover, the position of the ASM anticyclone is projected to shift equatorward, while its intensity is predicted to show weak changes in a warmer world.
4. The ASM is influenced by both the thermal forcing and mechanical barrier effects of the TP. The thermal forcing largely dictates the precipitation in summer, whereas the mechanical forcing is predominant in winter. The thermal and mechanical effects of the TP exert more significant impacts in the EASM than in the SASM region. The mechanism underlying the influence of the TP on monsoonal circulation is called TP-SHAP. That is, the surface SH on the slopes of the TP acts as an air pump that lifts the surrounding air mass and water vapor to produce surface convergent flows, ascent flow, and rainfall. The condensation heat of the rainfall further energizes this air pump, providing abundant water vapor for the continental monsoon rainfall and the large-scale ascending background for monsoon development.
5. TP uplift may have contributed to the current habitable Northern Hemisphere by promoting the AMOC, according to the limited simulations, which need to be verified by further research. Persistent TP thermal forcing from snowfall anomalies or other changes can cause hemisphere-scale variations in atmospheric circulation across all seasons. Namely, significantly elevated TP snow cover and snow water equivalent induced a negative West Pacific teleconnection and significant tropical responses. Moreover, persistent autumn–winter TP snow anomalies affect the PNA teleconnection, East Asian jet-stream migration, and North Pacific storm track in the winter. In the summer, the extensive influence of the TP is facilitated by its coupling with the ASM. Through this interaction, the TP modulates westerlies, hemispheric Rossby wave trains, zonal-vertical cells (TP to upstream and downstream), and meridional-vertical cells (TP to the Indian Ocean). In contrast, the TP's lessened influence on winter climates primarily occurs through Rossby waves, possibly deriving from the ASM's minimal contribution to TP-related diabatic heating throughout this season; thus, it can only trigger the thermal equilibrium (Plumb & Hou, 1992), leading to more stationary waves.
6. Climate model projections indicate continued increases in temperature and precipitation across the TP over the 21st century. Consequently, major effects on glaciers, runoff, snow cover, permafrost, and vegetation are expected. Likewise, spring SH over the TP is expected to maintain its increasing trend, although summer SH is expected to remain unchanged. Finally, summer thermal forcing effects are expected to weaken.

The TP will continue to play a unique role in the warming global climate of the coming decades. To gain a more systematic understanding of these effects, the focus should be placed on the following aspects:

1. Improving data collection to quantitatively understand the role of diabatic heating over the TP. Current satellite datasets and in situ observations fall short of such requirements, as considerable uncertainty remains surrounding the quantitative estimation of surface fluxes, energy budgets, clouds, and precipitation for all reanalysis products. Thus, to more fully understand the effects of the TP on global climate variability, it is necessary to establish more routine and automatic meteorological stations across the TP, particularly for data-scarce regions in the northwest, and at high elevations.
2. Improving the temporal resolution (e.g., hourly) of observations. This will enable accurate simulations of convection, cloud, and precipitation processes. Moreover, the improved resolution will improve latent heat profiles of cloud precipitation, to evaluate correlated model structures and the understanding of spatiotemporal changes in cloud parameters and the consequent effects on the radiation budget, precipitation efficiency, and water cycle. This will fully reveal the physical mechanisms underlying cloud precipitation processes.
3. Building a “digital twin” of the earth by improving regional and global climate system models, as they are becoming increasingly important for understanding the nature and variability of planetary patterning. The reliability of numerical simulations is limited by model uncertainties owing to coarse resolutions and physical parameterizations. Accordingly, most state-of-the-art models maintain substantial cold and wet biases across the TP, and it remains essential to develop a global kilometer-scale resolution coupled climate system model through resolving convection processes and complex terrains, improving the land surface processes, and taking full advantage of next-generation supercomputers.

Data Availability Statement

The ERA5 data used to produce Figure 14 can be accessed from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (91937302, 91637312, 91837311, 91637208, and 92037000).

References

Abe, M., Hori, M., Yasunari, T., & Kitoh, A. (2013). Effects of the Tibetan Plateau on the onset of the summer monsoon in South Asia: The role of the air-sea interaction. *Journal of Geophysical Research: Atmospheres*, *118*(4), 1760–1776. https://doi.org/10.1002/jgrd.50210

An, Z., Kutzbach, J. E., Prell, W. L., & Porter, S. C. (2001). Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature*, *411*(6833), 62–66. https://doi.org/10.1038/35075035

Ashfaq, M. (2020). Topographic controls on the distribution of summer monsoon precipitation over South Asia. *Earth Systems and Environment*, *4*(4), 667–683. https://doi.org/10.1007/s41748-020-00196-0

Baldwin, J. W., Vecchi, G. A., & Bordoni, S. (2019). The direct and ocean-mediated influence of Asian orography on tropical precipitation and cyclones. *Climate Dynamics*, *53*(1–2), 805–824. https://doi.org/10.1007/s00382-019-04615-5

Bian, J., Li, D., Bai, Z., Li, Q., Lyu, D., & Zhou, X. (2020). Transport of Asian surface pollutants to the global stratosphere from the Tibetan Plateau region during the Asian summer monsoon. *National Science Review*, *7*(3), 516–533. https://doi.org/10.1093/nsr/nwaa005

Bian, J., Pan, L. L., Paulik, L., Vömel, H., Chen, H., & Lu, D. (2012). In situ water vapor and ozone measurements in Lhasa and Kunming during the Asian summer monsoon. *Geophysical Research Letters*, *39*(19), L19808. https://doi.org/10.1029/2012GL052996

Bian, J., Yan, R., Chen, H., Lu, D., & Massie, S. T. (2011). Formation of the summertime ozone valley over the Tibetan Plateau: The Asian summer monsoon and air column variations. *Advances in Atmospheric Sciences*, *28*(6), 1318–1325. https://doi.org/10.1007/s00376-011-0174-9

Bibi, S., Wang, L., Li, X., Zhou, J., Chen, D., & Yao, T. (2018). Climatic and associated cryospheric, biospheric, and hydrological changes on the Tibetan Plateau: A review. *International Journal of Climatology*, *38*(S1), e1–e17. https://doi.org/10.1002/joc.5411

Blanford, H. F. (1884). On the connexion of the Himalayan snowfall with dry winds and seasons of droughts in India. *Proceedings of the Royal Society of London*, *37*(232–234), 3–22. https://doi.org/10.1098/rspl.1884.0003

Bolin, B. (1950). On the influence of the earth's orography on the general character of the westerlies. *Tellus*, *2*(3), 184–195. https://doi.org/10.3402/tellusa.v2i3.8547

Boos, W. R., & Kuang, Z. (2010). Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature*, *463*(7278), 218–222. https://doi.org/10.1038/nature08707

Buckley, M. W., & Marshall, J. (2016). Observations, inferences, and mechanisms of the Atlantic meridional overturning circulation: A review. *Reviews of Geophysics*, *54*(1), 5–63. https://doi.org/10.1002/2015RG000493

Cao, B., Zhang, T., Wu, Q., Sheng, Y., Zhao, L., & Zou, D. (2019). Permafrost zonation index map and statistics over the Qinghai–Tibet Plateau based on field evidence. *Permafrost and Periglacial Processes*, *30*(3), 178–194. https://doi.org/10.1002/ppp.2006

Che, T., Hao, X., Dai, L., Li, H., Huang, X., & Xiao, L. (2019). Snow cover variation and its impacts over the Qinghai-Tibet Plateau [in Chinese]. *Bulletin of Chinese Academy of Sciences*, *34*, 1247–1253. https://doi.org/10.16418/j.issn.1000-3045.2019.11.007

Chen, D., Xu, B., Yao, T., Guo, Z., Cui, P., Chen, F., et al. (2015). Assessment of past, present and future environmental changes on the Tibetan Plateau [in Chinese]. *Chinese Science Bulletin*, *60*(32), 3025–3035. https://doi.org/10.1360/N972014-01370

Chen, G.-S., Liu, Z., & Kutzbach, J. E. (2014). Reexamining the barrier effect of the Tibetan Plateau on the South Asian summer monsoon. *Climate of the Past*, *10*(3), 1269–1275. https://doi.org/10.5194/cp-10-1269-2014

Chen, H., Sun, J., Lin, W., & Xu, H. (2020). Comparison of CMIP6 and CMIP5 models in simulating climate extremes. *Science Bulletin*, *65*(17), 1415–1418. https://doi.org/10.1016/j.scib.2020.05.015

Chen, L., Pryor, S. C., Wang, H., & Zhang, R. (2019). Distribution and variation of the surface sensible heat flux over the central and eastern Tibetan Plateau: Comparison of station observations and multireanalysis products. *Journal of Geophysical Research: Atmospheres*, *124*(12), 6191–6206. https://doi.org/10.1029/2018JD030069

Chen, R., Duan, K., Shang, W., Shi, P., Meng, Y., & Zhang, Z. (2022). Increase in seasonal precipitation over the Tibetan Plateau in the 21st century projected using CMIP6 models. *Atmospheric Research*, *277*, 106306. https://doi.org/10.1016/j.atmosres.2022.106306

Chen, S., Huang, J., Zhao, C., Qian, Y., Leung, L. R., & Yang, B. (2013). Modeling the transport and radiative forcing of Taklimakan dust over the Tibetan Plateau: A case study in the summer of 2006. *Journal of Geophysical Research: Atmospheres*, *118*(2), 797–812. https://doi.org/10.1002/jgrd.50122

Chen, X., Liu, Y., & Wu, G. (2017). Understanding the surface temperature cold bias in CMIP5 AGCMs over the Tibetan Plateau. *Advances in Atmospheric Sciences*, *34*(12), 1447–1460. https://doi.org/10.1007/s00376-017-6326-9

Cheng, G., & Wu, T. (2007). Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *Journal of Geophysical Research*, *112*(F2), F02S03. https://doi.org/10.1029/2006JF000631

Cheng, M., Zhong, L., Ma, Y., Zou, M., Ge, N., Wang, X., & Hu, Y. (2019). A study on the assessment of multi-source satellite soil moisture products and reanalysis data for the Tibetan Plateau. *Remote Sensing*, *11*(10), 1196. https://doi.org/10.3390/rs11101196

Cui, Y., Duan, A., Liu, Y., & Wu, G. (2015). Interannual variability of the spring atmospheric heat source over the Tibetan Plateau forced by the North Atlantic SSTA. *Climate Dynamics*, *45*(5), 1617–1634. https://doi.org/10.1007/s00382-014-2417-9

Curio, J., Maussion, F., & Scherer, D. (2015). A 12-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. *Earth System Dynamics*, *6*(1), 109–124. https://doi.org/10.5194/esd-6-109-2015

Dai, Y., Wang, L., Yao, T., Li, X., Zhu, L., & Zhang, X. (2018). Observed and simulated lake effect precipitation over the Tibetan Plateau: An initial study at Nam Co Lake. *Journal of Geophysical Research: Atmospheres*, *123*(13), 6746–6759. https://doi.org/10.1029/2018JD028330

Das, S., Giorgi, F., Coppola, E., Panicker, A. S., Gautam, A. S., Nair, V. S., & Giuliani, G. (2021). Linkage between the absorbing aerosol-induced snow darkening effects over the Himalayas-Tibetan Plateau and the pre-monsoon climate over northern India. In *Theoretical and applied climatology*. Advance Online Publication. https://doi.org/10.1007/s00704-021-03871-y

Dessler, A. E., & Sherwood, S. C. (2004). Effect of convection on the summertime extratropical lower stratosphere. *Journal of Geophysical Research*, *109*(D23), D23301. https://doi.org/10.1029/2004JD005209

Duan, A., Li, F., Wang, M., & Wu, G. (2011). Persistent weakening trend in the spring sensible heat source over the Tibetan Plateau and its impact on the Asian summer monsoon. *Journal of Climate*, *24*(21), 5671–5682. https://doi.org/10.1175/jcli-d-11-00052.1

Duan, A., Liu, S., Zhao, Y., Gao, K., & Hu, W. (2018). Atmospheric heat source/sink dataset over the Tibetan Plateau based on satellite and routine meteorological observations. *Big Earth Data*, *2*(2), 179–189. https://doi.org/10.1080/20964471.2018.1514143

Duan, A., Sun, R., & He, J. (2017). Impact of surface sensible heating over the Tibetan Plateau on the western Pacific subtropical high: A land–air–sea interaction perspective. *Advances in Atmospheric Sciences*, *34*(2), 157–168. https://doi.org/10.1007/s00376-016-6008-z

Duan, A., & Xiao, Z. (2015). Does the climate warming hiatus exist over the Tibetan Plateau? *Scientific Reports*, *5*(1), 13711. https://doi.org/10.1038/srep13711

England, P. C., & Houseman, G. A. (1988). The mechanics of the Tibetan Plateau. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *326*(1589), 301–320. https://doi.org/10.1098/rsta.1988.0089

Fallah, B., Cubasch, U., Prömmel, K., & Sodoudi, S. (2016). A numerical model study on the behaviour of Asian summer monsoon and AMOC due to orographic forcing of Tibetan Plateau. *Climate Dynamics*, *47*(5–6), 1485–1495. https://doi.org/10.1007/s00382-015-2914-5

Fan, Q., Bian, J., & Pan, L. L. (2017a). Atmospheric boundary layer sources for upper tropospheric air over the Asian summer monsoon region. *Atmospheric and Oceanic Science Letters*, *10*(5), 358–363. https://doi.org/10.1080/16742834.2017.1344089

Fan, Q., Bian, J., & Pan, L. L. (2017b). Stratospheric entry point for upper-tropospheric air within the Asian summer monsoon anticyclone. *Science China Earth Sciences*, *60*(9), 1685–1693. https://doi.org/10.1007/s11430-016-9073-5

Fang, X., Han, Y., Ma, J., Song, L., Yang, S., & Zhang, X. (2004). Dust storms and loess accumulation on the Tibetan Plateau: A case study of dust event on 4 March 2003 in Lhasa. *Chinese Science Bulletin*, *49*(9), 953–960. https://doi.org/10.1007/BF03184018

Feng, X., Mao, R., Gong, D., Zhao, C., Wu, C., Zhao, C., et al. (2020). Increased dust aerosols in the high troposphere over the Tibetan Plateau from 1990s to 2000s. *Journal of Geophysical Research: Atmospheres*, *125*(13), e2020JD032807. https://doi.org/10.1029/2020JD032807

Ferreira, D., Cessi, P., Coxall, H. K., Boer, A. M., Dijkstra, H. A., Drijfhout, S., et al. (2018). Atlantic-Pacific asymmetry in deep water formation. *Annual Review of Earth and Planetary Sciences*, *46*(1), 327–352. https://doi.org/10.1146/annurev-earth-082517-010045

Flohn, H. (1957). Large-scale aspects of the "summer monsoon" in South and East Asia. *Journal of the Meteorological Society of Japanese Series II*, *35*, 180–186. https://doi.org/10.2151/jmsj1923.35A.0_180

Flohn, H. (1968). Contribution to a meteorology of the Tibetan Plateau on the formation of Asia monsoon circulation. In *Atmospheric Science Paper*. Colorado State University.

Flohn, H., & Reiter, E. R. (1968). Contributions to a meteorology of the Tibetan Highlands (Doctoral dissertation). Retrieved from https://mountainscholar.org/bitstream/handle/10217/225/0130_Bluebook.pdf;sequence=1

Fu, Y., Liu, G., Wu, G., Yu, R., Xu, Y., Wang, Y., et al. (2006). Tower mast of precipitation over the central Tibetan Plateau summer. *Geophysical Research Letters*, *33*(5), L05802. https://doi.org/10.1029/2005GL024713

Fu, Y., Pan, X., Liu, G., Li, R., & Zhong, L. (2016). Characteristics of precipitation based on cloud brightness temperatures and storm tops in summer Tibetan Plateau. *Chinese Journal of Atmospheric Sciences*, *40*(1), 102–120. https://doi.org/10.3878/j.issn.1006-9895.1507.15165

Fu, Y., Pan, X., Xian, T., Liu, G., Zhong, L., Liu, Q., et al. (2018). Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. *Climate Dynamics*, *51*(5–6), 1971–1989. https://doi.org/10.1007/s00382-017-3992-3

Fujinami, H., & Yasunari, T. (2001). The seasonal and intraseasonal variability of diurnal cloud activity over the Tibetan Plateau. *Journal of the Meteorological Society of Japanese Series II*, *79*(6), 1207–1227. https://doi.org/10.2151/jmsj.79.1207

Gao, K., Duan, A., Chen, D., & Wu, G. (2019). Surface energy budget diagnosis reveals possible mechanism for the different warming rate among Earth's three poles in recent decades. *Science Bulletin*, *64*(16), 1140–1143. https://doi.org/10.1016/j.scib.2019.06.023

Gao, Y., Chen, F., Miguez-Macho, G., & Li, X. (2020). Understanding precipitation recycling over the Tibetan Plateau using tracer analysis with WRF. *Climate Dynamics*, *55*(9), 2921–2937. https://doi.org/10.1007/s00382-020-05426-9

Gao, Y., Xiao, L., Chen, D., Xu, J., & Zhang, H. (2018). Comparison between past and future extreme precipitations simulated by global and regional climate models over the Tibetan Plateau. *International Journal of Climatology*, *38*(3), 1285–1297. https://doi.org/10.1002/joc.5243

Garny, H., & Randel, W. J. (2016). Transport pathways from the Asian monsoon anticyclone to the stratosphere. *Atmospheric Chemistry and Physics*, *16*(4), 2703–2718. https://doi.org/10.5194/acp-16-2703-2016

Ge, F., Sielmann, F., Zhu, X., Fraedrich, K., Zhi, X., Peng, T., & Wang, L. (2017). The link between Tibetan Plateau monsoon and Indian summer precipitation: A linear diagnostic perspective. *Climate dynamics*, *49*(11), 4201–4215. https://doi.org/10.1007/s00382-017-3585-1

Gettelman, A., Hoor, P., Pan, L. L., Randel, W. J., Hegglin, M. I., & Birner, T. (2011). The extratropical upper troposphere and lower stratosphere. *Reviews of Geophysics*, *49*(3), RG3003. https://doi.org/10.1029/2011RG000355

Gettelman, A., Kinnison, D. E., Dunkerton, T. J., & Brasseur, G. P. (2004). Impact of monsoon circulations on the upper troposphere and lower stratosphere. *Journal of Geophysical Research*, *109*(D22), D22101. https://doi.org/10.1029/2004JD004878

Gu, Y., Liao, H., & Bian, J. (2016). Summertime nitrate aerosol in the upper troposphere and lower stratosphere over the Tibetan Plateau and the South Asian summer monsoon region. *Atmospheric Chemistry and Physics*, *16*(11), 6641–6663. https://doi.org/10.5194/acp-16-6641-2016

Gu, Z. (1951). The influence of the Tibetan Plateau on the East Asian circulation and its importance [in Chinese]. *Acta Meteorologica Sinica*, *22*, 43–56.

Guo, D., Pepin, N., Yang, K., Sun, J., & Li, D. (2021). Local changes in snow depth dominate the evolving pattern of elevation-dependent warming on the Tibetan Plateau. *Science Bulletin*, *66*(11), 1146–1150. https://doi.org/10.1016/j.scib.2021.02.013

Guo, D., Sun, J., Yang, K., Pepin, N., & Xu, Y. (2019). Revisiting recent elevation-dependent warming on the Tibetan Plateau using satellite-based data sets. *Journal of Geophysical Research: Atmospheres*, *124*(15), 8511–8521. https://doi.org/10.1029/2019JD030666

Guo, D., & Wang, H. (2013). Simulation of permafrost and seasonally frozen ground conditions on the Tibetan Plateau, 1981–2010. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5216–5230. https://doi.org/10.1002/jgrd.50457

Hahn, D. G., & Manabe, S. (1975). The role of mountains in the south Asian monsoon circulation. *Journal of Atmospheric Sciences*, *32*(8), 1515–1541. https://doi.org/10.1175/1520-0469(1975)032<1515:TROMIT>2.0.CO;2

Han, X., Zhao, H., Klotzbach, P. J., Wu, L., & Raga, G. B. (2021). Impact of Tibetan plateau snow cover on tropical cyclogenesis via the Madden–Julian oscillation during the following boreal summer. *Climate Dynamics*, *56*(9–10), 3025–3043. https://doi.org/10.1007/s00382-021-05625-y

He, B., Liu, Y., Wu, G., Wang, Z., & Bao, Q. (2019). The role of air–sea interactions in regulating the thermal effect of the Tibetan–Iranian Plateau on the Asian summer monsoon. *Climate Dynamics*, *52*(7), 4227–4245. https://doi.org/10.1007/s00382-018-4377-y

He, B., Wu, G., Liu, Y., & Bao, Q. (2015). Astronomical and hydrological perspective of mountain impacts on the Asian summer monsoon. *Scientific reports*, *5*(1), 17586. https://doi.org/10.1038/srep17586

He, C., Wang, Z., Zhou, T., & Li, T. (2019). Enhanced latent heating over the Tibetan Plateau as a key to the enhanced East Asian summer monsoon circulation under a warming climate. *Journal of Climate*, *32*(11), 3373–3388. https://doi.org/10.1175/jcli-d-18-0427.1

Held, I. M. (1983). Stationary and quasi-stationary eddies in the extratropical troposphere: Theory. Large-scale dynamical processes in the atmosphere (pp. 127–168). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.226.5733&rep=rep1&type=pdf

Held, I. M., & Ting, M. (1990). Orographic versus thermal forcing of stationary waves: The importance of the mean low-level wind. *Journal of Atmospheric Sciences*, *47*(4), 495–500. https://doi.org/10.1175/1520-0469(1990)047<0495:OVTFOS>2.0.CO;2

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Höpfner, M., Ungermann, J., Borrmann, S., Wagner, R., Spang, R., Riese, M., et al. (2019). Ammonium nitrate particles formed in upper troposphere from ground ammonia sources during Asian monsoons. *Nature Geoscience*, *12*(8), 608–612. https://doi.org/10.1038/s41561-019-0385-8

Höpfner, M., Volkamer, R., Grabowski, U., Grutter, M., Orphal, S. G., Stiller, G., et al. (2016). First detection of ammonia (NH_3) in the Asian summer monsoon upper troposphere. *Atmospheric Chemistry and Physics*, *16*(22), 14357–14369. https://doi.org/10.5194/acp-16-14357-2016

Hoskins, B., Pedder, M., & Jones, D. W. (2003). The omega equation and potential vorticity. *Quarterly Journal of the Royal Meteorological Society*, *129*(595), 3277–3303. https://doi.org/10.1256/qj.02.135

Hoskins, B. J. (1991). Towards a PV-θ view of the general circulation. *Tellus A: Dynamic Meteorology and Oceanography*, *43*(4), 27–36. https://doi.org/10.3402/tellusa.v43i4.11936

Hoskins, B. J., & Karoly, D. J. (1981). The steady linear response of a spherical atmosphere to thermal and orographic forcing. *Journal of the atmospheric sciences*, *38*(6), 1179–1196. https://doi.org/10.1175/1520-0469(1981)038<1179:tslroa>2.0.co;2

Hsu, C. J., & Plumb, R. A. (2000). Nonaxisymmetric thermally driven circulations and upper-tropospheric monsoon dynamics. *Atmospheric Sciences*, *57*(9), 1255–1276. https://doi.org/10.1175/1520-0469(2000)057<1255:NTDCAU>2.0.CO;2

Hu, S., & Zhou, T. (2021). Skillful prediction of summer rainfall in the Tibetan Plateau on multiyear time scales. *Science Advances*, *7*(24), eabf9395. https://doi.org/10.1126/sciadv.abf9395

Huang, J., Chen, W., Wen, Z., Zhang, G., Li, Z., Zuo, Z., & Zhao, Q. (2019). Review of Chinese atmospheric science research over the past 70 years: Climate and climate change. *Science China Earth Sciences*, *62*(10), 1514–1550. https://doi.org/10.1007/s11430-019-9483-5

Huang, J., Minnis, P., Yi, Y., Tang, Q., Wang, X., Hu, Y., et al. (2007). Summer dust aerosols detected from CALIPSO over the Tibetan Plateau. *Geophysical Research Letters*, *34*(18), L18805. https://doi.org/10.1029/2007gl029938

Huang, J., Xie, Y., Guan, X., Li, D., & Ji, F. (2017). The dynamics of the warming hiatus over the Northern Hemisphere. *Climate Dynamics*, *48*(1–2), 429–446. https://doi.org/10.1007/s00382-016-3085-8

Huang, X., Deng, J., Ma, X., Wang, Y., Feng, Q., Hao, X., & Liang, T. (2016). Spatiotemporal dynamics of snow cover based on multi-source remote sensing data in China. *The Cryosphere*, *10*(5), 2453–2463. https://doi.org/10.5194/tc-10-2453-2016

IPCC. (2007). Climate change 2007: The Physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al. (Eds.), *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* (p. 996). Cambridge University Press.

IPCC. (2013). Climate change 2013: The Physical science basis. In T. F. Stocker, D. Qin, G. K. Plattner, & M. Tignor (Eds.), *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (p. 1535). Cambridge University Press.

Jia, K., Ruan, Y., Yang, Y., & Zhang, C. (2019). Assessing the Performance of CMIP5 global climate models for simulating future Precipitation change in the Tibetan Plateau. *Water*, *11*(9), 1771. https://doi.org/10.3390/w11091771

Jia, R., Liu, Y., Chen, B., Zhang, Z., & Huang, J. (2015). Source and transportation of summer dust over the Tibetan Plateau. *Atmospheric Environment*, *123*, 210–219. https://doi.org/10.1016/j.atmosenv.2015.10.038

Jia, R., Liu, Y., Hua, S., Zhu, Q., & Shao, T. (2018). Estimation of the aerosol radiative effect over the Tibetan Plateau based on the latest CALIPSO product. *Journal of Meteorological Research*, *32*(5), 707–722. https://doi.org/10.1007/s13351-018-8060-3

Jiang, X., Li, Y., Yang, S., Yang, K., & Chen, J. (2016). Interannual variation of summer atmospheric heat source over the Tibetan Plateau and the role of convection around the western Maritime Continent. *Journal of Climate*, *29*(1), 121–138. https://doi.org/10.1175/JCLI-D-15-0181.1

Kang, S., Xu, Y., You, Q., Flügel, W. A., Pepin, N., & Yao, T. (2010). Review of climate and cryospheric change in the Tibetan Plateau. *Environmental Research Letters*, *5*(1), 015101. https://doi.org/10.1088/1748-9326/5/1/015101

Kitoh, A. (2004). Effects of mountain uplift on East Asian summer climate investigated by a coupled atmosphere–ocean GCM. *Journal of Climate*, *17*(4), 783–802. https://doi.org/10.1175/1520-0442(2004)017<0783:EOMUOE>2.0.CO;2

Kitoh, A., & Arakawa, O. (2016). Reduction in the east–west contrast in water budget over the Tibetan Plateau under a future climate. *Hydrological Research Letters*, *10*(4), 113–118. https://doi.org/10.3178/hrl.10.113

Kitoh, A., Endo, H., Krishna Kumar, K., Cavalcanti, I. F., Goswami, P., & Zhou, T. (2013). Monsoons in a changing world: A regional perspective in a global context. *Journal of Geophysical Research: Atmospheres*, *118*(8), 3053–3065. https://doi.org/10.1002/jgrd.50258

Kuo, H., & Qian, Y. (1981). Influence of the Tibetian Plateau on cumulative and diurnal changes of weather and climate in summer. *Monthly Weather Review*, *109*(11), 2337–2356. https://doi.org/10.1175/1520-0493(1981)109<2337:IOTTPO>2.0.CO;2

Kurosaki, Y., & Kimura, F. (2002). Relationship between topography and daytime cloud activity around Tibetan Plateau. *Journal of the Meteorological Society of Japanese Series II*, *80*(6), 1339–1355. https://doi.org/10.2151/jmsj.80.1339

Latif, Y., Ma, Y., & Muhammad, Y. (2018). Spatial analysis of precipitation time series over Upper Indus Basin. *Theoretical and Applied Climatology*, *131*(1–2), 761–775. https://doi.org/10.1007/s00704-016-2007-3

Lee, S. S., Lee, J. Y., Ha, K. J., Wang, B., Kitoh, A., Kajikawa, Y., & Abe, M. (2013). Role of the Tibetan Plateau on the annual variation of mean atmospheric circulation and storm-track activity. *Journal of Climate*, *26*(14), 5270–5286. https://doi.org/10.1175/JCLI-D-12-00213.1

Lei, Y., Yang, K., Wang, B., Sheng, Y., Bird, B. W., Zhang, G., & Tian, L. (2014). Response of inland lake dynamics over the Tibetan Plateau to climate change. *Climatic Change*, *125*(2), 281–290. https://doi.org/10.1007/s10584-014-1175-3

Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., Li, Q., et al. (2018). High tropospheric ozone in Lhasa within the Asian summer monsoon anticyclone in 2013: Influence of convective transport and stratospheric intrusions. *Atmospheric Chemistry and Physics*, *18*(24), 17979–17994. https://doi.org/10.5194/acp-18-17979-2018

Li, D., Yang, K., Tang, W., Li, X., Zhou, X., & Guo, D. (2020). Characterizing precipitation in high altitudes of the western Tibetan plateau with a focus on major glacier areas. *International Journal of Climatology*, *40*(12), 5114–5127. https://doi.org/10.1002/joc.6509

Li, F., Peng, Y., Chen, L., Yang, G., Abbott, B. W., Zhang, D., et al. (2020). Warming alters surface soil organic matter composition despite unchanged carbon stocks in a Tibetan permafrost ecosystem. *Functional Ecology*, *34*(4), 911–922. https://doi.org/10.1111/1365-2435.13489

Li, W., Qiu, B., Guo, W., & Hsu, P. C. (2021). Rapid response of the East Asian trough to Tibetan Plateau snow cover. *International Journal of Climatology*, *41*(1), 251–261. https://doi.org/10.1002/joc.6618

Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., et al. (2008). Cryospheric change in China. *Global and Planetary Change*, *62*(3–4), 210–218. https://doi.org/10.1016/j.gloplacha.2008.02.001

Li, Z., Qin, H., Guo, D., Zhou, S., Huang, Y., Su, Y., et al. (2017). Impact of ozone valley over the Tibetan Plateau on the South Asian high in CAM5. *Advances in Meteorology*, *2017*, 9383495. https://doi.org/10.1155/2017/9383495

Liang, P., Chen, B. D., & Tang, X. (2010). Identification of cloud types over Tibetan Plateau by satellite remote sensing [in Chinese]. *Plateau Meteorology*, *29*(2), 268–277.

Lin, C., Yang, K., Chen, D., Guyennon, N., Balestrini, R., Yang, X., et al. (2021). Summer afternoon precipitation associated with wind convergence near the Himalayan glacier fronts. *Atmospheric Research*, *259*, 105658. https://doi.org/10.1016/j.atmosres.2021.105658

Lin, H., & Wu, Z. (2011). Contribution of the autumn Tibetan Plateau snow cover to seasonal prediction of North American winter temperature. *Journal of Climate*, *24*(11), 2801–2813. https://doi.org/10.1175/2010JCLI3889.1

Lin, H., & Wu, Z. (2012). Contribution of Tibetan Plateau snow cover to the extreme winter conditions of 2009/10. *Atmosphere-Ocean*, *50*(1), 86–94. https://doi.org/10.1080/07055900.2011.649036

Liu, J., & Chen, B. (2017). Cloud occurrence frequency and structure over the Qinghai-Tibetan Plateau from CloudSat observation [in Chinese]. *Plateau Meteorology*, *36*(3), 632–642.

Liu, N., & Liu, C. (2016). Global distribution of deep convection reaching tropopause in 1 year GPM observations. *Journal of Geophysical Research: Atmospheres*, *121*(8), 3824–3842. https://doi.org/10.1002/2015JD024430

Liu, S., Wu, Q., Ren, X., Yao, Y., Schroeder, S. R., & Hu, H. (2017). Modeled Northern Hemisphere autumn and winter climate responses to realistic Tibetan Plateau and Mongolia snow anomalies. *Journal of Climate*, *30*(23), 9435–9454. https://doi.org/10.1175/JCLI-D-17-0117.1

Liu, S., Wu, Q., Schroeder, S. R., Yao, Y., Zhang, Y., Wu, T., et al. (2020a). Near-global atmospheric responses to observed springtime Tibetan Plateau snow anomalies. *Journal of Climate*, *33*(5), 1691–1706. https://doi.org/10.1175/JCLI-D-19-0229.1

Liu, X., Li, W., & Wu, G. (2002). Correlation analysis of the annual Qinghai-Tibetan Plateau heating and the interannual variation of the northern hemisphere circulation [in Chinese]. *Acta Meteorologica Sinica*, *60*, 266–277.

Liu, X., & Yin, Z. Y. (2002). Sensitivity of East Asian monsoon climate to the uplift of the Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *183*(3–4), 223–245. https://doi.org/10.1016/S0031-0182(01)00488-6

Liu, Y., Hoskins, B., & Blackburn, M. (2007). Impact of Tibetan orography and heating on the summer flow over Asia. *Journal of the Meteorological Society of Japanese Series II*, *85B*, 1–19. https://doi.org/10.2151/jmsj.85B.1

Liu, Y., Jia, R., Dai, T., Xie, Y., & Shi, G. (2014). A review of aerosol optical properties and radiative effects. *Journal of Meteorological Research*, *28*(6), 1003–1028. https://doi.org/10.1007/s13351-014-4045-z

Liu, Y., Li, W., Liu, X., Wang, X., Fu, R., & Liu, P. (2020b). Physics of the control of the Tibetan Plateau on regional energetic processes and global climate [in Chinese]. *Transactions of Atmospheric Sciences*, *43*(1), 181–192. https://doi.org/10.13878/j.cnki.dqkxxb.20191229006

Liu, Y., Lu, M., Yang, H., Duan, A., He, B., Yang, S., & Wu, G. (2020c). Land–atmosphere–ocean coupling associated with the Tibetan Plateau and its climate impacts. *National Science Review*, *7*(3), 534–552. https://doi.org/10.1093/nsr/nwaa011

Liu, Y., Sato, Y., Jia, R., Xie, Y., Huang, J., & Nakajima, T. (2015). Modeling study on the transport of summer dust and anthropogenic aerosols over the Tibetan Plateau. *Atmospheric Chemistry and Physics*, *15*(21), 12581–12594. https://doi.org/10.5194/acp-15-12581-2015

Liu, Y., Wang, Z., Zhuo, H., & Wu, G. (2017). Two types of summertime heating over Asian large-scale orography and excitation of potential-vorticity forcing II. Sensible heating over Tibetan-Iranian Plateau. *Science China Earth Sciences*, *60*(4), 733–744. https://doi.org/10.1007/s11430-016-9016-3

Liu, Y., Wu, G., Hong, J., Dong, B., Duan, A., Bao, Q., & Zhou, L. (2012). Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: II. Change. *Climate Dynamics*, *39*(5), 1183–1195. https://doi.org/10.1007/s00382-012-1335-y

Lu, C., Yu, G., & Xie, G. (2005). Tibetan Plateau serves as a water tower. *IEEE*, *5*, 3120–3123. Retrieved from http://ir.igsnrr.ac.cn/handle/311030/25212

Lu, M., Huang, B., Li, Z., Yang, S., & Wang, Z. (2019). Role of Atlantic air–sea interaction in modulating the effect of Tibetan Plateau heating on the upstream climate over Afro-Eurasia–Atlantic regions. *Climate Dynamics*, *53*(1–2), 509–519. https://doi.org/10.1007/s00382-018-4595-3

Lu, M., Yang, S., Li, Z., He, B., He, S., & Wang, Z. (2018). Possible effect of the Tibetan Plateau on the "upstream" climate over West Asia, North Africa, south Europe and the North Atlantic. *Climate Dynamics*, *51*(4), 1485–1498. https://doi.org/10.1007/s00382-017-3966-5

Lu, M., Yang, S., Wang, J., Wu, Y., & Jia, X. (2021). Response of regional Asian summer monsoons to the effect of reduced surface albedo in different Tibetan Plateau domains in idealized model experiments. *Journal of Climate*, *34*(17), 7023–7036. https://doi.org/10.1175/JCLI-D-20-0500.1

Lun, Y., Liu, L., Cheng, L., Li, X., Li, H., & Xu, Z. (2021). Assessment of GCMs simulation performance for precipitation and temperature from CMIP5 to CMIP6 over the Tibetan Plateau. *International Journal of Climatology*, *41*(7), 3994–4018. https://doi.org/10.1002/joc.7055

Luo, M., Liu, Y., Zhu, Q., Tang, Y., & Alam, K. (2020). Role and mechanisms of black carbon affecting water vapor transport to Tibet. *Remote Sensing*, *12*(2), 231. https://doi.org/10.3390/rs12020231

Lyu, M., Wen, M., & Wu, Z. (2018). Possible contribution of the inter-annual Tibetan Plateau snow cover variation to the Madden-Julian oscillation convection variability. *International Journal of Climatology*, *38*(10), 3787–3800. https://doi.org/10.1002/joc.5533

Ma, Y., Hu, Z., Xie, Z., Ma, W., Wang, B., Chen, X., et al. (2020). A long-term (2005–2016) dataset of integrated land–atmosphere interaction observations on the Tibetan Plateau. *Earth System Science Data Discussions*. https://doi.org/10.5194/essd-2020-85

Ma, Y., Kang, S., Zhu, L., Xu, B., Tian, L., & Yao, T. (2008). Tibetan observation and research platform: Atmosphere–land interaction over a heterogeneous landscape. *Bulletin of the American Meteorological Society*, *89*(10), 1487–1492. Retrieved from https://www.jstor.org/stable/26220897

Ma, Y., Ma, W., Zhong, L., Hu, Z., Li, M., Zhu, Z., et al. (2017). Monitoring and modeling the Tibetan Plateau's climate system and its impact on East Asia. *Scientific Reports*, *7*(1), 44574. https://doi.org/10.1038/srep44574

Ma, Y., Wang, B., Chen, X., Zhong, L., Hu, Z., Ma, W., et al. (2022). Strengthening the three-dimensional comprehensive observation system of multi-layer interaction on the Tibetan Plateau to cope with the warming and wetting trend. *Atmospheric and Oceanic Science Letters*, *15*(4), 100224. https://doi.org/10.1016/j.aosl.2022.100224

Ma, Y., Yao, T., & Wang, J. (2006). Experimental study of energy and water cycle in Tibetan plateau—The progress introduction on the study of GAME/Tibet and CAMP/Tibet [in Chinese]. *Plateau Meteorology*, *25*(2), 344–351.

Mazhar, U., Jin, S., Duan, W., Bilal, M., Ali, M., & Farooq, H. (2021). Spatio-temporal trends of surface energy budget in Tibet from satellite remote sensing observations and reanalysis data. *Remote Sensing*, *13*(2), 256. https://doi.org/10.3390/rs13020256

Mishra, S., Jain, S., Salunke, P., & Sahany, S. (2019). Past and future climate change over the Himalaya-Tibetan Highland: Inferences from APHRODITE and NEX-GDDP data. *Climatic Change*, *156*(3), 315–322. https://doi.org/10.1007/s10584-019-02473-y

Miyakoda, K., Kinter, J. L., & Yang, S. (2003). The role of ENSO in the South Asian monsoon and pre-monsoon signals over the Tibetan Plateau. *Journal of the Meteorological Society of Japanese Series II*, *81*(5), 1015–1039. https://doi.org/10.2151/jmsj.81.1015

Molnar, P., England, P., & Martinod, J. (1993). Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon. *Reviews of Geophysics*, *31*(4), 357–396. https://doi.org/10.1029/93RG02030

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J. A., et al. (2008). *Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies* (p. 132). Intergovernmental Panel on Climate Change.

Moss, R., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

Nan, S., Zhao, P., & Chen, J. (2019). Variability of summertime Tibetan tropospheric temperature and associated precipitation anomalies over the central-eastern Sahel. *Climate Dynamics*, *52*(3), 1819–1835. https://doi.org/10.1007/s00382-018-4246-8

Nan, S., Zhao, P., Chen, J., & Liu, G. (2021). Links between the thermal condition of the Tibetan Plateau in summer and atmospheric circulation and climate anomalies over the Eurasian continent. *Atmospheric Research*, *247*, 105212. https://doi.org/10.1016/j.atmosres.2020.105212

Nan, S., Zhao, P., Yang, S., & Chen, J. (2009). Springtime tropospheric temperature over the Tibetan Plateau and evolutions of the tropical Pacific SST. *Journal of Geophysical Research*, *114*(D10), D10104. https://doi.org/10.1029/2008JD011559

Nitta, T. (1983). Observational study of heat sources over the eastern Tibetan Plateau during the summer monsoon. *Journal of the Meteorological Society of Japanese Series II*, *61*(4), 590–605. https://doi.org/10.2151/jmsj1965.61.4_590

Notaro, M., Zarrin, A., Vavrus, S., & Bennington, V. (2013). Simulation of heavy lake-effect snowstorms across the Great Lakes basin by RegCM4: Synoptic climatology and variability. *Monthly Weather Review*, *141*(6), 1990–2014. https://doi.org/10.1175/MWR-D-11-00369.1

Oku, Y., Ishikawa, H., Haginoya, S., & Ma, Y. (2006). Recent trends in land surface temperature on the Tibetan Plateau. *Journal of Climate*, *19*(12), 2995–3003. https://doi.org/10.1175/JCLI3811.1

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change-human and Policy Dimensions*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Pan, L. L., Honomichl, S. B., Kinnison, D. E., Abalos, M., Randel, W. J., Bergman, J. W., & Bian, J. (2016). Transport of chemical tracers from the boundary layer to stratosphere associated with the dynamics of the Asian summer monsoon. *Journal of Geophysical Research: Atmospheres*, *121*(23), 14159–14174. https://doi.org/10.1002/2016JD025616

Park, H. S., Chiang, J. C., & Bordoni, S. (2012). The mechanical impact of the Tibetan Plateau on the seasonal evolution of the South Asian monsoon. *Journal of Climate*, *25*(7), 2394–2407. https://doi.org/10.1175/JCLI-D-11-00281.1

Peng, X., Zhang, T., Frauenfeld, O. W., Wang, K., Cao, B., Zhong, X., et al. (2017). Response of seasonal soil freeze depth to climate change across China. *The Cryosphere*, *11*(3), 1059–1073. https://doi.org/10.5194/tc-11-1059-2017

Plumb, R. A., & Hou, A. (1992). The response of a zonally Symmetric atmosphere to subtropical thermal forcing: Threshold behavior. *Journal of the Atmospheric Sciences*, *49*(19), 1790–1799. https://doi.org/10.1175/1520-0469(1992)049<1790:TROAZS>2.0.CO;2

Pullen, A., Kapp, P., McCallister, A. T., Chang, H., Gehrels, G. E., Garzione, C. N., et al. (2011). Qaidam Basin and northern Tibetan Plateau as dust sources for the Chinese Loess Plateau and paleoclimatic implications. *Geology*, *39*(11), 1031–1034. https://doi.org/10.1130/G32296.1

Qin, J., Yang, K., Liang, S., & Guo, X. (2009). The altitudinal dependence of recent rapid warming over the Tibetan Plateau. *Climatic Change*, *97*(1–2), 321–327. https://doi.org/10.1007/s10584-009-9733-9

Qiu, J. (2008). China: The third pole. *Nature*, *454*(7203), 393–396. https://doi.org/10.1038/454393a

Qiu, J. (2013). Monsoon melee. *Science*, *340*(6139), 1400–1401. https://doi.org/10.1126/science.340.6139.1400

Qu, X., & Huang, G. (2016). The global warming–induced South Asian high change and its uncertainty. *Journal of Climate*, *29*(6), 2259–2273. https://doi.org/10.1175/jcli-d-15-0638.1

Queney, P. (1948). The problem of air flow over mountains: A summary of theoretical studies. *Bulletin of the American Meteorological Society*, *29*(1), 16–26. https://doi.org/10.1175/1520-0477-29.1.16

Ran, Y., Li, X., Cheng, G., Nan, Z., Che, J., Sheng, Y., et al. (2021). Mapping the permafrost stability on the Tibetan Plateau for 2005–2015. *Science China Earth Sciences*, *64*(1), 62–79. https://doi.org/10.1007/s11430-020-9685-3

Rangwala, I., & Miller, J. R. (2012). Climate change in mountains: A review of elevation-dependent warming and its possible causes. *Climatic Change*, *114*(3–4), 527–547. https://doi.org/10.1007/s10584-012-0419-3

Ren, L., Duan, K., & Xin, R. (2020). Impact of future loss of glaciers on precipitation pattern: A case study from south-eastern Tibetan Plateau. *Atmospheric Research*, *242*, 104984. https://doi.org/10.1016/j.atmosres.2020.104984

Senan, R., Orsolini, Y. J., Weisheimer, A., Vitart, F., Balsamo, G., Stockdale, T. N., et al. (2016). Impact of springtime Himalayan–Tibetan Plateau snowpack on the onset of the Indian summer monsoon in coupled seasonal forecasts. *Climate Dynamics*, *47*(9–10), 2709–2725. https://doi.org/10.1007/s00382-016-2993-y

Sharma, A., Bhattacharya, A., & Venkataraman, C. (2021). Influence of aerosol radiative effects on surface temperature and snow melt in the Himalayan region. *Science of the Total Environment*, *810*, 151299. https://doi.org/10.1016/j.scitotenv.2021.151299

Sheng, Y., & Li, J. (2011). Satellite-observed Endorheic Lake dynamics across the Tibetan Plateau between Circa 1976 and 2000. In Y. Wang (Ed.), *Remote sensing of protected lands* (pp. 328–343). CRC Press.

Si, D., & Ding, Y. (2013). Decadal change in the correlation pattern between the Tibetan Plateau winter snow and the East Asian summer precipitation during 1979–2011. *Journal of Climate*, *26*(19), 7622–7634. https://doi.org/10.1175/jcli-d-12-00587.1

Solomon, S., Daniel, J. S., Neely, R. R., Vernier, J. P., Dutton, E. G., & Thomason, L. W. (2011). The persistently variable "background" stratospheric aerosol layer and global climate change. *Science*, *333*(6044), 866–870. https://doi.org/10.1126/science.1206027

Solomon, S., Kinnison, D., Garcia, R. R., Bandoro, J., Mills, M., Wilka, C., et al. (2016). Monsoon circulations and tropical heterogeneous chlorine chemistry in the stratosphere. *Geophysical Research Letters*, *43*(24), 12624–12633. https://doi.org/10.1002/2016GL071778

Solomon, S., Rosenlof, K. H., Portmann, R. W., Daniel, J. S., Davis, S. M., Sanford, T. J., & Plattner, G. K. (2010). Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science*, *327*(5970), 1219–1223. https://doi.org/10.1126/science.1182488

Son, J. H., Seo, K. H., & Wang, B. (2019). Dynamical control of the Tibetan Plateau on the East Asian summer monsoon. *Geophysical Research Letters*, *46*(13), 7672–7679. https://doi.org/10.1029/2019GL083104

Son, J. H., Seo, K. H., & Wang, B. (2020). How does the Tibetan Plateau dynamically affect downstream monsoon precipitation? *Geophysical Research Letters*, *47*(23), e2020GL090543. https://doi.org/10.1029/2020GL090543

Su, B., Jiang, D., Zhang, R., Sepulchre, P., & Ramstein, G. (2018). Difference between the North Atlantic and Pacific meridional overturning circulation in response to the uplift of the Tibetan Plateau. *Climate of the Past*, *14*(6), 751–762. https://doi.org/10.5194/cp-14-751-2018

Su, J., Duan, A., & Xu, H. (2017). Quantitative analysis of surface warming amplification over the Tibetan Plateau after the late 1990s using surface energy balance equation. *Atmospheric Science Letters*, *18*(3), 112–117. https://doi.org/10.1002/asl.732

Su, Y., Zhao, C., Wang, Y., & Ma, Z. (2020). Spatiotemporal variations of precipitation in China using surface gauge observations from 1961 to 2016. *Atmosphere*, *11*(3), 303. https://doi.org/10.3390/atmos11030303

Su, Z., Wen, J., Dente, L., Velde, R. V. D., Wang, L., Ma, Y., et al. (2011). The Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products. *Hydrology and Earth System Sciences*, *15*(7), 2303–2316. https://doi.org/10.5194/hess-15-2303-2011

Subba, S., Ma, Y., & Ma, W. (2019). Spatial and temporal analysis of precipitation extremities of Eastern Nepal in the last two decades (1997–2016). *Journal of Geophysical Research: Atmospheres*, *124*(14), 7523–7539. https://doi.org/10.1029/2019JD030639

Sun, H., & Liu, X. (2021). Impacts of dynamic and thermal forcing by the Tibetan Plateau on the precipitation distribution in the Asian arid and monsoon regions. *Climate Dynamics*, *56*(7–8), 2339–2358. https://doi.org/10.1007/s00382-020-05593-9

Sun, R., Duan, A., Chen, L., Li, Y., Xie, Z., & Zhao, Y. (2019). Interannual variability of the North Pacific mixed layer associated with the spring Tibetan Plateau thermal forcing. *Journal of Climate*, *32*(11), 3109–3130. https://doi.org/10.1175/JCLI-D-18-0577.1

Sun, X., Ding, Y., & Li, Q. (2021). Interdecadal variation of the atmospheric heat source over the Tibetan Plateau and surrounding Asian monsoon region: Impact on the northern hemisphere summer circulation. *Journal of Meteorological Research*, *35*(2), 238–257. https://doi.org/10.1007/s13351-021-0101-7

Tang, B., Hu, W., Duan, A., Gao, K., & Peng, Y. (2022). Reduced risks of temperature extremes from 0.5°C less global warming in the Earth's three poles. *Earth's Future*, *10*(2), e2021EF002525. https://doi.org/10.1029/2021EF002525

Tang, M., Liang, J., Shao, M., & Shi, G. (1984). A Preliminary analysis of the interannual variation of the Xizangi-Tibetan Plateau monsoon [in Chinese]. *Plateau Meteorology*, *3*(3), 76–82.

Tang, M., Shen, Z., & Chen, Y. (1979). On climatic characteristics of the Xizangi-Tibetan Plateau monsoon [in Chinese]. *Acta Meteorologica Sinica*, *34*(1), 33–42.

Tao, S., & Chen, L. (1957). The structure of the Atmospheric Circulation over the Asian continent in summer [in Chinese]. *Acta Meteorologica Sinica*, *28*, 233–247.

Valdes, P. J., & Hoskins, B. J. (1991). Nonlinear orographically forced planetary waves. *Journal of the Atmospheric Sciences*, *48*(18), 2089–2106. https://doi.org/10.1175/1520-0469(1991)048<2089:nofpw>2.0.co;2

Vernier, J. P., Fairlie, T. D., Natarajan, M., Wienhold, F. G., Bian, J., Martinsson, B. G., et al. (2015). Increase in upper tropospheric and lower stratospheric aerosol levels and its potential connection with Asian pollution. *Journal of Geophysical Research: Atmospheres*, *120*(4), 1608–1619. https://doi.org/10.1002/2014JD022372

Walker, G. T. (1910). *Correlations in seasonal variations of weather* (Vol. 21, pp. 22–45). Memoirs of the India Meteorological Department.

Wan, W., Zhao, L., Xie, H., Liu, B., Li, H., Cui, Y., et al. (2018). Lake surface water temperature change over the Tibetan plateau from 2001 to 2015: A sensitive indicator of the warming climate. *Geophysical Research Letters*, *45*(20), 11177–11186. https://doi.org/10.1029/2018GL078601

Wang, B., Bao, Q., Hoskins, B., Wu, G., & Liu, Y. (2008). Tibetan Plateau warming and precipitation changes in East Asia. *Geophysical Research Letters*, *35*(14), L14702. https://doi.org/10.1029/2008GL034330

Wang, B., Ma, Y., Chen, X., Ma, W., Su, Z., & Menenti, M. (2015). Observation and simulation of lake-air heat and water transfer processes in a high-altitude shallow lake on the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *120*(24), 12327–12344. https://doi.org/10.1002/2015JD023863

Wang, B., Ma, Y., Su, Z., Wang, Y., & Ma, W. (2020a). Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. *Science Advances*, *6*(26), eaay8558. https://doi.org/10.1126/sciadv.aay8558

Wang, L., Liu, H., Shao, Y., Liu, Y., & Sun, J. (2018). Water and CO_2 fluxes over semiarid alpine steppe and humid alpine meadow ecosystems on the Tibetan Plateau. *Theoretical and Applied Climatology*, *131*(1–2), 547–556. https://doi.org/10.1007/s00704-016-1997-1

Wang, M., & Duan, A. (2015). Quasi-biweekly oscillation over the Tibetan Plateau and its link with the Asian summer monsoon. *Journal of Climate*, *28*(12), 4921–4940. https://doi.org/10.1175/JCLI-D-14-00658.1

Wang, M., Wang, J., Chen, D., Duan, A., Liu, Y., Zhou, S., et al. (2019a). Recent recovery of the boreal spring sensible heating over the Tibetan Plateau will continue in CMIP6 future projections. *Environmental Research Letters*, *14*(12), 124066. https://doi.org/10.1088/1748-9326/ab57a3

Wang, T., Han, Y., Huang, J., Sun, M., Jian, B., Huang, Z., & Yan, H. (2020b). Climatology of dust-forced radiative heating over the Tibetan Plateau and its surroundings. *Journal of Geophysical Research: Atmospheres*, *125*(17), e2020JD032942. https://doi.org/10.1029/2020JD032942

Wang, Z., Duan, A., & Yang, S. (2019b). Potential regulation on the climatic effect of Tibetan Plateau heating by tropical air–sea coupling in regional models. *Climate Dynamics*, *52*(3–4), 1685–1694. https://doi.org/10.1007/s00382-018-4218-z

Wei, Z., Huang, R., & Dong, W. (2003). Interannual and interdecadal variations of air temperature and precipitation over the Tibetan Plateau [in Chinese]. *Chinese Journal of Atmospheric Sciences*, *27*(2), 157–170.

Wen, Q., Döös, K., Lu, Z., Han, Z., & Yang, H. (2020). Investigating the role of the Tibetan Plateau in ENSO variability. *Journal of Climate*, *33*(11), 4835–4852. https://doi.org/10.1175/JCLI-D-19-0422.1

Wen, Q., & Yang, H. (2020). Investigating the role of the Tibetan Plateau in the formation of Pacific meridional overturning circulation. *Journal of Climate*, *33*(9), 3603–3617. https://doi.org/10.1175/JCLI-D-19-0206.1

Wu, G. (1984). The nonlinear response of the atmosphere to large-scale mechanical and thermal forcing. *Journal of Atmospheric Sciences*, *41*(16), 2456–2476. https://doi.org/10.1175/1520-0469(1984)041<2456:TNROTA>2.0.CO;2

Wu, G., Duan, A., Liu, Y., Mao, J., Ren, R., Bao, Q., et al. (2015a). Tibetan Plateau climate dynamics: Recent research progress and outlook. *National Science Review*, *2*(1), 100–116. https://doi.org/10.1093/nsr/nwu045

Wu, G., Guan, Y., Liu, Y., Yan, J., & Mao, J. (2012a). Air–sea interaction and formation of the Asian summer monsoon onset vortex over the Bay of Bengal. *Climate Dynamics*, *38*(1–2), 261–279. https://doi.org/10.1007/s00382-010-0978-9

Wu, G., He, B., Duan, A., Liu, Y., & Yu, W. (2017). Formation and variation of the atmospheric heat source over the Tibetan Plateau and its climate effects. *Advances in Atmospheric Sciences*, *34*(10), 1169–1184. https://doi.org/10.1007/s00376-017-7014-5

Wu, G., He, B., Liu, Y., Bao, Q., & Ren, R. (2015b). Location and variation of the summertime upper-troposphere temperature maximum over South Asia. *Climate Dynamics*, *45*(9), 2757–2774. https://doi.org/10.1007/s00382-015-2506-4

Wu, G., Li, W., Guo, H., Liu, H., Xue, J., & Wang, Z. (1997). Qinghai-Tibetan Plateau sensible air Pump and Asian summer monsoon. In D. Ye (Ed.), *Zhao Jiuzhang Memorial collection [in Chinese]* (pp. 116–126). Science Press.

Wu, G., & Liu, Y. (2016). Impacts of the Tibetan Plateau on Asian climate. *Meteorological Monographs*, *56*(1), 7.1–7.29. https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0018.1

Wu, G., Liu, Y., Dong, B., Liang, X., Duan, A., Bao, Q., & Yu, J. (2012b). Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: I. Formation. *Climate Dynamics*, *39*(5), 1169–1181. https://doi.org/10.1007/s00382-012-1334-z

Wu, G., Liu, Y., & He, B. (2020). The nature of the thermal forcing of the Asian summer monsoon. In C.-P. Chang, R. H. Johnson, K. J. Ha, D. Kim, G. Ngar-Cheung Lau, B. Wang, et al. (Eds.), *The multiscale global monsoon system* (pp. 27–36). World Scientific.

Wu, G., Liu, Y., He, B., Bao, Q., Duan, A., & Jin, F. (2012c). Thermal controls on the Asian summer monsoon. *Scientific Reports*, *2*(1), 404. https://doi.org/10.1038/srep00404

Wu, G., Liu, Y., He, B., Bao, Q., & Wang, Z. Q. (2018). Review of the impact of the Tibetan Plateau sensible heat driven air-pump on the Asian summer monsoon [in Chinese]. *Chinese Journal of Atmospheric Sciences*, *42*(3), 488–504. https://doi.org/10.3878/j.issn.1006-9895.1801.17279

Wu, G., Liu, Y., Zhang, Q., Duan, A., Wang, T., Wan, R., et al. (2007). The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *Journal of Hydrometeorology*, *8*(4), 770–789. https://doi.org/10.1175/JHM609.1

Wu, G., & Zhang, Y. (1998). Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China sea. *Monthly Weather Review*, *126*(4), 913–927. https://doi.org/10.1175/1520-0493(1998)126<0913:TPFATT>2.0.CO;2

Wu, G., Zhuo, H., Wang, Z., & Liu, Y. (2016). Two types of summertime heating over the Asian large-scale orography and excitation of potential-vorticity forcing I. Over Tibetan Plateau. *Science China Earth Sciences*, *59*(10), 1996–2008. https://doi.org/10.1007/s11430-016-5328-2

Wu, Q., Hu, H., & Zhang, L. (2011). Observed influences of autumn–early winter Eurasian snow cover anomalies on the hemispheric PNA-like variability in winter. *Journal of Climate*, *24*(7), 2017–2023. https://doi.org/10.1175/2011JCLI4236.1

Wu, Y., Yang, S., Hu, X., & Wei, W. (2020). Process-based attribution of long-term surface warming over the Tibetan Plateau. *International Journal of Climatology*, *40*(15), 6410–6422. https://doi.org/10.1002/joc.6589

Wu, Z., Zhang, P., Chen, H., & Li, Y. (2016). Can the Tibetan Plateau snow cover influence the interannual variations of Eurasian heat wave frequency? *Climate Dynamics*, *46*(11–12), 3405–3417. https://doi.org/10.1007/s00382-015-2775-y

Xiao, Z., & Duan, A. (2016). Impacts of Tibetan Plateau snow cover on the interannual variability of the East Asian summer monsoon. *Journal of Climate*, *29*(23), 8495–8514. https://doi.org/10.1175/JCLI-D-16-0029.1

Xie, J., Yu, Y., Li, J. L., Ge, J., & Liu, C. (2019). Comparison of surface sensible and latent heat fluxes over the Tibetan Plateau from reanalysis and observations. *Meteorology and Atmospheric Physics*, *131*(3), 567–584. https://doi.org/10.1007/s00703-018-0595-4

Xie, Z., & Wang, B. (2019). Summer atmospheric heat sources over the western–central Tibetan Plateau: An integrated analysis of multiple reanalysis and satellite datasets. *Journal of Climate*, *32*(4), 1181–1202. https://doi.org/10.1175/JCLI-D-18-0176.1

Xie, Z., & Wang, B. (2021). Summer heat sources changes over the Tibetan Plateau in CMIP6 models. *Environmental Research Letters*, *16*(6), 064060. https://doi.org/10.1088/1748-9326/ac0279

Xu, C., Ma, Y., Yang, K., & You, C. (2018). Tibetan Plateau impacts on global dust transport in the upper troposphere. *Journal of Climate*, *31*(12), 4745–4756. https://doi.org/10.1175/JCLI-D-17-0313.1

Xu, C., Ma, Y., You, C., & Zhu, Z. (2015). The regional distribution characteristics of aerosol optical depth over the Tibetan Plateau. *Atmospheric Chemistry and Physics*, *15*(20), 12065–12078. https://doi.org/10.5194/acp-15-12065-2015

Xu, L., Hu, Z., Zhao, Y., & Hong, X. (2019). Climate change characteristics in Qinghai-Tibetan plateau during 1961-2010 [in Chinese]. *Plateau Meteorology*, *38*(5), 911–919.

Xu, S., & Gao, Y. (1962). Monsoon phenomenon on the Tibetan Plateau [in Chinese]. *Acta Geographica Sinica*, *28*, 111–123.

Xu, W., Ma, L., Ma, M., Zhang, H., & Yuan, W. (2017). Spatial-temporal variability of snow cover and depth in the Qinghai-Tibetan Plateau. *Journal of Climate*, *30*(4), 1521–1533. https://doi.org/10.1175/JCLI-D-15-0732.1

Xu, W., Song, Q., Li, Y., Shi, C., Sun, B., Su, Y., et al. (2021). Effects of stationary and transient transport of ozone on the ozone valley over the Tibetan Plateau in summer. *Frontiers in Earth Science*, *9*, 608018. https://doi.org/10.3389/feart.2021.608018

Xu, X., & Chen, L. (2006). Advances of the study on Tibetan Plateau experiment of atmospheric sciences [in Chinese]. *Journal of Applied Meteorological Science*, *17*(6), 756–772.

Xu, X., Lu, C., Shi, X., & Gao, S. (2008). World water tower: An atmospheric perspective. *Geophysical Research Letters*, *35*(20), L20815. https://doi.org/10.1029/2008GL035867

Xu, X., Zhao, T., Lu, C., Guo, Y., Chen, B., Liu, R., et al. (2014). An important mechanism sustaining the atmospheric "water tower" over the Tibetan Plateau. *Atmospheric Chemistry and Physics*, *14*(20), 11287–11295. https://doi.org/10.5194/acp-14-11287-2014

Xu, X., Zhou, M., Chen, J., Bian, L., Zhang, G., Liu, H., et al. (2002). A comprehensive physical pattern of land-air dynamic and thermal structure on the Qinghai-Xizang Plateau. *Science in China Series D: Earth Sciences*, *45*(7), 577–594. https://doi.org/10.1360/02yd9060

Yan, R., & Bian, J. (2015). Tracing the boundary layer sources of carbon monoxide in the Asian summer monsoon anticyclone using WRF-Chem. *Advances in Atmospheric Sciences*, *32*(7), 943–951. https://doi.org/10.1007/s00376-014-4130-3

Yan, Y., Liu, X., Liu, Y., & Lu, J. (2020). Comparison of mixed-phase clouds over the Arctic and the Tibetan Plateau: Seasonality and vertical structure of cloud radiative effects. *Climate Dynamics*, *54*(11–12), 4811–4822. https://doi.org/10.1007/s00382-020-05257-8

Yan, Y., Liu, Y., Liu, X., & Wang, X. (2021). Effects of cloud microphysics on the vertical structures of cloud radiative effects over the Tibetan Plateau and the Arctic. *Remote Sensing*, *13*(14), 2651. https://doi.org/10.3390/rs13142651

Yanai, M., Li, C., & Song, Z. (1992). Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *Journal of the Meteorological Society of Japanese Series II*, *70*(1B), 319–351. https://doi.org/10.2151/jmsj1965.70.1B_319

Yanai, M., & Wu, G. X. (2006). Effects of the Tibetan plateau. In B. Wang (Ed.), *The Asian monsoon* (pp. 513–549). Springer.

Yang, H., Shen, X., Yao, J., & Wen, Q. (2020). Portraying the impact of the Tibetan Plateau on global climate. *Journal of Climate*, *33*(9), 3565–3583. https://doi.org/10.1175/JCLI-D-18-0734.1

Yang, H., & Wen, Q. (2020). Investigating the role of the Tibetan Plateau in the formation of Atlantic meridional overturning circulation. *Journal of Climate*, *33*(9), 3585–3601. https://doi.org/10.1175/JCLI-D-19-0205.1

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., & Zhou, M. (2004). The daytime evolution of the atmospheric boundary layer and convection over the Tibetan Plateau: Observations and simulations. *Journal of the Meteorological Society of Japanese Series II*, *82*(6), 1777–1792. https://doi.org/10.2151/jmsj.82.1777

Yang, K., Qin, J., Zhao, L., Chen, Y., Tang, W., Han, M., et al. (2013). A multiscale soil moisture and freeze–thaw monitoring network on the third pole. *Bulletin of the American Meteorological Society*, *94*(12), 1907–1916. https://doi.org/10.1175/BAMS-D-12-00203.1

Yang, K., Tang, Q., & Lu, H. (2022). Precipitation recycling ratio and water vapor sources on the Tibetan Plateau. *Science China Earth Sciences*, *65*(3), 584–588. https://doi.org/10.1007/s11430-021-9871-5

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, *112*, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001

Yang, M., Wang, X., Pang, G., Wan, G., & Liu, Z. (2019). The Tibetan Plateau cryosphere: Observations and model simulations for current status and recent changes. *Earth-Science Reviews*, *190*, 353–369. https://doi.org/10.1016/j.earscirev.2018.12.018

Yang, S., Lau, K. M., & Kim, K. M. (2002). Variations of the East Asian jet stream and Asian–Pacific–American winter climate anomalies. *Journal of Climate*, *15*(3), 306–325. https://doi.org/10.1175/1520-0442(2002)015<0306:VOTEAJ>2.0.CO;2

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., et al. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, *2*(9), 663–667. https://doi.org/10.1038/nclimate1580

Yao, T., Xue, Y., Chen, D., Chen, F., Thompson, L., Cui, P., et al. (2019). Recent third pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: Multidisciplinary approach with observations, modeling, and analysis. *Bulletin of the American Meteorological Society*, *100*(3), 423–444. https://doi.org/10.1175/BAMS-D-17-0057.1

Yao, X., Yang, K., Zhou, X., Wang, Y., Chen, Y., & Lu, H. (2021). Surface friction contrast between water body and land enhances precipitation downwind of a large lake in Tibet. *Climate Dynamics*, *56*(7–8), 2113–2126. https://doi.org/10.1007/s00382-020-05575-x

Ye, D., & Gao, Y. (1979). *Qinghai-Tibetan Plateau Meteorology [in Chinese]*. Science Press.

Ye, D., Luo, S., & Zhu, B. (1957). The flow field structure in the Tibetan Plateau and its Vicinity and the heat balance in the troposphere atmosphere [in Chinese]. *Acta Meteorologica Sinica*, *28*, 108–121.

Yeh, T. (1950). The circulation of the high troposphere over China in the winter of 1945–46. *Tellus*, *2*(3), 173–183. https://doi.org/10.1111/j.2153-3490.1950.tb00329.x

Yeh, T. (1954). On the orographical and thermal influence of the land-and-sea distribution on the general circulation of the atmosphere [in Chinese]. *Acta Meteorologica Sinica*, *25*, 123–140.

You, Q., Cai, Z., Pepin, N., Chen, D., Ahrens, B., Jiang, Z., et al. (2021). Warming amplification over the Arctic Pole and third Pole: Trends, mechanisms and consequences. *Earth-Science Reviews*, *217*, 103625. https://doi.org/10.1016/j.earscirev.2021.103625

You, Q., Chen, D., Wu, F., Pepin, N., Cai, Z., Ahrens, B., et al. (2020a). Elevation dependent warming over the Tibetan Plateau: Patterns, mechanisms and perspectives. *Earth-Science Reviews*, *210*, 103349. https://doi.org/10.1016/j.earscirev.2020.103349

You, Q., Wu, F., Shen, L., Pepin, N., Jiang, Z., & Kang, S. (2020b). Tibetan Plateau amplification of climate extremes under global warming of 1.5°C, 2°C and 3°C. *Global and Planetary Change*, *192*, 103261. https://doi.org/10.1016/j.gloplacha.2020.103261

You, Q., Wu, T., Shen, L., Pepin, N., Zhang, L., Jiang, Z., et al. (2020c). Review of snow cover variation over the Tibetan Plateau and its influence on the broad climate system. *Earth-Science Reviews*, *201*, 103043. https://doi.org/10.1016/j.earscirev.2019.103043

Yu, J., Liu, Y., & Wu, G. (2011a). An analysis of the diabatic heating characteristic of atmosphere over the Tibetan Plateau in winter I: Climatology [in Chinese]. *Acta Meteorologica Sinica*, *69*, 79–88.

Yu, J., Liu, Y., & Wu, G. (2011b). An analysis of the diabatic heating characteristic of atmosphere over the Tibetan Plateau in winter II: Interannal variation [in Chinese]. *Acta Meteorologica Sinica*, *69*, 89–98.

Yu, P., Rosenlof, K. H., Liu, S., Telg, H., Thornberry, T. D., Rollins, A. W., et al. (2017). Efficient transport of tropospheric aerosol into the stratosphere via the Asian summer monsoon anticyclone. *Proceedings of the National Academy of Sciences*, *114*(27), 6972–6977. https://doi.org/10.1073/pnas.1701170114

Yu, W., Liu, Y. M., Yang, X. Q., Wu, G. X., He, B., Li, J. X., & Bao, Q. (2021). Impact of North Atlantic SST and Tibetan Plateau forcing on seasonal transition of springtime South Asian monsoon circulation. *Climate Dynamics*, *56*(1–2), 559–579. https://doi.org/10.1007/s00382-020-05491-0

Yue, S., Yang, K., Lu, H., Zhou, X., Chen, D., & Guo, W. (2021). Representation of stony surface-atmosphere interactions in WRF reduces cold and wet biases for the southern Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *126*(21), e2021JD035291. https://doi.org/10.1029/2021JD035291

Zhang, B. (2017). Editors' selection of papers from China's academic journals. *National Science Review*, *4*(3), 287–289. https://doi.org/10.1093/nsr/nwx061

Zhang, D., Huang, Y., Zhou, B., & Wang, H. (2022). Interdecadal changes of the south Asian high in CMIP5/6 and projection of its future changes. *Journal of Climate*, *35*(17), 5661–5675. https://doi.org/10.1175/jcli-d-21-0921.1

Zhang, G., Luo, W., Chen, W., & Zheng, G. (2019). A robust but variable lake expansion on the Tibetan Plateau. *Science Bulletin*, *64*(18), 1306–1309. https://doi.org/10.1016/j.scib.2019.07.018

Zhang, G., Yao, T., Xie, H., Qin, J., Ye, Q., Dai, Y., & Guo, R. (2014a). Estimating surface temperature changes of lakes in the Tibetan Plateau using MODIS LST data. *Journal of Geophysical Research: Atmospheres*, *119*(14), 8552–8567. https://doi.org/10.1002/2014JD021615

Zhang, J., Tian, W., Xie, F., Tian, H., Luo, J., Zhang, J., et al. (2014b). Climate warming and decreasing total column ozone over the Tibetan Plateau during winter and spring. *Tellus B: Chemical and Physical Meteorology*, *66*(1), 23415. https://doi.org/10.3402/tellusb.v66.23415

Zhang, L., Ma, Y., Ma, W., & Wang, B. (2018). Comparison of different generation mechanisms of free convection between two stations on the Tibetan Plateau. *Advances in Atmospheric Sciences*, *35*(9), 1137–1144. https://doi.org/10.1007/s00376-018-7195-6

Zhang, P., Yang, S., & Kousky, V. E. (2005). South Asian high and Asian-Pacific-American climate teleconnection. *Advances in Atmospheric Sciences*, *22*(6), 915–923. https://doi.org/10.1007/BF02918690

Zhang, R., Koike, T., Xu, X., Ma, Y., & Yang, K. (2012). A China-Japan cooperative JICA atmospheric observing network over the Tibetan Plateau (JICA/Tibet Project): An overviews. *Journal of the Meteorological Society of Japan. Ser. II*, *90C*(0), 1–16. https://doi.org/10.2151/jmsj.2012-C01

Zhang, R., Su, F., Jiang, Z., Gao, X., Guo, D., Ni, J., et al. (2015). An overview of projected climate and environmental changes across the Tibetan Plateau in the 21st century [in Chinese]. *Chinese Science Bulletin*, *60*(32), 3036–3047. https://doi.org/10.1360/N972014-01296

Zhang, Y., Li, T., & Wang, B. (2004). Decadal change of the spring snow depth over the Tibetan Plateau: The associated circulation and influence on the East Asian summer monsoon. *Journal of Climate*, *17*(14), 2780–2793. https://doi.org/10.1175/1520-0442(2004)017<2780:DCOTSS>2.0.CO;2

Zhao, C., Liu, L., Wang, Q., Qiu, Y., Wang, W., Wang, Y., & Fan, T. (2016). Toward understanding the properties of high ice clouds at the naqu site on the Tibetan Plateau using ground-based active remote sensing measurements obtained during a short period in July 2014. *Journal of Applied Meteorology and Climatology*, *55*(11), 2493–2507. https://doi.org/10.1175/JAMC-D-16-0038.1

Zhao, C., Liu, L., Wang, Q., Qiu, Y., Wang, Y., & Wu, X. (2017). MMCR-based characteristic properties of non-precipitating cloud liquid droplets at Naqu site over Tibetan Plateau in July 2014. *Atmospheric Research*, *190*, 68–76. https://doi.org/10.1016/j.atmosres.2017.02.002

Zhao, C., Yang, Y., Fan, H., Huang, J., Fu, Y., Zhang, X., et al. (2020). Aerosol characteristics and impacts on weather and climate over the Tibetan Plateau. *National Science Review*, *7*(3), 492–495. https://doi.org/10.1093/nsr/nwz184

Zhao, P., & Chen, L. (2001). Interannual variability of atmospheric heat source/sink over the Qinghai—Xizang (Tibetan) Plateau and its relation to circulation. *Advances in Atmospheric Sciences*, *18*(1), 106–116. https://doi.org/10.1007/s00376-001-0007-3

Zhao, P., Li, Y., Guo, X., Xu, X., Liu, Y., Tang, S., et al. (2018a). Land-air coupled system on the Qinghai-Tibetan Plateau and its weather and climate effects: The third Qinghai-Tibetan Plateau atmospheric science experiment [in Chinese]. *Acta Meteorologica Sinica*, *76*, 833–860.

Zhao, P., Xu, X., Chen, F., Guo, X., Zheng, X., Liu, L., et al. (2018b). The third atmospheric scientific experiment for understanding the Earth–atmosphere coupled system over the Tibetan Plateau and its effects. *Bulletin of the American Meteorological Society*, *99*(4), 757–776. https://doi.org/10.1175/BAMS-D-16-0050.1

Zhao, P., Zhou, X., Chen, J., Liu, G., & Nan, S. (2019). Global climate effects of summer Tibetan Plateau. *Science Bulletin*, *64*(1), 1–3. https://doi.org/10.1016/j.scib.2018.11.019

Zhao, Y., Duan, A., & Wu, G. (2018c). Interannual variability of late-spring circulation and diabatic heating over the Tibetan Plateau associated with Indian Ocean forcing. *Advances in Atmospheric Sciences*, *35*(8), 927–941. https://doi.org/10.1007/s00376-018-7217-4

Zhao, Y., Zhou, T., Zhang, W., & Li, J. (2022). Change in Precipitation over the Tibetan Plateau Projected by weighted CMIP6 models. *Advances in Atmospheric Sciences*, *39*(7), 1133–1150. https://doi.org/10.1007/s00376-022-1401-2

Zhong, L., Ma, Y., Xue, Y., & Piao, S. (2019). Climate change trends and impacts on vegetation greening over the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *124*(14), 7540–7552. https://doi.org/10.1029/2019JD030481

Zhou, X., Li, W., Chen, L., & Liu, Y. (2004). The study on atmospheric ozone changes in the Qinghai-Tibetan Plateau [in Chinese]. *Acta Meteorologica Sinica*, *62*, 513–527.

Zhou, X., Luo, C., Li, W., & Shi, J. (1995). Changes in total ozone in China and low-value centers in the Qinghai-Tibetan Plateau [in Chinese]. *Chinese Science Bulletin*, *40*, 1396–1398.

Zhou, X., Yang, K., Ouyang, L., Wang, Y., Jiang, Y., Li, X., et al. (2021). Added value of kilometer-scale modeling over the third pole region: A CORDEX-CPTP pilot study. *Climate Dynamics*, *57*(7–8), 1673–1687. https://doi.org/10.1007/s00382-021-05653-8

10.1029/2022RG000771

Zhou, X., Zhao, P., Chen, J., Chen, L., & Li, W. (2009). Impacts of thermodynamic processes over the Tibetan Plateau on the northern hemispheric climate. *Science in China Series D: Earth Sciences*, *52*(11), 1679–1693. https://doi.org/10.1007/s11430-009-0194-9

Zhu, B. (1957). Constant disturbances of large-scale heat source/sinks and topography to the westerly zone [in Chinese]. *Acta Meteorologica Sinica*, *28*, 198–224.

Zhu, C., Ren, R., & Wu, G. (2018). Varying Rossby Wave trains from the developing to decaying period of the upper atmospheric heat source over the Tibetan Plateau in boreal summer. *Advances in Atmospheric Sciences*, *35*(9), 1114–1128. https://doi.org/10.1007/s00376-017-7231

Zhuo, H., Liu, Y., & Jin, J. (2016). Improvement of land surface temperature simulation over the Tibetan Plateau and the associated impact on circulation in East Asia. *Atmospheric Science Letters*, *17*(2), 162–168. https://doi.org/10.1002/asl.638