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• Editorial Notes •

Understanding Third Pole Atmospheric Dynamics and Land Surface Processes and Their Associations with the Cryosphere, Air Quality, and Climate Change※

——Preface to the Special Issue on Third Pole Atmospheric Physics, Chemistry, and Hydrology

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The Tibetan Plateau (TP), widely known as the Third Pole, is the highest and largest plateau on Earth. The TP not only plays an important role in influencing the atmospheric circulation, surface energy budget, ecology, weather, and climate but also acts as the Asian Water Tower by holding the largest ice mass outside the polar regions to supply fresh water to over 1.4 billion people downstream in Asia (Qin et al., 2006). The observed historical warming and projected future warming over the TP are much stronger than the corresponding global average (Wang et al., 2008). Glaciers on the TP have been retreating extensively in recent decades, driven by atmospheric warming and circulation changes associated with increasing concentrations of greenhouse gases and aerosols in the atmosphere, light-absorbing particles (e.g., black carbon, dust) on snow, and other factors (Duan et al., 2012; Qian et al., 2011; Zhao et al.,2020). In addition, due to the thermal and dynamical effects of the TP, as well as its proximity to the stratosphere, unique atmospheric boundary layer structures often develop over the TP and in the surrounding areas, which have important impacts on local weather, climate, and mixing and transport of atmospheric constituents (Zhao et al., 2020). The TP is considered a natural laboratory to study multi-sphere interactions. A systematic mechanistic understanding of the atmospheric chemical and microphysical processes, climate change, cryospheric variability, and the subsequent environmental impacts is particularly important in the context of the unprecedented warming over the TP (Yao et al., 2019).

This special issue, as indicated by its theme "Third Pole Atmospheric Physics, Chemistry, and Hydrology", focuses on observational data analysis of in-situ and remote sensing measurements as well as global and regional modeling at different spatiotemporal scales to acquire a better understanding of the atmospheric physical, chemical, and dynamical processes over the TP and improve the modeling and predictive capability of the impact of those processes on the environment, climate, cryosphere, and hydrological cycle over the TP. In this special issue, we collected 12 articles on topics associated with 1) atmospheric dynamics and clouds, 2) snow and land surface processes, and 3) climate change and air quality over the TP region.

1) Atmospheric dynamics and clouds

Investigation into the atmospheric dynamical (e.g., plateau shear line and vorticity) and microphysical (e.g., clouds and

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precipitation) processes is highly desired due to their importance to regional weather and climate as well as the hydrological cycle. As a result of unprecedented advances in observational techniques and increased measurements over the TP, observational studies on clouds and precipitation processes have become possible in recent years. Meanwhile, to understand the detailed cloud formation/evolution process and quantify the roles of various influential factors, modeling studies with cloud-resolving models (CRM) remain critical and irreplaceable.

Using a composite analysis that decomposes the kinetic energy (K) near the zonal shear lines (ZSL) into its divergent (K_D) and rotational (K_R) parts along with their interaction part (K_{RD}), Bao and Yao (2022, Page 1021) show that certain rotation and convergence associated with ZSL can cause heavy precipitation over the TP in summer. The intensity of ZSL is controlled by the energy conversion from K_D to K_R, which is determined by geostrophic effects, implying a dominant contribution to ZSL intensity by the zonal, rotational, and meridional divergent wind components.

Chen et al. (2021, Page 1034) analyzed seasonal and diurnal variations of deep convective clouds (DCCs) and their associated precipitation over the eastern TP from two-dimensional CRM simulations and compared their properties to those over eastern China. Unlike DCCs throughout the year in eastern China, over the TP, DCCs mainly occur in the warm season with a 20%–30% shallower depth. DCCs dictate the diurnal variation of warm-season rainfall with afternoon and nocturnal peaks. Strong surface heat fluxes around local noon are the driver of DCCs in the warm season, while they are too weak to drive DCCs in winter due, in part, to the very dry ambient conditions.

A close relationship is found between the East Asian summer rainfall (EASR) and the surface potential vorticity negative uniform leading mode (PVNUM) over the TP using MERRA-2 reanalysis data, in which PVNUM refers to the negative uniform mode shown by the first empirical orthogonal function (EOF) mode on surface potential vorticity. With a positive (negative) phase of PVNUM over the TP, more (less) precipitation occurs in the Yangtze River valley, South Korea, Japan, and part of northern China, while less (more) occurs in southern China. A potential mechanism for this correlation, related to the variation of the circulation pattern along with water vapor transport induced by the PVNUM over the TP, is detailed by Sheng et al. (2022, Page 1050).

Differences in raindrop size distributions (DSDs) between the two sites of Mêdog and Nagqu over the TP were investigated by Wang et al. (2022, Page 1062) using disdrometer data during the rainy season from June to September. There are more large-size raindrops (with diameters larger than 0.6 mm) at Nagqu than at Mêdog, resulting in a larger mass-weighted mean diameter at Nagqu. Cold rain processes lead to large drops over Nagqu, while the warm rain processes with smaller drops dominate over Mêdog.

2) Snow and land surface processes

The cryosphere has been experiencing rapid changes, regulating regional water resources and ecosystems and impacting climate change. The transboundary transport of anthropogenic pollutants and dust aerosols significantly impacts the climate system over the TP by modulating the atmospheric circulation and accelerating ice/snow melt. The snowpack on the TP is an important component of the cryosphere. Its albedo change alters the energy balance of the earth-atmosphere system, which subsequently affects the Asian summer monsoon. Liu et al. (2022, Page 1079) improved the albedo scheme in the Noah land surface model to simulate a heavy snowfall event. Taking their efforts a step further, they plan to simulate snowfall and melting processes in different time periods to evaluate the generalizability of the improved scheme.

Liu et al. (2021, Page 1103) analyzed the relationship between snow cover in the east-central TP and the interannual variability of surface temperature in Central Asia. They found a positive correlation between the interannual variability of surface temperature in Central Asia in summer and the snow cover anomaly over the central-eastern TP in April. Snow cover anomalies in April generate atmospheric wave trains that can propagate into Central Asia in the presence of an Asian subtropical westerly jet. In summer, while a high-pressure system controls Central Asia, bringing warm air down through subsidence, the northward movement of the subtropical westerly jet strengthens the warm air advection, resulting in a warm anomaly in Central Asia.

Vegetation dynamics are vitally important to the exchange of water, energy, and carbon between terrestrial ecosystems and the atmosphere. Refining forcing data can improve the simulation of vegetation dynamics over the TP. Kang et al. (2022, Page 1115) conducted vegetation dynamics simulations over the TP using the SSiB4/TRIFFID land surface model driven by realistic and high-resolution meteorological forcing data. They concluded that the quality of vegetation dynamics simulations in offline land surface models largely depends on the quality and spatial resolution of the meteorological forcing data.

3) Climate change and air quality

Accurately projecting future climate change in terms of precipitation, temperature, and the associated changes in air quality and hydrology over the TP are critical for making mitigation and adaptation policy. Zhao et al. (2022, Page 1133) applied a model weighting method based on the model's historical skill and independence to reduce the CMIP6 projection uncertainty of precipitation over the TP by the end of the century. Their results with this method show stronger precipitation increases over the TP than the original model prediction, especially over the northwestern TP and in the spring season.

Zhang et al. (2022a, Page 1198) analyzed the changes in both annual and seasonal near-surface temperature over the

TP in response to the transient and stabilized 2.0/1.5°C global warming based on the simulations of the Community Earth System Model (CESM). Their results clearly indicated amplified warming over the TP in this scenario. They also found a positive elevation-dependent warming, with higher rates of warming at higher elevations, resulting from uneven changes in surface albedo.

In Li et al. (2022, Page 1151), a non-hydrostatic variable-resolution global atmospheric model (MPAS-Atmosphere) was used to simulate moisture transport and precipitation over the TP at convection-permitting scales during the south Asian monsoon. They found that the model could well-reproduce the key meteorological fields over the TP. The sensitivity experiments with different topography show that the differences in simulated precipitation due to topographical complexity stem from the different extents of resolved southern slopes and valleys of the Himalayas.

The long-term trend in stratospheric ozone over the TP was studied by Zhang et al. (2022b, Page 1167) based on the CMIP6 simulations. They found that most CMIP6 models with chemical-radiative-dynamical processes can capture the seasonal cycles and spatial characteristics of the TP ozone valley (i.e., a low column ozone center over the TP). The multimodel mean of CMIP6 simulations predicts that the TP ozone valley in summer will deepen in the future.

Yang et al. (2022, Page 1184) performed year-long simulations using the regional climate-chemistry model WRF-Chem. The detailed spatiotemporal distributions of ozone and aerosols over South Asia and the TP are analyzed. Their sensitivity experiments show that while biomass burning over South Asia barely modulates ozone formation over the TP, it contributes more than 60% to $PM_{2.5}$ concentrations over the TP during the pre-monsoon season.

While new advances have been made from observations, reanalysis, and CRM simulations, large uncertainties and challenges still exist in attaining a better understanding of both atmospheric dynamical and microphysical processes over the TP. Long-term reliable observations at more locations/sites are highly desirable to ascertain current findings and promote new investigations, particularly considering that most existing observational studies are based on data at very limited stations/locations during short time periods. A combination of multi-source observations and CRM simulations is also highly recommended to disentangle the complex atmospheric processes coupled with land surface processes over the TP. Cross-cutting studies are also strongly in demand considering the connections of the TP with its surrounding regions via atmospheric circulations, which can greatly improve our understanding of future changes in weather, climate, and the environment over and around the TP region.

To better understand the snow and land surface processes over the TP, an integrated observational network, especially over the high elevations and western TP, should be established to obtain comprehensive and high-resolution first-hand data. Currently, the sparse in-situ observations largely limit the evaluation and improvement of model simulations on cryospheric and atmospheric processes in the TP (Qian et al., 2015). To better characterize the atmospheric transport of aerosols, multiple remote sensing data sources should be integrated for analysis and model evaluation. It is critical to develop high-fidelity atmospheric models coupled with complex terrain and cryospheric components over the TP. Meanwhile, light-absorbing aerosols play a key role in climate and cryospheric changes across the TP because of the combined effects of solar radiation absorption and long-range transport of other atmospheric constituents. They can modulate ice/snow melting processes and potentially alter the regional hydrological cycle (Kang et al., 2019, 2020). How to quantify their contributions to the melting of the cryosphere and estimate their related impact on the hydrological changes needs to be strengthened in future studies.

Future changes in regional climate and air quality over the TP under a global warming scenario are important to local and downstream water cycles (Zhao et al., 2020), as well as to the associated ecosystems. Still, they require further understanding based on historical observations and simulations of climate models. So far, no consensus has been reached on a robust method of obtaining reliable projections. A complete physical attribution of climate change over the TP needs further analysis. In addition, the abovementioned studies suggest that the regional feedbacks from topography, snow cover, and the chemical-radiative-dynamical coupling processes are critical processes in climate systems, which should be better resolved/parameterized to improve simulations of regional climate and air quality over the TP.

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