

Land-Atmosphere Interactions and Effects on the Climate of the Tibetan Plateau and Surrounding Regions

Remote Sensing

Ma, Yaoming; Zhong, Lei ; Jia, Li; Menenti, Massimo

DOI

[10.3390/rs15010286](https://doi.org/10.3390/rs15010286)

Publication date

2023

Document Version

Final published version

Published in

Remote Sensing

Citation (APA)

Ma, Y., Zhong, L., Jia, L., & Menenti, M. (2023). Land-Atmosphere Interactions and Effects on the Climate of the Tibetan Plateau and Surrounding Regions: Remote Sensing. *Remote Sensing*, 15(1), Article 286. <https://doi.org/10.3390/rs15010286>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

Land-Atmosphere Interactions and Effects on the Climate of the Tibetan Plateau and Surrounding Regions

Yaoming Ma ^{1,2,3,4,5,6}, Lei Zhong ^{7,8,9,10,*}, Li Jia ¹¹ and Massimo Menenti ^{11,12}

- ¹ State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
 - ² College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
 - ³ College of Atmospheric Science, Lanzhou University, Lanzhou 730000, China
 - ⁴ National Observation and Research Station for Qomolangma Special Atmospheric Processes and Environmental Changes, Dingri 858200, China
 - ⁵ Kathmandu Center of Research and Education, Chinese Academy of Sciences, Beijing 100101, China
 - ⁶ China-Pakistan Joint Research Center on Earth Sciences, Chinese Academy of Sciences, Islamabad 45320, Pakistan
 - ⁷ School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China
 - ⁸ CAS Center for Excellence in Comparative Planetology, USTC, Hefei 230026, China
 - ⁹ Frontiers Science Center for Planetary Exploration and Emerging Technologies, University of Science and Technology of China, Hefei 230026, China
 - ¹⁰ Jiangsu Collaborative Innovation Center for Climate Change, Nanjing 210023, China
 - ¹¹ Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100101, China
 - ¹² Department of Geoscience and Remote Sensing, Technische Universiteit Delft, 2600 GA Delft, The Netherlands
- * Correspondence: zhonglei@ustc.edu.cn

1. Introduction

The global climate has undergone unequivocal warming. According to the sixth assessment report of the Intergovernmental Panel on Climate Change, the global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 °C (0.84 to 1.10 °C) higher than that from 1850–1900. Moreover, the global surface temperature from 2011–2020 was 1.09 °C (0.95 to 1.20 °C) higher than that from 1850–1900 [1]. Meanwhile, accelerating climate change exerts more influence on polar regions, high-altitude zones, and ecologically fragile areas. Often referred to as ‘the Third Pole’ and ‘the Roof of the World’, the Tibetan Plateau (TP) conserves vast areas of mountain glaciers, permafrost, and seasonally frozen soil and is the largest high-elevation portion of the cryosphere sensitive to global climate change [2]. In this context, quantitative assessment of the land–atmosphere interaction processes, as well as their effects on the TP and its surrounding regions, is not only essential for understanding the energy and water cycles in the cryosphere and hydrosphere but also crucial for understanding the Asian monsoon system and predicting the climate of Asia and the Northern Hemisphere [3].

To this end, this Special Issue aimed to present recent scientific advances on (1) the estimation of key land surface properties, (2) processes in the atmospheric boundary layer, (3) monitoring of glaciers and glacial lakes, (4) hydrometeorological processes, (5) vegetation dynamics and their response to weather and climate, etc.

Twenty-three articles are published in this Special Issue, covering progress on the following: land surface energy budget, glacier elevation change and snow phenology, the spatiotemporal distribution of precipitation, properties of land surface characteristic parameters, and evaluations of current models and products. The effects of climate change on high-altitude lakes were also included in this Special Issue.

2. Highlights of Research Articles

Citation: Ma, Y.; Zhong, L.; Jia, L.; Menenti, M. Land–Atmosphere Interactions and Effects on the Climate of the Tibetan Plateau and Surrounding Regions. *Remote Sens.* **2023**, *15*, 286. <https://doi.org/10.3390/rs15010286>

Received: 27 December 2022

Accepted: 28 December 2022

Published: 3 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

The land surface energy budget over the TP was analyzed via both remote sensing datasets and in situ observations. Based on empirical orthogonal function analysis of the summer surface sensible heating, a decadal decreasing trend was reported as the first dominant mode over the TP with an explained variance of 20.1% [4]. An enhanced water vapor supply and convergence over the TP were revealed, which led to an increase in the total cloud cover and a decrease in surface downwelling shortwave radiation. The reduction in downwelling shortwave radiation was found to dominate the shrinkage of surface sensible heating. Meanwhile, a zonally asymmetric pattern with positive (negative) sensible heating anomalies in the western (eastern) TP represented the second dominant mode (with an explained variance of 14.2%) [4]. At the station level, the sensible (latent) heat flux was the dominant energy balance component at the Ngari and Qomolangma (Linzhi, Muztagh, Nagqu, and Nam Co) stations. The radiation/energy balance components and surface characteristic parameters exhibited distinct diurnal cycles (e.g., a 'U' shaped curve of the surface broadband albedo was reported) [5]. Based on measurements at eight plateau stations in TIPEX III (the third Tibetan Plateau experiment for atmospheric sciences), the daily mean surface heating field varied from 70.2 to 101.2 W/m², with sensible (latent) heat flux from 18.8 to 60.1 W/m² (10.1 to 74.7 W/m²) [6]. A negative correlation between surface heating field density and the intensity of the South Asian summer monsoon was also verified at Baingoin, Nagqu, Nam Co, and Lhari stations [6].

Glaciers and snow phenology are sensitive indicators of climate change, both being involved in and affecting energy/water transfer processes. Global warming has led to significant changes in high-altitude glaciers. Shen et al. [7] developed an 'elevation-aspect bin analysis method' to estimate the intra- and interannual elevation changes of glaciers in the High Mountain Asia (HMA) region. An accelerating decreasing trend of glacier elevation was reported in most regions of the HMA, with mean change rates of -0.21 ± 0.12 m/year during 2003–2008 and -0.26 ± 0.11 m/year during 2003–2020. The variation in glacier elevation showed distinct spatial differences. The decreasing rate gradually decreased from the marginal region to the inner area of HMA, which indicates that the marginal areas of the TP may be zones facing significant risk [7]. Meanwhile, the spatiotemporal variation characteristics of snow disasters over the TP were also evaluated [8]. The frequency, duration, average snow depth, and grade of snow disasters over the TP all depicted a declining trend in the long run. Using the farmer and pastoralist well-being (FPWB) index, which has a negative relation with snow disaster risk, the whole TP area was divided into five distinct regions: Kashgar (I), Shigatse (II), Nagqu (III), Qamdo (IV), and Yushu (V), with gradually decreasing risks of snow disasters [8]. According to Wu et al. [9], factors such as precipitation, solar radiation, and air temperature significantly affect snow phenology. Precipitation was positively correlated with snow accumulation and maintenance, while solar radiation and air temperature functioned negatively. Comparatively, the quantity of snow was more sensitive to solar radiation, while its persistence was more sensitive to air temperature. The mean change rates of snow depth and snow cover maintenance days were estimated to be -0.06 cm/year and -0.37 day/year, respectively [9].

The spatiotemporal variability of precipitation was also focused on in this Special Issue. Meng et al. [10] reported that precipitation in most areas of the three rivers' source regions decreased in spring, autumn, and winter, while summer contributed the most increases. In contrast with the 2000s, the afternoon precipitation slightly decreased in the 2010s, while the nighttime precipitation increased significantly. Cao et al. [11] derived similar results, i.e., the diurnal maximum precipitation was found to be concentrated in the early evening, showing a distinct diurnal cycle. In addition, the raindrop size exhibited significant seasonal variability in the premonsoon, monsoon, and postmonsoon periods. The highest (lowest) concentration of small raindrops was observed in monsoon (winter) precipitation, while large raindrops dominated the premonsoon precipitation [12]. Shen et al. [13] found that the precipitation particles above high mountains have distinct characteristics, such as lower droplet number concentrations and larger diameters, compared

with those over plains. In addition, both Wang et al. [14] and Yang et al. [15] concluded that soil moisture plays a more dominant role in precipitation-use efficiency and evapotranspiration-precipitation coupling. Moreover, Shikhovtsev et al. [16] utilized the fifth generation ECMWF (European Centre for Medium-range Weather Forecasts) atmospheric reanalysis (ERA5) precipitable water vapor (PWV) data within 2010–2020 to establish a functional relation between the PWV and the elevation, exhibiting that the decrease of PWV with the elevation was exponential with a height scale of 1000 m. The ERA5 product was also reported to overestimate the PWV values by 1–2 mm in the Big Telescope Altazimuthal region (40°N–50°N, 35°E–55°E) [16].

Surface characteristic parameters are significant factors affecting the accuracy of surface process assessments. Li et al. [17] developed an algorithm to generate high-spatial-resolution soil moisture during the thawing season in the permafrost environment using Sentinel-1 and Sentinel-2 data. The comparison with ERA5-Land, Global Land Data Assimilation System (GLDAS), and European Space Agency Climate Change Initiative (ESA CCI) products indicated that this proposed method is able to provide more spatial details and achieve better performance in permafrost areas over the TP. The typical land cover types, alpine desert, alpine steppe, alpine meadow, and alpine swamp meadow, displayed distinct differences in soil moisture, with mean values of 0.16, 0.20, 0.23, and 0.26 m³/m³, respectively [17]. The soil's apparent thermal diffusivity (k) is also vital for investigating soil surface heat transfer. Tong et al. [18] determined the magnitude of k at hourly, daily, and monthly scales via a conduction–convection method. The monthly k varied from 0.4×10^{-6} to 1.1×10^{-6} m²/s at the wet site, with values from 1.7×10^{-7} to 3.3×10^{-7} m²/s at two dry sites, displaying magnitude differences under different soil moisture conditions. In addition, Ren et al. [19] reported that the Bowen ratio decreased significantly with an increase in soil moisture or effective precipitation. The Bowen ratio in the semiarid region was 1.5 times higher than that in the semihumid region during the growing season. Moreover, Zhang et al. [20] analyzed the profiles of the atmospheric refractive index structure constant (C_n^2), reporting unique optical turbulence characteristics compared with plain areas.

Several articles have evaluated the current models or products of near-surface hydrometeorological variables. Huang et al. [21] conducted a systematic assessment of three widely used air temperature products, namely, ERA5L, GLDAS, and China Meteorological Administration Land Data Assimilation System (CLDAS). Among these three products, CLDAS is more consistent with observations and can better describe temperature distribution and variation details than ERA5L and GLDAS for the Asian region. CLDAS is 0.53 K higher than the in situ observation, while ERA5L and GLDAS are lower than in situ measurements by −3.45 K and −1.40 K, respectively [21]. Liu et al. [22] reported that WRF applying the default glacial albedo scheme overestimates the albedo with a mean error of 0.18, while WRF applying a modified glacial albedo scheme slightly underestimates the albedo with a mean error of only −0.08. The default glacial albedo scheme gives a relatively high albedo value of 0.68, causing an underestimation of the net shortwave and net radiation. In contrast, the modified glacial albedo scheme provides a mean albedo value of 0.35, which is close to in situ measurements. In addition, Liu et al. [23] compared the leaf area index (LAI) estimations from 35 Earth system models that participated in the sixth Coupled Model Intercomparison Project (CMIP6) and found that these models overestimated the LAI trend over alpine vegetation, grassland, and forest but underestimated it over meadow and shrub. More than 70% of the models overestimated the LAI during the 1981–2014 growing seasons, indicating that the greening of grassland in the TP was greatly overestimated. Moreover, five complementary relationship-based models, requiring only routine meteorological variables to estimate actual terrestrial evapotranspiration, were evaluated by Shang et al. [24], with biases ranging from −94.2 to 28.3 mm/year. These models provide a simple and convenient approach for evapotranspiration estimates.

Finally, the responses of TP lakes to climate change were also quantitatively investigated. The lake surface water temperature of the largest freshwater lake in the TP, Ngoring Lake, was estimated to have a warming rate of 0.6 K/decade. However, comparison with its nearby small saline lake, the Hajiang Salt Pond, depicted distinct differences due to the salinity effect. The high salinity of the small saline lake made the annual mean lake surface water temperature 2.6 K higher and resulted in a 0.02 K/decade more significant warming trend than freshwater lakes at the same depth [25]. Moreover, the lakes in the Qaidam Basin were estimated to have undergone accelerated expansion. In the two study periods of 2003–2011 and 2011–present, the air temperature, precipitation, and runoff increased steadily, while the expansion rate of Tuosu Lake in the Qaidam Basin increased from 1.22 km²/year to 3.38 km²/year. This significant increase in the lake expansion rate reflects groundwater's substantial contribution to lake expansion [26].

3. Conclusions

This Special Issue compiles the up-to-date progress on the following: land surface energy budget, glacier/snow phenology, the spatiotemporal distribution of precipitation, properties of land surface characteristic parameters, evaluations of current models and products, and high-altitude lake processes over the TP and its surrounding regions. These selected papers are novel and timely in informing the land–atmosphere interactions driven by climate change. The collation of these papers will provide quantitative references for better assessment and prediction of the land–atmosphere interactions and their effects on “the Third Pole” and its surrounding regions.

Author Contributions: Conceptualization, Y.M. and L.Z.; formal analysis, Y.M., L.Z., L.J. and M.M.; investigation, L.Z.; writing—original draft preparation, L.Z.; writing—review and editing, Y.M., L.J. and M.M.; supervision, Y.M.; funding acquisition, Y.M. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was jointly funded by the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program, Ministry of Science and Technology of the People's Republic of China (Grant No. 2019QZKK0103), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA20060101), the National Natural Science Foundation of China (Grant Nos. 41875031, 91837208, and 4223061), and CLIMATE-Pan-TPE (ID 58516) in the framework of the ESA-MOST Dragon 5 program.

Conflicts of Interest: The author declares no conflict of interest.

References

1. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; p. 2391.
2. Ma, Y.; Hu, Z.; Xie, Z.; Ma, W.; Wang, B.; Chen, X.; Li, M.; Zhong, L.; Sun, F.; Gu, L.; et al. A Long-Term (2005–2016) Dataset of Hourly Integrated Land-Atmosphere Interaction Observations on the Tibetan Plateau. *Earth Syst. Sci. Data* **2020**, *12*, 2937–2957.
3. Su, Z.; Ma, Y.; Chen, X.; Dong, X.; Du, J.; Han, C.; He, Y.; Hofste, J.; Li, M.; Li, M.; et al. Monitoring Water and Energy Cycles at Climate Scale in the Third Pole Environment (CLIMATE-TPE). *Remote Sens.* **2021**, *13*, 3661.
4. Fan, W.; Hu, Z.; Ma, W.; Ma, Y.; Han, C.; Han, X.; Yang, Y.; Yu, H.; Fu, C.; Wu, D. Dominant Modes of Tibetan Plateau Summer Surface Sensible Heating and Associated Atmospheric Circulation Anomalies. *Remote Sens.* **2022**, *14*, 956.
5. Ma, J.; Wen, X.; Li, M.; Luo, S.; Zhu, X.; Yang, X.; Chen, M. Analysis of Surface Energy Changes over Different Underlying Surfaces Based on MODIS Land-Use Data and Green Vegetation Fraction over the Tibetan Plateau. *Remote Sens.* **2022**, *14*, 2751.
6. Li, H.; Zhou, L.; Wang, G. The Observed Impact of the South Asian Summer Monsoon on Land-Atmosphere Heat Transfers and Its Inhomogeneity over the Tibetan Plateau. *Remote Sens.* **2022**, *14*, 3236.
7. Shen, C.; Jia, L.; Ren, S. Inter- and Intra-Annual Glacier Elevation Change in High Mountain Asia Region Based on ICESat-1&2 Data Using Elevation-Aspect Bin Analysis Method. *Remote Sens.* **2022**, *14*, 1630.
8. Li, J.; Zou, Y.; Zhang, Y.; Sun, S.; Dong, X. Risk Assessment of Snow Disasters for Animal Husbandry on the Qinghai–Tibetan Plateau and Influences of Snow Disasters on the Well-Being of Farmers and Pastoralists. *Remote Sens.* **2022**, *14*, 3358.
9. Wu, L.; Li, C.; Xie, X.; Lv, J.; Zou, S.; Zhou, X.; Shen, N. Land Surface Snow Phenology Based on an Improved Downscaling Method in the Southern Gansu Plateau, China. *Remote Sens.* **2022**, *14*, 2848.
10. Meng, X.; Deng, M.; Liu, Y.; Li, Z.; Zhao, L. Remote Sensing-Detected Changes in Precipitation over the Source Region of Three Rivers in the Recent Two Decades. *Remote Sens.* **2022**, *14*, 2216.

11. Cao, B.; Yang, X.; Li, B.; Lu, Y.; Wen, J. Diurnal Variation in Cloud and Precipitation Characteristics in Summer over the Tibetan Plateau and Sichuan Basin. *Remote Sens.* **2022**, *14*, 2711.
12. Li, R.; Wang, G.; Zhou, R.; Zhang, J.; Liu, L. Seasonal Variation in Microphysical Characteristics of Precipitation at the Entrance of Water Vapor Channel in Yarlung Zangbo Grand Canyon. *Remote Sens.* **2022**, *14*, 3149.
13. Shen, C.; Li, G.; Dong, Y. Vertical Structures Associated with Orographic Precipitation during Warm Season in the Sichuan Basin and Its Surrounding Areas at Different Altitudes from 8-Year GPM DPR Observations. *Remote Sens.* **2022**, *14*, 4222.
14. Wang, S.; Zhang, Q.; Yue, P.; Wang, J.; Yang, J.; Wang, W.; Zhang, H.; Ren, X. Precipitation-Use Efficiency and Its Conversion with Climate Types in Mainland China. *Remote Sens.* **2022**, *14*, 2467.
15. Yang, Z.; Zhang, Q.; Zhang, Y.; Yue, P.; Zhang, L.; Zeng, J.; Qi, Y. Hydrothermal Factors Influence on Spatial-Temporal Variation of Evapotranspiration-Precipitation Coupling over Climate Transition Zone of North China. *Remote Sens.* **2022**, *14*, 1448.
16. Shikhovtsev, A.Y.; Kovadlo, P.G.; Khaikin, V.B.; Kiselev, A.V. Precipitable Water Vapor and Fractional Clear Sky Statistics within the Big Telescope Alt-Azimuthal Region. *Remote Sens.* **2022**, *14*, 6221.
17. Li, Z.; Zhao, L.; Wang, L.; Zou, D.; Liu, G.; Hu, G.; Du, E.; Xiao, Y.; Liu, S.; Zhou, H.; et al. Retrieving Soil Moisture in the Permafrost Environment by Sentinel-1/2 Temporal Data on the Qinghai–Tibet Plateau. *Remote Sens.* **2022**, *14*, 5966.
18. Tong, B.; Xu, H.; Horton, R.; Bian, L.; Guo, J. Determination of Long-Term Soil Apparent Thermal Diffusivity Using Near-Surface Soil Temperature on the Tibetan Plateau. *Remote Sens.* **2022**, *14*, 4238.
19. Ren, X.; Zhang, Q.; Yue, P.; Yang, J.; Wang, S. Environmental and Biophysical Effects of the Bowen Ratio over Typical Farmland Ecosystems in the Loess Plateau. *Remote Sens.* **2022**, *14*, 1897.
20. Zhang, K.; Wang, F.; Weng, N.; Wu, X.; Li, X.; Luo, T. Optical Turbulence Characteristics in the Upper Troposphere–Lower Stratosphere over the Lhasa within the Asian Summer Monsoon Anticyclone. *Remote Sens.* **2022**, *14*, 4104.
21. Huang, X.; Han, S.; Shi, C. Evaluation of Three Air Temperature Reanalysis Datasets in the Alpine Region of the Qinghai–Tibet Plateau. *Remote Sens.* **2022**, *14*, 4447.
22. Liu, L.; Menenti, M.; Ma, Y. Evaluation of Albedo Schemes in WRF Coupled with Noah-MP on the Parlung No. 4 Glacier. *Remote Sens.* **2022**, *14*, 3934.
23. Liu, J.; Lu, Y. How Well Do CMIP6 Models Simulate the Greening of the Tibetan Plateau? *Remote Sens.* **2022**, *14*, 4633.
24. Shang, C.; Wu, T.; Ma, N.; Wang, J.; Li, X.; Zhu, X.; Wang, T.; Hu, G.; Li, R.; Yang, S.; et al. Assessment of Different Complementary-Relationship-Based Models for Estimating Actual Terrestrial Evapotranspiration in the Frozen Ground Regions of the Qinghai–Tibet Plateau. *Remote Sens.* **2022**, *14*, 2047.
25. Wen, L.; Wang, C.; Li, Z.; Zhao, L.; Lyu, S.; Leppäranta, M.; Kirillin, G.; Chen, S. Thermal Responses of the Largest Freshwater Lake in the Tibetan Plateau and Its Nearby Saline Lake to Climate Change. *Remote Sens.* **2022**, *14*, 1774.
26. Zhang, X.; Chen, J.; Chen, J.; Ma, F.; Wang, T. Lake Expansion under the Groundwater Contribution in Qaidam Basin, China. *Remote Sens.* **2022**, *14*, 1756.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.