Integrated Atmospheric and Environmental Observations in the Himalayan Region Supporting the Development of Earth System Science on the Tibetan Plateau: Postprint

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Abstract

The Chinese Academy of Sciences Qomolangma Atmospheric and Environmental Comprehensive Observation and Research Station (hereinafter referred to as "Qomolangma Station") is located in the core area of the Qomolangma Nature Reserve. Focusing on the national strategic scientific and technological needs for ecological protection on the Tibetan Plateau, the construction of an ecological civilization highland, and sustainable economic and social development, it is dedicated to research on atmospheric processes and environmental changes in complex mountainous terrain of the Earth's "Third Pole". Qomolangma Station takes the study of land-atmosphere interaction processes on the Tibetan Plateau under climate change as its main research line, and has carried out long-term fixed-point monitoring and field scientific observation experiments on processes related to the surface, atmosphere, environment, glaciers, ecology, and geophysics; it has constructed a multi-temporal and spatial, multi-method, high-precision, multi-element integrated land-atmosphere interaction comprehensive observation and research platform in the Qomolangma region, significantly enhancing meteorological observation capabilities on the Tibetan Plateau, particularly in the Qomolangma area. Qomolangma Station is an important base for Earth system science research in the Himalayan region, providing fundamental data for in-depth and systematic Earth system science research on the Tibetan Plateau, while also serving as a supporting platform for understanding the role of the Tibetan Plateau in global change and its response to global change.

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Preamble

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Comprehensive Atmospheric and Environmental Observations in the Himalayan Region Advances Development of Earth System Science on the Tibetan Plateau

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Abstract

The Himalayan region, home to the world's highest mountain ranges including Mount Qomolangma (Everest), represents one of the most glacier- and snow-covered areas globally. Influenced by complex terrain, intense ocean-land-atmosphere multi-sphere interactions, and interspersed glaciers, rivers, and

snow cover, this region has formed unique atmospheric circulation systems and distinctive climatic and environmental characteristics. It serves as a natural laboratory for meteorological and ecological research in complex mountainous terrain. In recent years, global warming has caused significant climate and environmental changes in the Qomolangma region, with rapid temperature increases profoundly affecting its natural environment. These changes manifest as overall glacier retreat, rapid expansion of glacial lakes with increasing numbers, reduced snow cover area and rising snow lines, continuous vegetation greening, and generally improving ecosystem conditions. These environmental shifts influence regional and global climate change through land-atmosphere energy and water cycle processes, affect local atmospheric and hydrological cycles, cause frequent extreme weather events, and trigger natural disasters such as landslides, debris flows, and glacial lake outburst floods, threatening local populations and water resources.

To scientifically understand these changes, Chinese scientists have conducted multiple scientific expeditions to the Qomolangma region since the mid-20th century, overcoming numerous difficulties. However, expedition-based observations are limited in duration and cannot comprehensively capture seasonal and long-term atmospheric and environmental processes, nor do they address research objectives systematically. Therefore, the Qomolangma Station for Atmospheric and Environmental Observation and Research, Chinese Academy of Sciences (QOMS), was established to provide long-term comprehensive atmospheric and environmental observations. Building a permanent observation station in the Himalayan region, represented by the northern slope of Qomolangma, is scientifically crucial for comprehensively understanding the role and response of this region and the entire Tibetan Plateau in global change.

Construction of QOMS began during the fourth comprehensive scientific expedition to Qomolangma (March–May 2005) and was completed by the end of August 2005. In October 2021, it was approved as a National Field Scientific Observation and Research Station by the Ministry of Science and Technology, officially named the "National Field Scientific Observation and Research Station for Special Atmospheric Processes and Environmental Change in Tibet Qomolangma Region." The main station is located at 4,276 m elevation, approximately 30 km from the Qomolangma Base Camp, and represents the only long-term comprehensive observation and research station on the northern slope of Qomolangma. It is also a key field station in both the "Chinese Observation and Research Network of Land Surface Processes and Environment in Cold Regions" and the "Third Pole Environment" (TPE) international research program.

Keywords: Qomolangma, Himalayan region, land-atmosphere interactions, atmospheric boundary layer, water and heat fluxes, global change

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1. Establishment of a Multi-Layer Land-Atmosphere Interaction Observation Network in the Qomolangma Region

Research on land-atmosphere interactions over complex underlying surfaces and their weather and climate effects represents a major international scientific focus. To deepen understanding of energy and water exchange characteristics and atmospheric boundary layer structure over the complex terrain and surface features of the plateau, QOMS has established a meteorological gradient observation system along the Rongbuk Valley covering different elevation zones and major geographic-ecological units including glaciers, alpine gravel, alpine shrubland, alpine wetlands, and alpine desert grassland [Figure 1: see original paper]. This system enables multi-element, multi-scale, and refined gradient monitoring of atmospheric processes and environmental changes in the region. Critical zone observation research areas have been established to conduct various observation programs at site, transect, watershed, and regional scales, encompassing atmospheric physics, atmospheric environment, vegetation ecology, hydrological processes, and geophysics.

Atmospheric physics observations primarily include boundary layer gradient observation systems, eddy covariance atmospheric turbulence observation systems, wind profiler systems, radiosonde observation systems, soil water-heat observation systems, and ground-based multi-channel microwave radiometers. The integrated observation system performs real-time continuous monitoring of atmospheric turbulence processes, near-surface (0–40 m) and lower atmospheric (80–5,000 m) boundary layer structural changes (wind speed, wind direction, air temperature, relative humidity), surface radiation budget processes, and soil water-heat transfer processes at frequencies ranging from 10 Hz to 30 minutes. These multi-element observations enable investigation of boundary layer turbulence characteristics, turbulent transport of water vapor, carbon dioxide, sensible heat, and latent heat fluxes, boundary layer vertical structure and its temporal variation, surface radiation and energy balance characteristics, and soil water-heat properties, thereby advancing understanding of water vapor transport, water cycling, and spatiotemporal precipitation distribution and their impacts on mesoscale weather systems in the Qomolangma region and surrounding areas.

While expanding and improving the comprehensive observation network for land-atmosphere interactions in the Qomolangma region, QOMS has also strengthened and standardized observation methodologies and data quality control procedures. The station has enhanced integration with national science and technology resource sharing service platforms and other national science and technology innovation bases, formulated standards for open sharing of observation data from field stations, and provided orderly open access and sharing services. The comprehensive observation data on land-atmosphere interaction processes from QOMS since its establishment have been openly shared [4], effectively promoting the sharing of scientific facilities, data, and other technological resources.

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2. Analysis of Key Turbulence Characteristics and Energy Exchange Features in the Qomolangma Region

Aerodynamic and thermodynamic roughness lengths are critical parameters affecting momentum and energy exchange between the surface and atmosphere, essential for surface process and climate change research. Analysis of key characteristic parameters of land-atmosphere interaction processes based on long-term comprehensive observation data from the station helps improve parameterization schemes for land surface and atmospheric boundary layer processes in numerical models and deepens understanding of key scientific issues in land-atmosphere interactions over complex underlying surfaces.

Long-term comprehensive observation data analysis from QOMS reveals that the relationship between dimensionless wind speed component variance and static stability in the near-surface layer of the Rongbuk Valley follows the "1/3" power law, confirming the applicability of Monin-Obukhov similarity theory in this region [5]. Using eddy covariance and meteorological data, key parameters for material and energy exchange between land and atmosphere have been analyzed, including the total momentum transfer coefficient (CD), total heat transfer coefficient (CH), aerodynamic roughness length (z0m), thermodynamic roughness length (z0h), and excess resistance coefficient for heat transfer (kB^{-1}) [6]. These studies reveal the "non-stationary" spatiotemporal variation patterns of key turbulence exchange parameters over the complex plateau surface, such as dynamic and thermodynamic roughness and excess resistance for heat transfer [Figure 2: see original paper], and indicate that using "stationary" characteristic parameters in current numerical models causes serious "distortion" effects. Additionally, based on wind-temperature profile data, turbulence observations, and surface meteorological data, the effective aerodynamic roughness length for the QOMS area has been determined, showing that effective aerodynamic roughness in mountainous areas is 1–2 orders of magnitude larger than local-scale aerodynamic roughness [7]. Research on observed parameters of material and energy exchange between the surface and atmosphere over complex plateau underlying surfaces has laid the foundation for improving weather and climate model simulation accuracy over the Tibetan Plateau.

Influenced by monsoon precipitation, surface sensible and latent heat fluxes in the Qomolangma region exhibit alternating seasonal variations [3,8]. Sensible and latent heat fluxes are comparable in winter, sensible heat dominates surface energy transfer in spring, while latent heat prevails in summer, with latent heat reaching twice the sensible heat during the peak monsoon period [Figure 3c: see original paper]. Sensible heat flux variation is primarily controlled by solar radiation, whereas latent heat flux variation is jointly influenced by solar radiation and precipitation. Due to differences in surface conditions and soil physical properties (such as soil texture and porosity) among different sites, surface energy balance components show consistent seasonal trends, but sensible heat flux, latent heat flux, reflected shortwave radiation, and emitted longwave radiation differ significantly between sites [3], highlighting the necessity of water-heat flux observations for different underlying surface conditions in complex mountainous areas. Furthermore, multi-year clear-sky daytime radiation observations show decreasing trends in downward shortwave radiation and increasing trends in upward longwave radiation across different years [9].

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3. Revealing the Interaction Between Complex Plateau Mountainous Terrain and Westerly Circulation and Its Influence on Atmospheric Boundary Layer Development

The atmospheric boundary layer is the primary region where energy and material exchange occurs between the surface and atmosphere. Revealing the atmospheric boundary layer structure and its development mechanisms in the Qomolangma region provides important insights for understanding heat and water budgets and weather and climate changes in the region and surrounding plateau areas. QOMS is currently equipped with a complete atmospheric boundary layer integrated observation system comprising atmospheric boundary layer towers, radiosondes, microwave radiometers, and wind profiler radar, capable of acquiring, processing, and analyzing vertical structures of atmospheric pressure, temperature, humidity, wind speed, and wind direction from the surface to mid-lower altitudes.

Analysis of atmospheric boundary layer structure and atmospheric circulation characteristics shows significant seasonal differences in atmospheric boundary layer height in the Qomolangma region. Generally, the boundary layer develops deeply during both monsoon and non-monsoon periods, with dry season boundary layer heights much greater than wet season heights. Under the influence of glacier winds, atmospheric boundary layer height exhibits significant diurnal variation. Strong afternoon winds prevail in the Qomolangma region, with southwesterly winds dominating in the non-monsoon period and southeasterly winds prevailing during the monsoon period. The strong southwesterly near-surface winds during the non-monsoon period result from downward momentum transfer from the upper-level westerly jet, while during the monsoon period, the northward shift of the westerly belt means the region is no longer controlled by the westerly jet. Instead, terrain and South Asian monsoon effects generate strong southeasterly winds in the afternoon [11]. Weather Research and Forecasting (WRF) model simulations also show that the intense southwesterly near-surface winds around QOMS during the non-monsoon period are influenced by upper-level westerlies, while southeasterly winds during the monsoon period originate from valleys crossing the Himalayas east of Qomolangma [12].

The unique local circulation characteristics in the Qomolangma region are influenced by large-scale circulation systems [8,10–12]. For example, Lai et al. [10] demonstrated that when large-scale westerly winds above ridge height in the Rongbuk Valley are parallel to the valley axis, westerly momentum more easily transfers downward into the valley, increasing surface wind speed and sensible heat flux while forming an anomalous local thermally-driven wind in the valley [Figure 4: see original paper]. Additionally, valley winds and glacier winds triggered by the complex surrounding mountainous terrain also play important roles in forming the region's unique local circulation characteristics [3,8,10–13]. For instance, glacier wind effects dominate after 15:00, reaching maximum speeds of 10 m/s, causing valley winds to disappear and creating local cooling and moistening [13]. Meanwhile, interaction between mountainous terrain and large-scale westerly circulation systems plays a key role in atmospheric boundary layer growth on the northern side of the central Himalayas. Using radiosonde data, surface observations, ERA5 reanalysis data, and boundary layer simulations, the formation and development mechanisms of the deep atmospheric boundary layer in the central Himalayas have been elucidated [10].

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4. Development of Remote Sensing Inversion Algorithms and Numerical Model Parameterization Schemes for Surface Water-Heat Fluxes in Complex Mountainous Areas

Discrete "point" observations can only represent surface energy processes at specific locations or under particular surface characteristics, making it difficult to capture the essence of regional "area" land-atmosphere energy exchange. Satellite remote sensing or numerical modeling is required to extend site observations to the regional scale. Furthermore, the accuracy and uncertainty of remote sensing inversion and numerical model simulations of surface water-heat fluxes in complex mountainous areas require evaluation and validation using ground-based measurements. Therefore, based on comprehensive ground observation data from alpine mountainous areas, validating the reliability and applicability of remote sensing inversion and numerical model simulation results for water-heat fluxes [14,15] and establishing effective "point-area combination" methods for estimating surface water-heat fluxes [16–18] are crucial for revealing regional-scale surface water-heat flux exchange characteristics in complex mountainous areas.

Using satellite remote sensing data combined with ground observations from

QOMS, surface characteristic parameters in the Qomolangma region have been estimated (surface albedo, vegetation index NDVI, etc.). Combined with surface and atmospheric parameters determined from ground observations (such as aerodynamic roughness z0m, thermodynamic roughness z0h, excess resistance coefficient kB^{-1}, etc.), regional-scale surface water-heat fluxes have been derived [16–19]. Building on this work, an upscaling theory combining satellite remote sensing and ground observations has been established for the Tibetan Plateau, introducing new methods of "mosaic approximation" and "mixed-height hypothesis" for accurately estimating plateau regional surface heat fluxes [Figure 5: see original paper]. These approaches significantly improve the estimation accuracy of surface water-heat fluxes and quantitatively reveal the high-resolution spatiotemporal distribution characteristics of water-heat states and warming-wetting trends over the complex plateau surface [20]. Based on station observation data, the accuracy of remote sensing data products including MODIS and FY-2C in this region has been validated [14,15], and the roughness scheme in the Surface Energy Balance System (SEBS) model has been improved [21], further enhancing numerical model simulation accuracy for plateau surface water-heat fluxes. These studies are essential for understanding energy and water cycle patterns and their weather and climate impact mechanisms in high-altitude complex terrain regions.

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5. Providing Critical Support for Major National Activities, Frontier Scientific Exploration, and Implementation of Major National Science and Technology Tasks

Since its establishment, QOMS has consistently adhered to its primary functions and positioning of "observation, research, support, and service." As an important scientific research base in the Qomolangma region, QOMS provides scientific instruments, observation data, and support for major national activities (such as ensuring the successful summit of the 2008 Beijing Olympic torch), frontier scientific exploration, and implementation of major national science and technology tasks. With continuously improving infrastructure, QOMS has become a research base supporting major science and technology tasks, having approved and implemented numerous research projects including the National Natural Science Foundation of China's major research plans, key projects, international cooperation and exchange programs, the Second Tibetan Plateau Scientific Expedition Program, the Chinese Academy of Sciences' Strategic Priority Research Program (Category A), and the Ministry of Science and Technology's National Key R&D Program. These initiatives have effectively supported regional scientific activities, promoted frontier exploration, and enhanced China's international influence in Tibetan Plateau research.

Since 2018, with the launch and implementation of the Chinese Academy of Sciences' Strategic Priority Research Program (Category A) "Pan-Third Pole

Environmental Change and Green Silk Road Construction" and the Second Tibetan Plateau Scientific Expedition, QOMS has become an even more important scientific expedition and research base. During the "Earth Summit Mission 2022" joint scientific expedition, QOMS conducted atmospheric vertical detection using radiosondes, ground-based microwave radiometers, and wind lidar, obtaining real-time three-dimensional atmospheric structure characteristics of the Qomolangma region [22]. During summit attempts and airship deployment operations, intensive radiosonde observation experiments were conducted to maximize real-time monitoring of weather condition changes, collecting various meteorological observation data to support observation and forecasting of extreme weather processes and participating in weather consultation meetings for the expedition's meteorological support team, providing meteorological support for the safe and successful summit of expedition members. In summary, through continuous observation and technical support, QOMS demonstrates greater responsibility and contributes more significantly to promoting regional scientific development and serving major national strategies.

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6. Conclusion

Over the past two decades, QOMS has focused on atmospheric and environmental changes in the important special environment and high-altitude region of Qomolangma. By establishing a national field scientific observation and research station based on multidisciplinary intersection of atmospheric environmental changes in this region, QOMS has constructed a comprehensive observation system for land-atmosphere interaction processes in the Qomolangma region that is multi-temporal and spatial, multi-method, high-precision, and multi-element integrated. From three perspectives—observation experiments, satellite remote sensing, and numerical simulation—QOMS has effectively advanced research on complex surface energy and water cycle patterns and their weather and climate impact mechanisms. The station has identified key parameters of surface features affecting material and energy exchange between land and atmosphere, revealed interaction processes between complex plateau mountainous terrain and westerly large-scale atmospheric circulation and their impacts on atmospheric boundary layer development, developed and validated remote sensing inversion algorithms and numerical model parameterization schemes for regional surface energy fluxes, and established a "point-area combination" theory for satellite remote sensing inversion of complex land surface water-heat fluxes on the Tibetan Plateau.

Looking ahead, QOMS will leverage the opportunity of national station construction, focus on national and local sustainable development needs of Tibet, adhere to its scientific research characteristics and disciplinary development features, and maintain the vision of "establishing innovation based on the polar region and becoming an innovation highland." The station will continue combining long-term atmospheric and environmental process monitoring, scientific experiments, satellite remote sensing, and numerical simulation to conduct technical integration and demonstration research from "point" to "area" and from "unit" to "system." By strengthening hardware and software construction, QOMS will enhance its comprehensive observation capabilities, basic research level, and support capacity for scientific expeditions, becoming a high-level scientific and technological innovation base supporting major national research tasks, a field scientific expedition base supporting major expedition missions, a demonstration base for regional ecological civilization construction, and a science education base for knowledge popularization and dissemination. The station will achieve its primary goals of "observation, research, support, and service" and establish itself as a comprehensive field scientific observation and research station on the Tibetan Plateau with international influence.

References

1. Ma Y M. An introduction to atmospheric and environmental comprehensive observation and research station on Mt. Qomolangma, Chinese academy of sciences (AECORSQ): A new base for the study of atmosphere-land interaction over the Himalaya area. Plateau Meteorology, 2007, 26(6): 1141-1145. (in Chinese)
2. Kang S C, Zhang Q G, Zhang Y L, et al. Warming and thawing in the Mt. Everest region: A review of climate and environmental changes. Earth-Science Reviews, 2022, 225: 103941.
3. Ma Y M, Xie Z P, Ma W Q, et al. QOMS: A comprehensive observation station for climate change research on the top of earth. Bulletin of the American Meteorological Society, 2023, 104(3): E563-E584.
4. Ma Y M, Hu Z Y, Xie Z P, et al. A long-term (2005-2016) dataset of hourly integrated land-atmosphere interaction observations on the Tibetan Plateau. Earth System Science Data, 2020, 12(4): 2937-2957.
5. Zhong L, Ma Y M, Li M S. An analysis of atmosphere turbulence and energy transfer characteristics of surface layer over rongbu valley in Mt. Qomolangma area. Chinese Journal of Atmospheric Sciences, 2007, 31(1): 48-56. (in Chinese)
6. Han C B, Ma Y M, Chen X L, et al. Estimates of land surface interaction parameters over the Tibetan Plateau. Journal of Hydrometeorology, 2011, 12(4): 702-708.
7. Han C B, Ma Y M, Su Z B, et al. Estimates of effective aerodynamic roughness length over mountainous areas of the Tibetan Plateau. Quarterly Journal of the Royal Meteorological Society, 2015, 141(689): 1457-1465.
8. Ma Y M, Wang Y J, Ma W Q, et al. Determinating the regional distributions of surface heat fluxes over heterogeneous landscape of Mt. Qo-

molangma area using the satellite remote sensing and field observations. Plateau Meteorology, 2007, 26(6): 1231-1236. (in Chinese)

9. Gu X Y, Ma Y M, Ma W Q, et al. Climatic characteristics of surface radiation flux over the qinghai-tibetan plateau. Plateau Meteorology, 2018, 37(6): 1458-1469. (in Chinese)
10. Lai Y, Chen X L, Ma Y M, et al. Impacts of the westerlies on planetary boundary layer growth over a valley on the north side of the central Himalayas. Journal of Geophysical Research: Atmospheres, 2021, 126(3): e2020JD033928.
11. Sun F L, Ma Y M, Hu Z Y, et al. Observation of strong winds on the northern slopes of mount Everest in monsoon season. Arctic, Antarctic, and Alpine Research, 2017, 49(4): 687-697.
12. Sun F L, Ma Y M, Hu Z Y, et al. Mechanism of daytime strong winds on the northern slopes of Himalayas, near mount Everest: Observation and simulation. Journal of Applied Meteorology and Climatology, 2018, 57(2): 255-272.
13. Sun F L, Ma Y M. Characteristics of local circulation in a Himalayan valley on the northern slop of Mt. Qomolangma. Plateau Meteorology, 2007, 26(6): 1187-1190. (in Chinese)
14. Chen X L, Su Z B, Ma Y M, et al. An accurate estimate of monthly mean land surface temperatures from MODIS clear-sky retrievals. Journal of Hydrometeorology, 2017, 18(10): 2609-2622.
15. Han C B, Ma Y M, Chen X L, et al. Estimates of land surface heat fluxes of the Mt. Everest region over the Tibetan Plateau utilizing ASTER data. Atmospheric Research, 2016, 168: 20-36.
16. Tian H, Ma Y M, Wen J, et al. Study on autumn land surface fluxes over complex terrain using satellite remote sensing data over the Mt. Qomolangma region. Plateau Meteorology, 2007, 26(6): 1293-1299. (in Chinese)
17. Ma Y M, Han C B, Zhong L, et al. Using MODIS and AVHRR data to determine regional surface heating field and heat flux distributions over the heterogeneous landscape of the Tibetan Plateau. Theoretical and Applied Climatology, 2014, 117(3): 643-652.
18. Zhong L, Ma Y M, Su Z B, et al. Assessment of regional surface heat fluxes on the Tibetan Plateau from 2001 to 2012. International Journal of Climatology, 2017, 37(14): 4757-4766.
19. Ma Y M, Zhong L, Su Z B, et al. A mosaic approximation and a mixed pixel method for determining regional surface heating fields and heat flux distributions over the heterogeneous landscape of the Tibetan Plateau. Plateau Meteorology, 2007, 26(6): 1141-1145. (in Chinese)

20. Ma Y M, Zhong L, Su Z B, et al. Determination of regional distributions of surface fluxes over heterogeneous land surfaces on the Tibetan Plateau. Plateau Meteorology, 2007, 26(6): 1231-1236. (in Chinese)

21. Chen X L, Su Z B, Ma Y M, et al. An improved aerodynamic roughness height parameterization of the surface energy balance system (SEBS) over the Tibetan Plateau. Journal of Applied Meteorology and Climatology, 2013, 52(3): 607-622.

22. Ma Y M, Ma W Q, Dai H G, et al. Earth summit mission 2022: Scientific expedition research on Mt. Qomolangma helps reveal the synergy between westerly winds and monsoon and resulting climatic and environmental effects. Advances in Atmospheric Sciences, 2023, 40(2): 187-193.

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Note: Figure translations are in progress. See original paper for figures.