Permafrost Survey and Monitoring Provides Scientific Support for Tibetan Plateau Earth Science Research, Environmental Protection, and Engineering Construction Postprint

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Abstract

With the implementation of China' s Western Development Strategy and the increasingly significant impacts of climate warming on the Tibetan Plateau, the effects of permafrost changes on ecology, hydrology, climate, and engineering construction have become increasingly prominent. Long-term fixed-point monitoring and large-scale field investigations of permafrost have become a critical demand for deepening research and addressing major scientific and engineering problems in cryosphere, ecology, hydrology, climate, and cold region engineering construction. Since its establishment, the Cryosphere Research Station on the Qinghai-Tibet Plateau, Chinese Academy of Sciences (abbreviated as the "Plateau Cryosphere Station"), has conducted long-term continuous monitoring and large-scale field investigations of permafrost on the Tibetan Plateau, and carried out comprehensive research on the change mechanisms, model simulations, and ecological effects of permafrost hydrothermal regimes. Particularly in recent years, with support from major projects of the Ministry of Science and Technology, the National Natural Science Foundation of China, and the Chinese Academy of Sciences, the Plateau Cryosphere Station has actively promoted domestic and international scientific cooperation, standardized methods for permafrost field investigation and fixed-point monitoring, and established a comprehensive permafrost monitoring network that is internationally leading; systematically conducted quantitative research on the spatial differentiation patterns of permafrost distribution, temperature, thickness, and ground ice on the plateau, and based on multi-source data and multi-model comparisons, released spatial grid data of permafrost temperature, thickness, and ground ice on the plateau with a spatial resolution of 1 km. Based on long-term monitoring data, one-dimensional heat conduction models and land surface process models suit-

able for permafrost on the Tibetan Plateau were constructed and improved, and the changes and physical mechanisms of permafrost at the plateau scale over the past 30 years were quantitatively evaluated. These scientific research achievements not only provide strong foundational data support for solving problems such as Qinghai-Tibet Railway construction, ecological protection of Sanjiangyuan National Park, and regional climate simulation, but also address national needs and major national project research, promoting decision-making consultation services. Research results on the spatial distribution of vegetation, ecology, and soil organic carbon and nitrogen in permafrost regions of the Tibetan Plateau have filled international gaps in this field, providing the most fundamental baseline data support for the Future Earth international scientific research program and the development of Earth system models.

Full Text

Preamble

The Cryosphere Research Station on the Qinghai-Xizang Plateau (hereafter referred to as the "QTP Cryosphere Station") of the Chinese Academy of Sciences (CAS) was established to conduct long-term monitoring and research on the unique characteristics, processes, changes, and impacts of permafrost, thereby accumulating fundamental data and theoretical support for geoscience research and production practices on the Tibetan Plateau. Over the past 30 years, the station has built the most comprehensive permafrost monitoring network in the world, yielding valuable observational and first-hand survey data while conducting systematic research on permafrost and its role in the Earth system.

Abstract

Due to climate warming and the implementation of China' s western development strategy, permafrost variation on the Qinghai-Tibet Plateau (QTP) has increasingly and significantly influenced regional ecology, hydrology, climate, and engineering construction over recent decades. Long-term in-situ monitoring and large-scale field investigation of permafrost have become essential for addressing key scientific and engineering challenges in cryospheric, ecological, hydrological, climatic, and cold-region engineering domains. Since its establishment in 1987, the QTP Cryosphere Station has conducted continuous long-term monitoring and extensive field investigations of permafrost across the plateau, synthetically studying the mechanisms of hydrothermal condition changes, model simulations, and ecological effects. Supported by major programs from the Ministry of Science and Technology, the National Natural Science Foundation of China, and CAS, the station has actively promoted international cooperation, standardized field investigation and monitoring methodologies, and established a world-leading comprehensive permafrost monitoring network. Through quantitative studies on the spatial distribution, ground temperature, thickness, and ground ice of plateau permafrost, and by integrating multi-source data with multi-model comparisons, the station has released 1 km resolution grid datasets of permafrost temperature, thickness, and ground ice for the entire plateau. Based on long-term monitoring data, we developed and improved one-dimensional heat conduction and land surface process models suitable for QTP permafrost, quantitatively evaluating plateau-scale permafrost changes and their physical mechanisms over the past 30 years. These results provide critical baseline data support for the Qinghai-Tibet Railway construction, Three-River Source National Park ecological protection, and regional climate modeling, while also informing national needs and major research programs. Research findings on vegetation, ecology, and soil organic carbon and nitrogen spatial distributions in QTP permafrost regions fill international gaps in these fields, providing fundamental baseline data for future Earth international scientific research programs and Earth system model development.

Keywords: Qinghai-Tibet Plateau (QTP), permafrost, investigation, monitoring, ground ice, carbon cycle

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Main Text

The Tibetan Plateau, formed through several tectonic movements over more than 200 million years, has risen from the "Tethys Sea" with average elevations below sea level to become the highest plateau at mid-low latitudes globally. Its climate has gradually shifted from warm-humid to overall cold-arid conditions, with permafrost forming as elevation increased and temperatures cooled. While existing knowledge cannot pinpoint the exact timing and location of initial permafrost development on the plateau, during the Last Glacial Maximum over 20,000 years ago, permafrost underlay 85% of the plateau surface, covering at least 2.2 million km² [1]. Subsequent climate warming during the Holocene Optimum caused permafrost extent to retreat to its minimum. Overall, QTP permafrost has been shrinking since the Late Pleistocene, currently developing primarily across the plateau interior as large continuous masses that transition radially to discontinuous "border" patterns around the periphery. The main continuous permafrost zone extends eastward from the Anyêmaqên Mountains to the western Himalayas and western Karakoram slopes, and northward from the southern Tanggula Mountains to the northern Kunlun slopes. The "border" permafrost appears as "caps" covering mountain tops around the plateau periphery, mainly in the Qilian Mountains to the north, Anyêmaqên and Hengduan Mountains to the east, and Nyenchen Thanglha, Gangdise, and Himalaya Mountains to the south and west, forming discontinuous, island-like bands around the plateau interior.

Known as the world' s "Third Pole" due to its high elevation and vast area, the Tibetan Plateau significantly influences regional climate and global environment through thermal and mechanical forcing, serving as a "sensitive zone" and "trigger region" for China' s climate change and a "driver" and "amplifier" of global change. Currently, QTP permafrost covers 1.06 million km^2 [2], representing the highest and largest high-altitude permafrost region at mid-low latitudes globally, occupying an important position in worldwide permafrost distribution [1]. Over the past 50+ years, the plateau has experienced significant warming that may continue, causing permafrost temperature rise, active layer thickening, extent shrinkage, and thickness reduction [3]. These changes affect ground ice and organic carbon formation/storage environments, alter interactions among water, soil, atmosphere, and biological elements in permafrost regions, and consequently impact regional hydrology, ecology, and even global climate systems, while also influencing human engineering activities and regional sustainable development.

From 1987 to 1997, supported by horizontal production-oriented projects, the QTP Cryosphere Station maintained four shallow permafrost temperature monitoring boreholes (maximum depth 30 m) and one manually observed boundary layer gradient meteorological tower along the Qinghai-Tibet Highway from Xidatan to Wudaoliang, obtaining the first continuous permafrost temperature data from the plateau interior [4]. Between 1990 and the early 21st century, through international cooperation funding, the station established five active layer hydrothermal monitoring sites and three automatic gradient meteorological stations along the highway, forming the initial integrated monitoring system combining meteorology, active layer hydrothermal conditions, and permafrost temperature. These observations not only supported highway maintenance but also provided the primary basis for permafrost subgrade stability classification, foundation design, and construction during subsequent Qinghai-Tibet Railway construction, while meeting single-point simulation data requirements for land surface process models and promoting simulation of surface energy and water processes in plateau permafrost regions.

Beginning in 2009, supported primarily by the Ministry of Science and Technology' s Special Program for Basic Research "Permafrost Background Investigation on the Qinghai-Tibet Plateau" and integrating various CAS and NSFC research funds, the station standardized field investigation and monitoring methods [5] while establishing a permafrost monitoring network covering the western Karakoram to eastern Anyêmaqên Mountains, northern Qilian and Altun Mountains to southern Gangdise Mountains, essentially covering the main plateau permafrost region. This effort updated and improved monitoring systems established in the 1980s-1990s at the Urumqi River source in Xinjiang and Maxian Mountain in Yuzhong County, Gansu. Spanning four provinces (Gansu, Qinghai, Tibet, Xinjiang) at average elevations above 4,500 m, the network comprises over 130 sites [Figure 1: see original paper], including 10 three-to-four-layer gradient meteorological stations, five eddy covariance systems, 20 active layer hydrothermal observation points, and 100 permafrost temperature boreholes. Except for borehole temperature measurements, all observations are automatically recorded, covering meteorological elements, surface energy and water balance, active layer hydrothermal characteristics, permafrost temperature, greenhouse gas emissions, soil carbon-nitrogen cycling, and other elements related to surface ecology and hydrology, forming an integrated sky-ground-space observation system. Most sites are located in previously unobserved areas, filling monitoring gaps and significantly improving data coverage for high-altitude plateau regions.

Long-term monitoring data and typical area surveys indicate that most QTP permafrost belongs to "warm permafrost" with mean annual ground temperatures (MAGT) above -1.0°C, while permafrost below -2.0°C occurs only in some high mountains [3,6]. Warm permafrost, characterized by complex warming processes and significant impacts on regional environment and engineering, has received widespread attention. Using continuous high-precision monitoring data, the station conducted in-depth analysis of hydrothermal dynamics in the active layer and permafrost, first dividing the seasonal freeze-thaw cycle into four stages with comprehensive elaboration of hydrothermal coupling processes at each stage, deepening understanding of freeze-thaw cycles [7]. Extensive temperature monitoring reveals continuous changes in thermal physical parameters, vertical ground temperature distribution patterns, and energy allocation ratios at different depths. Permafrost warming leads to decreasing annual temperature variation depth and soil thermal diffusivity, promoting top-down permafrost degradation (active layer thickening) [6]. These results reasonably explain why active layer thickening is more obvious than ground temperature rise on the QTP, providing strong scientific support for major engineering projects like the Qinghai-Tibet Railway/Highway.

Based on field survey data and monitoring records, the station investigated relationships between permafrost characteristics (temperature, ground ice, thickness) and climate, soil, vegetation, and geological/geomorphological background, constructing spatial distribution models for permafrost and active layer temperature/thickness. Using corrected remote sensing surface temperature data and newly compiled soil/vegetation spatial data, validated with permafrost distribution data from five typical areas and three survey profiles, the station produced the latest and highest-resolution "Permafrost Map of the Qinghai-Tibet Plateau" [Figure 3: see original paper] [2]. This map delineates not only spatial distribution but also detailed permafrost temperature information [12], indicating actual permafrost area of 1.06 million km^2 with temperatures mainly around -0.5°C. Through multi-model comparisons using extensive thickness data, the station compiled a permafrost thickness distribution map, showing average thickness of about 39 m—60-130 m in high mountains and hills, but only several meters to 60 m in broad plateau surfaces and valleys. Updated Stefan equation parameters using remote sensing surface temperature and soil survey data simulated active layer thickness, yielding a plateau-scale average of 1.9 m (90% concentrated between 0.9-2.7 m). Additionally, by analyzing historical borehole data and studying how permafrost conditions and geological/geomorphological factors control ground ice development, the station reassessed ground ice reserves in plateau permafrost at approximately 12.7×10^{12} m^3, with about 2.2×10^{12} m^3

occurring below 10 m depth .

Since 2009, the station has conducted large-scale permafrost status surveys for five consecutive years under the Ministry of Science and Technology' s Special Program. Using typical areas including Wenquan in Xinghai County, Hoh Xil in Qumarlêb County, Zaduo County in Qinghai; Gaizê and Amdo Counties in Tibet; and Altun and Tianshuihai areas in western Kunlun, Xinjiang, comprehensive investigations employed radar, electromagnetic surveys, drilling, soil profiles, vegetation quadrats, and UAV aerial photography to examine permafrost distribution boundaries, thickness, ground ice, active layer thickness, soil, vegetation, climate, geology, and geomorphology. This formed a permafrost investigation network covering different climatic, geological, and geomorphological regions of the plateau interior, centered on seven typical survey areas with two transverse and three longitudinal survey lines [Figure 2: see original paper], obtaining substantial field data from uninhabited areas for the first time. Integrating multi-source remote sensing inversion and multi-model simulations, the station compiled 1 km resolution maps of soil and vegetation in typical survey areas and across the plateau [8-11], greatly advancing understanding of soil and vegetation resources in the plateau interior.

Permafrost occupies over half of the QTP land surface and plays crucial roles in plateau climate, hydrology, and ecosystems. However, previous research was limited mainly to areas along the Qinghai-Tibet Highway/Railway and Gonghe-Yushu section of the Qinghai-Tibet Highway, leaving other plateau regions largely unstudied and limiting integrated Earth system science research. The station' s work has filled these gaps.

The freeze-thaw process in the active layer and monsoon precipitation are primary causes of greater latent heat flux in permafrost regions compared to non-permafrost areas [13]. Daily freeze-thaw cycles begin in the active layer surface around mid-to-late April. By mid-to-late May, the surface soil completely thaws while the freezing front beneath blocks downward water percolation. After May, enhanced Indian monsoon and westerly winds increase precipitation, raising surface soil moisture and latent heat output. By September, when the active layer reaches maximum thaw depth and monsoons retreat, surface moisture decreases rapidly and latent heat diminishes.

Field monitoring and research show that along the Qinghai-Tibet Highway in Hoh Xil, Beiluhe, Kaixinling, and Tongtianhe areas, shallow soil thermal conductivity in frozen state is smaller than in thawed state [14-17]—in Wudaoliang's dry-cold steppe region, unfrozen thermal conductivity is 1.81 times that of frozen conditions [18]. The ratio of unfrozen to frozen thermal conductivity correlates closely with underlying surface types, being largest in desert steppe, moderate in degraded meadow, and smallest in meadow [17]. Based on these findings, the station' s research team pioneered acquisition of dynamic parameters difficult to measure, such as soil saturation, porosity, and ice content, investigated physical mechanisms controlling thermal parameter variations, and established preliminary statistical models of soil thermal parameters for typical plateau sections, providing thermodynamic parameters for accurately predicting climate and permafrost change trends.

To explore climate change impacts on QTP permafrost, the station improved parameterization schemes for soil unfrozen water content, thermal properties, surface roughness, and albedo in land surface process models (SHAW, CoLM, NOAH, SIB2, CoupModel) based on comprehensive atmosphere-vegetation-permafrost monitoring. The simulation depth was extended from 2-4 m to 15-17 m to accommodate permafrost characteristics. Improved models simulate active layer hydrothermal processes and surface-atmosphere energy-water exchange well [16,19-21] and were used to simulate spatial distribution changes across the plateau over the past 30 years. Results show permafrost area reduction lags behind climate warming rates, consistent with measurements along the Qinghai-Tibet Highway [Figure 4: see original paper] [11].

To determine soil organic carbon pool storage and source-sink effects, the station conducted extensive investigations on soil organic carbon distribution and composition in QTP permafrost regions beginning in 2003, systematically analyzing relationships between soil organic carbon/nitrogen and soil texture, physicochemical properties, climate, vegetation, geology, and geomorphology [22-29]. Using statistical and numerical methods, the station first produced spatial grid data of organic carbon density at different depths (0.5 m, 1 m, and 2 m) [Figure 5: see original paper] , revealing that the top 2 m of QTP permafrost regions stores approximately 25.37 Pg of soil organic carbon (1 Pg = 10^{1} g) and 2.40 Pg of total nitrogen. In western arid areas, differences in soil carbon and nitrogen between permafrost and non-permafrost regions are insignificant [24], though carbon-nitrogen ratios are higher in permafrost areas [25]. In eastern plateau regions, swamp meadows contain the highest soil carbon, nitrogen, and nutrient contents [26,27]. Overall, precipitation differences primarily cause east-west variations in soil organic carbon and total nitrogen, while at local scales, soil texture and active layer thickness are determining factors [28].

Research shows that active carbon fractions undergo clear seasonal changes with soil hydrothermal conditions. Non-permafrost zone surface soil enzyme activity is stronger than in permafrost zones, with greater organic matter cycling intensity [30-35]. Soil microbial community composition correlates closely with organic carbon content and soil pH [34], indicating that warming-induced soil temperature rise, active layer thickening, and surface moisture reduction could enhance organic carbon decomposition and greenhouse gas emission potential. Carbon flux and cycling process monitoring reveal that QTP permafrost regions currently act as weak carbon sinks. Soil respiration correlates closely with active layer thickness—areas with thicker active layers have smaller vegetation biomass but still high soil respiration [36], and even in non-permafrost areas, high respiration rates suggest permafrost degradation may accelerate soil organic carbon decomposition [37]. Thermokarst, a typical permafrost degradation feature, can shift surface soil from carbon sink to source while reducing methane emissions [38].

The QTP Cryosphere Station has become a primary data production center for permafrost and cryospheric environment baseline data, a global permafrost research field base, and a talent training center with broad international influence. Currently, the station is improving its cryospheric research and observation systems, supplementing monitoring in uninhabited areas, strengthening UAV regional real-time monitoring, emphasizing talent training, and enhancing management to further improve researchers' scientific, collaborative, and innovative capabilities, striving to build a world-class permafrost observation and research platform.

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