Observing multi-sphere hydrological changes in the largest river basin of the Tibetan Plateau

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ABSTRACT

Upper Brahmaputra (UB) is the largest (~240,000km²) river basin of the Tibetan Plateau, where hydrological processes are highly sensitive to climate change. However, constrained by difficult access and sparse in-situ observations, the variations in precipitation, glaciers, frozen ground and vegetation across the UB basin remain largely unknown, and consequently the impacts of climate change on streamflow cannot be accurately assessed. To fill this gap, this project aims to establish a basin-wide, large-scale observational network (that includes hydrometeorology, glacier, frozen ground, and vegetation observations), which helps quantify the UB runoff processes under climate-cryosphere-vegetation changes. At present, a multi-sphere observational network has been established throughout the catchment. (1) Twelve stations with custom-built weighing automatic rain/snow meters and temperature probes to obtain elevation-dependent gradients. (2) Nine stations with soil moisture/temperature observations at four layers (10/40/80/120cm) covering alpine meadow, grasslands, shrub and forest to measure vegetation (biomass and vegetation types) and soil (physical properties) simultaneously. (3) Thirty-four sets of probes to monitor frozen ground temperatures from 4500 to 5200m elevation (100m intervals), and two observation systems to monitor water and heat transfer processes in frozen ground at Xuegela (5278m) and Mayoumula (5256m) Mountains, for improved mapping of permafrost and active layer characteristics. (4) Five sets of altimetry discharge observations along ungauged cross-sections to supplement existing operational gauges. (5) High-precision glacier boundary and ice-surface elevation observations at Namunani Mountain with differential GPS, to supplement existing glacier observations for validating satellite imagery. This network provides an excellent opportunity to monitor UB catchment processes in great detail.
This project has constructed a multi-sphere hydrological observational network at Tibetan Plateau’s largest river basin (“Yarlung Zangbo” or “upper Brahmaputra”), which helps quantify runoff processes under climate-cryosphere-vegetation changes.

1. Introduction

The Tibetan Plateau (TP) is an important water source for most large rivers in Asia (Immerzeel et al., 2010; Biemans et al., 2019; Pritchard et al., 2019; Wang et al., 2021). Due to its unique geographical and climatic characteristics, the hydrological cycle of the TP is affected by multi-sphere interactions between the cryosphere, hydrosphere, atmosphere, and biosphere (Koike et al., 1999; Ma et al., 2008; Xu et al., 2008; Su et al., 2011; Li et al., 2013; Yang et al., 2013; Chen et al., 2015; Zhao et al., 2018; Chen et al., 2021). Since the mid-1980s, the TP hydrological cycle has undergone dramatic changes owing to climate change (Cuo et al., 2014; Yang et al., 2014; Bibi et al., 2018; Liu Z et al., 2018; Yao et al., 2019). Due to the particular sensitivity of the cryosphere to a warming climate, significant changes have taken place in the land surface environment of the plateau (Li et al., 2008; Kang et al., 2010), including glacier retreat (Yao et al., 2012; Shean et al., 2020; Bhattacharya et al., 2021), deepening of the permafrost active layer (Cheng et al., 2019), and snow cover change (Smith and Bookhagen, 2018), which have, in turn, significantly affected the hydrological cycles of all TP river basins. Specifically, there have been changes in the runoff of high-mountain rivers, brought about by changes in climate (e.g., precipitation), glacier and snow melting, permafrost degradation, and vegetation greening (Bibi et al., 2018; Yao et al., 2019). However, the contribution of each of these factors to changes in runoff varies across different river basins (Zhang et al., 2013; Lutz et al., 2014; Luo et al., 2018b; Zhao et al., 2019; Khanal et al., 2021), and is largely unclear for regions with poor or no gauge coverage. Since 2017, quite a few mega-projects about the TP’s Earth System Science have been launched in China, with a focus on TP’s water, ecosystem, and human activities, which have spent a total amount of billions of Chinese Yuan (Liu Z et al., 2020).

The Upper Brahmaputra (UB; also called “Yarlung Zangbo” in Tibetan) basin is the largest (~240,000 km²) and highest (>4000 m on average) river basin of the TP. The hydrological processes in this high-elevation basin are highly sensitive and susceptible to...
changes in the climate system (e.g., Indian summer monsoon and elevation-dependent warming; Pepin et al., 2015; Sang et al., 2016; Wang et al., 2020), the cryosphere (e.g., melting glaciers in the Himalaya and Nyainqêntanglha Mountains that surround the UB; Yang et al., 2013; Yang et al., 2016; Ye et al., 2017; Yi et al., 2020), and the unique vegetation system along longitudes and elevations (influenced by the monsoon moisture flux that goes against stream along the Brahmaputra River valley). Further, previous studies have largely neglected the effects of frozen ground on UB hydrological processes (Zhang et al., 2013; Lutz et al., 2014; Zhao et al., 2019). Owing to the scarcity of ground-based observations (e.g., hydrometeorology and cryosphere data; Zhang et al., 2013; Wang et al., 2020) for this remote, high-elevation, large river basin, we currently have a very limited understanding of the variations in precipitation, glacier coverage, frozen ground, and vegetation caused by climate change, and their effects on runoff processes.

The UB is a key project area within the framework of the “Runoff variation and adaptive utilization in the source area of rivers in southwest China” program of the National Science Foundation of China, which was implemented in 2017 to address the issues outlined above. This project aims to strengthen ground-based meteorology–cryosphere–hydrology observations, using the existing observational stations in and around the UB basin, so that multi-sphere hydrological changes and impacts on river runoff can be elucidated via remote sensing and cryosphere–hydrology modeling. We aim to provide new knowledge of cryospheric basin hydrological cycles and to pave the way for basin-scale integrated water resources management across the TP; this would benefit millions of inhabitants of Asia and help achieve the goal of sustainable development under the influence of climate change.

2. Project design

a. Study area

The Brahmaputra, a trans-boundary river that flows through China, India, and Bangladesh, has a profound impact on the water resources and social development of the TP and parts of southern Asia (see Nepal and Shrestha, 2015). The UB basin (27°–32°N, 81°–98°E) is located in the southern portion of the TP (Figure 1), having a mean elevation >4610 m; the topography of the basin is highly variable, ranging in elevation from ~140 to ~7260 m.
Fig. 1. The Upper Brahmaputra (UB) basin. (a) Current and (b) Supplement denote existing and newly built observational sites, respectively. The integrated observational stations of the ITPCAS surrounding the UB basin includes: ①The Ngari Station for Desert Environment Observation and Research (the Ngari station; about 4270 m a.s.l.), ②The Atmospheric and Environmental Comprehensive Observation and Research Station on Mt. Qomolangma (the Qomolangma station; about 4276 m a.s.l.), ③The Nam Co Station for Multisphere Observation and Research (the Nam Co station; about 4730 m a.s.l.), ④The South-East Tibetan Plateau Station for integrated observation and research of alpine environment (the SETS; about 3326 m a.s.l.), and ⑤The Motuo Observation & Research Center for Earth Landscape and Earth System (the Motuo station; about 800 m a.s.l.). Here, the Pasighat (the outlet of the UB basin) is a virtual discharge gauge, and the upper and lower UB basins have been divided at the Nuxia hydrological station. It can be seen that the demarcation is done hydrologically with a light grey line at Nuxia station.

The climate of the UB basin is largely shaped by the Indian monsoon in summer and the westerlies in winter, and is characterized by a trend of declining precipitation from the humid...
southeast to the arid northwest (from ~4000 mm/year down to ~400 mm/year). With recent intensified cryosphere melting, particularly the retreating glaciers of the Himalayas and the Nyainqêntanglha Mountains (Yao et al., 2012, 2019), as well as vegetation greening (Liu X et al., 2019), the discharge regimes (e.g., annual total river discharges and the intra-annual distributions) of the UB have changed significantly as a result of multi-sphere changes (Liu Z et al., 2014; Cuo et al., 2019; Wang J et al., 2021; Xin et al., 2021), which may threaten the water and food security of local and downstream populations.

b. Scientific objectives and project tasks

Overall, this UB project is expected to improve our understanding of cryosphere–hydrology processes, and to provide guidance for integrated water resources management, ecosystem conservation, and development, in the UB basin. The roadmap of the UB project is presented in Figure 2, and the major scientific objectives and project tasks are summarized below:

1) **ESTABLISH A LARGE-SCALE METEOROLOGY–CRYOSPHERE–HYDROLOGY OBSERVATIONAL NETWORK.**

Using existing observation stations in and around the UB basin (belonging to the Institute of Tibetan Plateau Research, Chinese Academic Sciences (ITPCAS)), this project aims to strengthen observations of meteorology, glaciers, frozen ground, vegetation, and runoff, to establish a comprehensive ground observation network and build up much-needed meteorology–cryosphere–hydrology datasets for this poorly-observed large river basin.

2) **ELUCIDATE CHANGES IN MULTI-SPHERE INTERACTIONS IN BOTH UPSTREAM AND DOWNSTREAM REGIONS.**

This project aims to elucidate changes in the climate, cryosphere, vegetation, and streamflows moving from upstream to downstream regions of the UB basin, as well as to quantify the co-variation between frozen ground and vegetation in the UB basin; this basin is located in the southern TP, and is expected to behave differently to the TP interior.

3) **QUANTIFY THE IMPACTS OF CLIMATE–CRYOSPHERE–VEGETATION CO-VARIATIONS ON STREAMFLOWS**

This project aims to clarify the co-variations of glaciers, frozen ground, and vegetation, and their influences on streamflows in the UB basin, and to compare the uncertainty in results
caused by individual physically-based cryosphere-hydrology models (with very different structure and parameters). To achieve this goal, we will validate physically-based, distributed cryosphere–hydrology models that incorporate glacial, frozen ground, and vegetation processes, and quantify the co-variations of glaciers, frozen ground, and vegetation, and their impacts on discharge in the UB basin.

3. Implementation of the project

a. Basin-wide observation network and generation of basic datasets

This task aims to establish a comprehensive cryosphere–hydrology observation network, including meteorological, glacial, frozen soil, vegetation, and hydrological observations, using the existing observation stations in and around the UB basin, and to build up basic datasets in this poorly-gauged river basin (see Figure 3 for the roadmap).
1) PRECIPITATION AND TEMPERATURE GRADIENT OBSERVATION NETWORK

National weather stations managed by the China Meteorological Administration (CMA) in the UB basin are mainly located in the valley and plain areas to the east of Lazi (Figure 4). There are only four stations at an altitude >4000 m, and there is little or no long-term meteorological observation to the west of Lazi (Wang Y et al., 2020). Consequently, the spatial patterns of temperature and precipitation in the upper reaches of the UB basin are unknown. Hence, based on existing CMA meteorological observations, we plan to carry out temperature/precipitation gradient observation in the upstream region and enhance observations in the downstream region of the UB basin.
Fig. 4. Precipitation and temperature gradient observation network in the UB basin. a) 3 stations of automatic rain/snow meters and thermometers (Y2-Y4) are arranged along the main stream valley from east to west to the headwater of UB, forming an east-west gradient section; b) new observation stations (L1-L2, N1-N2) at the two major tributaries (the Lhasa River, and the Nyang Qu) to the east of Lhaze, forming the gradient sections on both sides of the mainstream of UB with an altitude span of 4000-4700 m together with the existing CMA stations; c) new observation stations of M1-M4 between Yangcun and Nuxia discharge gauges, forming a north-south and an east-west gradient section at the mainstream of UB with the existing CMA stations; d) one station of S1 near Lhasa City for instrument calibration. The observation station of Y1 was originally set up between Y2 and Lazi, but was destroyed later.

Since 2017, we have constructed 12 sets of customized automatic-weighing rain/snow meters and temperature probes (see Table S1 for the major instruments used in the UB project) to obtain elevation-dependent precipitation and temperature gradients in the UB basin. These new precipitation and temperature observations can not only fill the gap in meteorological observations to the west of Lazi, but also enable the calculation of the vertical temperature and precipitation gradients of the east–west and north–south slopes of different sub-basins. The observation scheme was set up as follows: a) three sets of automatic rain/snow meters and thermometers (Y2–Y4 in Figure 4) were arranged along the main stream valley from east to west at the headwater of the UB, to establish an east-west gradient section; b) new observations (L1–L2, N1–N2) were carried out on two important tributaries (Lhasa River and Nyang Qu River) to the east of Lazi, to establish gradient sections on both sides of the main stream with an altitude span of 4000–4700 m, including the existing CMA stations; c) new observation stations (M1–M4) were set up between the Yangcun and Nuxia
discharge gauges, forming north–south and east–west gradient sections of the main stream, including the existing CMA stations; and d) one station (S1) was set up near Lhasa City for instrument calibration. Additionally, we made full use of the existing ITPCAS high-mountain meteorological observations. For example, the Parlung No. 94 Glacier terminus (Yang et al., 2013, 2016) at an altitude of 4600 m, which has recorded observations of wind speed/direction, air temperature, relative humidity, and air pressure since June 2006, and precipitation since June 2009; and the Southeast Tibetan Plateau Station (SETS) for integrated observation and research of alpine environment of the ITPCAS (Lulang County, altitude of 3326 m), which has recorded precipitation observations since October 2015.

Combined with these existing meteorological stations in and around the UB basin, the 12 sets of newly-erected rain/snow gauges and thermometers, will deliver a basin-wide temperature-precipitation observation network covering various elevation zones (Figure 4). Observations will be mainly carried out by the project team in cooperation with the Lhasa Department of the ITPCAS.

As illustrated in Figure 5, by using rainfall observations from the 12 newly-constructed stations (L1–L2, M1–M4, N1–N2, Y2–Y4, and S1), as well as rainfall observations from six major CMA stations (Jiangzi, Lazi, Zedang, Dangxiong, Linzhi, and Bomi) in the UB basin, we have evaluated and compared eight different precipitation datasets (see Table 1 for details) for the monsoon season (from June to September) of 2018. Our results show that six out of eight precipitation datasets tended to overestimate the 2018 monsoon precipitation in the UB basin, with considerable (>300 mm) root mean square errors (RMSEs); the lowest RMSEs occurred in the CMFD (103 mm) and CMAP (167 mm) datasets (see Table 1 for details). The state-of-the-art GPM satellite precipitation dataset ranked second (behind only CMFD) in terms of the Pearson correlation coefficient (0.69), but still consistently overestimated the 2018 monsoon precipitation across the ground-based stations of the UB basin. The reasons for the discrepancies at the UB basin are still under investigation. Firstly, there is a common overestimation of precipitation at the TP by most global climate models and reanalysis products, due to their coarse spatial resolution (that cannot resolve the steep terrains around the TP and thus overestimate the water vapor entering the TP; You et al., 2015). Secondly, although satellite products can well capture the spatial pattern of precipitation, the accuracy of satellite precipitation may be largely reduced with steeper terrains (Xu et al., 2017). Therefore, we conclude that the 8 precipitation products still cannot well capture the water vapor transportsations in the west and east of the UB basin (e.g.,
reanalysis products), and/or cannot resolve the complex topography (e.g., satellite, and reanalysis products).

Fig. 5. Evaluation of eight different precipitation products (see Table 1 for details) in the monsoon season (from June to September; unit: mm) of 2018 at the UB basin with the observations from six major CMA stations (Jiangzi, Lazi, Zedang, Dangxiong, Linzhi and Bomi), and the 12 newly-built stations (L1-L2, M1-M4, N1-N2, Y2-Y4, and S1) by this project. The Pearson correlation coefficient and Root Mean Square Error (in bracket) are also given at the legend for reference.
Fig. 5. Continued (unit: mm)
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<th>Dataset</th>
<th>Resolution</th>
<th>Expansion and reference</th>
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<tbody>
<tr>
<td>GPM</td>
<td>0.1°×0.1°</td>
<td>Global Precipitation Measurement (Huffman et al., 2014)</td>
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<td>(<a href="https://gpm.nasa.gov/data">https://gpm.nasa.gov/data</a>)</td>
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<tr>
<td>GPCP</td>
<td>2.5°×2.5°</td>
<td>Global Precipitation Climatology Project (Adler et al., 2003)</td>
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<td>(<a href="http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html">http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html</a>)</td>
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<tr>
<td>CMAP</td>
<td>2.5°×2.5°</td>
<td>CPC Merged Analysis of Precipitation (Xie and Arkin, 1997)</td>
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<td>(<a href="http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html">http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html</a>)</td>
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<tr>
<td>ERA5</td>
<td>0.25°×0.25°</td>
<td>ERA5 monthly averaged data on single levels from 1979 to present (Hersbach et al., 2019)</td>
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<tr>
<td>JRA55</td>
<td>about 0.5625°</td>
<td>Japanese 55-year Reanalysis, Monthly Means and Variances (Kobayashi et al., 2015)</td>
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<td>CPC Morphing technique (Joyce et al., 2004)</td>
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<tr>
<td>CMFD</td>
<td>0.1°×0.1°</td>
<td>China Meteorological Forcing Dataset (Yang and He, 2016)</td>
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Table 1. Precipitation datasets used in this study with full expansion and reference.
Fig. 6. Glacier and discharge observations in the UB basin. Where, R1-R5 (red circle) displays the discharge gauges at Saga (R1), Xietongmen (R2), Paizhen (R3), Dexing (R4), and Bomi (R5), and the G1-G4 (black triangle) represent the glacier observations at the Namunani, Langadine, Guren Estuary, and Parlung No. 94 glaciers (see Table S2 for details). An extreme flooding event at Dexing (in Motuo) due to the river blocking and outburst at the UB upstream (at Milin County) from 29 October to 1 November 2018 has been well captured by our in-situ water level observations.

2) Monitoring changes in glacier coverage

This project aims to generate reliable multi-period glacier coverage datasets, as well as documenting glacier ice storage changes in the UB basin. Glacier outline datasets for the UB basin from the 1970s to 2020 were obtained from a series of Landsat MSS/TM/ETM+/OLI
(MSS: multi-spectral scanner; TM: thematic mapper; ETM+: enhanced thematic mapper plus; OLI: operational land imager) satellite data, while data documenting the surface elevation change of glaciers was extracted from remote sensing stereo images and existing digital elevation models (DEM; Ye et al., 2017; Yi et al., 2020). These data were combined with glacier area data extracted from multi-spectral images over the same period, to estimate the change of glacier ice storage in the basin.

The glaciers in the south-eastern Kangri Karpo Mountains (Yang et al., 2008), at the east end of the Nyainqêntanglha Range, plus those on the eastern border of the UB basin were also studied. Geodetic glacier mass balance of these glaciers were studied using bistatic SAR data, including one pair of TerraSAR / TanDEM-X data (TerraSAR-X is an X-band satellite imaging radar Earth observation satellite; TandDEM-X is a TerraSAR-X add-on for digital elevation measurements) on Feb.7th, 2014 (the data spanning between 28°50′N, 29°20′N, 96°50′E and 97°20′E), C- and X- band SRTM DEM in 2000. Glacier surface elevation changes were derived using the D-InSAR (Differential Interferometric Synthetic Aperture Radar) method respect to C-band SRTM DEM. According to the orbital information from TerraSAR / TanDEM-X- and C-band SRTM DEM data, the flat earth and the topographic phase was simulated. Then they were removed from the original bistatic interferogram by TerraSAR / TanDEM-X data and it leaves a differential interferogram, where the topographic residual phase dominates. As it mainly comes from glacier surface elevation changes, the topographic residual phase can be directly transformed to glacier surface elevation changes by unwrapping the differential interferogram. Penetration depth of SRTM C- band SAR signals into the glacier surface was estimated and corrected by the penetration depth difference between C- and X-band SRTM (Gardelle et al., 2013; Li et al., 2018). It was 2.21 m in Mt. Kangri Karpo region (Ji et al., 2021). Our results indicate that: (1) During 2000—2014, the glacier mass change was -1.69±0.12 Gt, with an averaged glacier surface elevation change of -0.86±0.13 m a⁻¹ (i.e. geodetic glacier mass balance was -0.73±0.11 m w.e.a⁻¹). This is consistent with the adjacent in-situ stake glacier mass balance investigations (Yang et al., 2008, 2013, 2016) that showed the glacier mass balance of Parlung No.4 glacier was -0.71 m w.e.a⁻¹ over the period 2006-2007, and that of Parlung No.10 glacier was -0.78 m w.e.a⁻¹ over the period 2005-2009. It validates our results from remote sensing techniques. Some previous studies have reported region-averaged glacier mass balance in southeastern TP. Our results are comparable with the result from Brun et al. (2017), a little more negative than -0.62 ±0.11 m w.e.a⁻¹ in Nyainqêntanglha, and a slightly less negative than that of -0.80 ±0.25 m w.e.a⁻¹.
for the hypsometric average of the tile spanning between 29°N, 30°N, 97°E and 98°E. Our research extent just located at the south west part of Brun et al. (2017) tile. Neckle et al. (2017) reported a similar mass balance of -0.71 ±0.58 m w.e.a⁻¹ over 2000-2014 for 5 glaciers in eastern Nyainqentanglha. Our results were more negative than regional averaged mass balance by -0.60 ±0.16 m w.e.a⁻¹ during 2000-2010s in the southeastern TP from Ke et al. (2020) and -0.60 ±0.20 m w.e.a⁻¹ in central Nyainqentanglha over 2000-2013 but less negative than Kaab et al. (2015) by -1.14 ±0.58 m w.e.a⁻¹. The difference might come from different research spatial scope and glacier coverage data in usage.

Our initial satellite-derived results show that the glaciers in the UB basin are mainly distributed in the Nyainqêntanglha Mountains, the Himalaya, and the Gangdis Mountains, which account for 78%, 14%, and 7% in 2020, respectively. Over the past five decades, the total area of glacier coverage in basin has decreased from 9011 km² (1976) to 7937 km² (2020), representing a marked glacier retreat of 1074 km² (-11.9% or -244 km² decade⁻¹). Of this, 621 km² of glaciers has disappeared in the lower UB basin (downstream of Paizhen; see R3 in Figure 6). According to the time series of DEMs derived from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer; Yamaguchi et al., 1993) stereo-imagery from 2000 to 2016 by Brun et al. (2017), the averaged geodetic glacier mass balance in UB was calculated by -0.43±0.05 m w.e.a⁻¹, with a total glacier mass loss by -4.39±1.15 Gt a⁻¹ in UB.

This project also carried out in situ glacier boundary and ice-surface elevation observation of a typical glacier (Namunani; Figure 6) in or close to the basin, to obtain high-precision location and elevation information using differential GPS (Global Positioning System); this will supplement existing glacier observations for validating satellite imagery. This included the following observations: a) accurate in situ measurement of the position of the glacier tongue, which was used to check and correct the results of remote sensing extraction, and monitor the change of the glacier terminus; b) intensive observation of typical sections on the glacier surface, carried out using differential GPS. This obtained high-precision glacier surface elevation data, which can then be used to check and correct the accuracy of DEMs, and to monitor the short-term (3–5 years) surface elevation change of the glacier; c) collection of differential GPS observation points in the stable terrain around the glacier, providing valuable in situ observations for image correction, control point selection,
DEM generation, error analysis and inspection, as well as the effective evaluation of data processing results.

Fig. 7. The soil-vegetation allied observation network in the UB basin. Nine stations with soil moisture/temperature observations at four layers (10, 40, 80, and 120 cm) covering alpine meadow, alpine grassland, alpine shrub and alpine forest to measure vegetation (biomass and species composition) and soil (physical properties) simultaneously (see Table S3 for details).
In addition, we incorporated the existing glacier mass balance and glacier meteorological observation data of ITPCAS (Table S2 and Figure 6), so that the glacier accumulation and melting parameters in different climatic regions could be estimated; this provides the observational basis for validating satellite imagery as well as the development and verification of cryosphere-hydrology models.

3) SOIL–VEGETATION ALLIED OBSERVATION NETWORK

This project has set up nine observation stations covering different vegetation types and climate zones from the west to the east of the basin, to monitor basin-wide vegetation, soil temperature, and moisture of shallow soil (≤1 m). Soil samples were taken from the soil temperature/moisture observation stations to measure soil hydraulic and thermal properties in the laboratory; knowledge of such properties is essential for hydrological model calibration and validation, especially in simulating soil water and energy balance processes (van Genuchten, 1980). When combined with the existing observation sites in the basin, this will establish a soil–vegetation observation network covering the entire UB basin.

Nine stations, covering alpine meadow, alpine grassland, alpine shrub, and alpine forest have been set up from the west to the east in the UB basin, to simultaneously observe the characteristics of vegetation (biomass and vegetation types) and soil physical properties (Figure 7 and Table S3). The choice of these stations was based on characteristics of vegetation type, topography, climate, existing permafrost distribution map, river distribution, and literature and field surveys. The measurements recorded at each station include soil temperature and moisture (hourly data from four different depths of 10, 40, 80, and 120 cm), soil texture, soil porosity, saturated soil hydraulic conductivity, soil heat capacity, and soil thermal conductivity, as well as vegetation indicators such as species composition and biomass.

Based on the hourly soil temperature observations, a year-long period (from 1 July, 2018 to 30 June, 2019) was divided into completely-frozen and completely-thawed periods, plus the frequent diurnal freeze-thaw period (or transition period), as shown in Figure 8. Comparison of the observed daily soil moisture and temperature during this period at an alpine meadow station (S1, the westernmost soil–vegetation station) and an alpine forest station (S9, the easternmost soil–vegetation station) showed that S1 has lower soil moisture and lower soil moisture variability than does S9 during the study period (Figure 8). It is not
surprising since there is much rainfall at the eastern S9 where the soil moisture responds frequently to the rainfall events. At the alpine forest station, the completely-frozen period lasts only one month at most, whereas at the alpine meadow site, the completely-frozen period is almost four months long. With more suitable soil moisture and temperature conditions for vegetation growth, S9 has much better vegetation conditions, and both leaf area index (LAI) and biomass are greater here than at S1.

To monitor and model the changes in basin-wide soil moisture/ice can be crucial in improving our understanding of the water budget of the UB basin. These in-situ soil observations at different stations across the UB basin can be very useful in validations and improvements of the modeling of the frozen soil processes in the UB basin. Preliminary validation results of the VIC-Glacier (a variable infiltration capacity hydrology model coupled with an energy balance glacier melt scheme; Liang et al., 1994; Ren et al., 2018) model in simulating the evolution of soil moisture (at 10 cm depth) from 15 July 2018 to 31 December 2019 (Figure S1), show that the current model generally captured the seasonal variations of soil moistures, but tended to overestimate the summer soil moisture at the stations in the upper and middle UB basin. Besides a refinement of soil parameters, this discrepancy in soil moisture simulations may be largely caused by the uncertainty in precipitation inputs due to a lack of rain gauge observations at the western UB. The further improvements of frozen soil processes are still ongoing at the UB basin with the VIC-Glacier and WEB-DHM (water and energy budget-based distributed hydrological model; Wang et al., 2009, 2017) models, and will be introduced in the future studies.

Additionally, this project will make full use of the existing 27 ITPCAS soil temperature/moisture observational sites in the south and east of the UB basin (25 sites built by Professor Kun Yang’s group in the Pali region, one site at the SETS of ITPCAS, and another site in the Parlung Zangbo sub-basin), as well as the 16 CMA soil temperature/moisture observation sites in the UB basin, thus forming a basin-wide soil–vegetation observation network.
Fig. 8. Observed soil moisture and temperature variations from 1 July 2018 to 30 June 2019 at the 10-cm depth at the westmost soil-vegetation station (S1 with alpine meadow; see Figure 7 and Table S3 for details) where LAI is 0.32 m²/m² and biomass is 145 g/m², and at the eastmost soil-vegetation station (S9 with alpine forest) where LAI is 0.82 m²/m² and biomass is 2570 g/m². For reference, the annual mean of soil moisture has been given for S1 and S9, respectively (black dotted line).

4) FROZEN GROUND SURFACE TEMPERATURE (GST) OBSERVATION NETWORK

The GST serves as the true upper thermal boundary of the permafrost (Luo et al., 2018a). From July to August 2018, frozen ground and periglacial landform surveys were carried out in the UB basin, and the GST monitoring network was set up, considering the distribution of perennially and seasonally frozen ground. Concurrently, the wet bulk density of soil was investigated and the thermal conductivity was measured on-site.

A total of 34 GST probes were deployed to monitor the GSTs under different local conditions and altitudes in real-time, with a time resolution of thirty minutes (Figure 9). These observations are mainly from Mayoumula Mountain (7 sites), Zhongba County (5 sites), Saga County (7 sites), the Xuegela Mountain (7 sites), Dangxiong Yangbajing (3 sites), and Mila Mountain (4 sites). Following the principle of an elevation gradient of about 100 m, these observational sites were built ranging in altitude from 4500 to 5200 m. The GST
monitoring network in the UB basin will help explore the lower limits of permafrost distribution for those monitoring sections with obvious temperature/elevation gradients.

Fig. 9. Frozen ground surface temperature observation network in the UB basin. Following the principle of an elevation gradient of about 100 m, totally 34 ground temperature probes were mainly built at the Mayoumula Mountain (MYML), Zhongba County (ZB), Saga County (SG), the Xuegela Mountain (XGL), Dangxiong Yangbajing (DX), and the Mila Mountain (MLS) in 2018 ranging from 4500 to 5200 m a.s.l. In 2020, new frozen-ground water and heat transfer process observation systems have been built at two stations, with one station at an altitude of 5278 m on the Xuegela Mountain and the other at an altitude of 5256 m on the Mayoumula Mountain (red triangle).
Fig. 10. Annual mean diurnal cycle of the observed half-hourly ground surface temperatures (GST) in 2019 at the four major frozen-ground monitoring regions (MLS, XGL, SG, and MYML). Where, MLS is the Mila Mountain, XGL is the Xuegela Mountain, SG is near Saga County, and MYML is the Mayoumula Mountain. In each of four regions (MLS, XGL, SG, and MYML), the observed GST values at individual stations have been averaged, with a standard deviation showing the varying range.

In 2020, new frozen-ground water and heat transfer process observation systems were built at two stations, one on Xuegela Mountain (5278 m), and the other at an altitude of 5256 m on Mayoumula Mountain (Figure 9). The Xuegela station has 9-layer observations of soil temperature and moisture (at 0-10, 20, 40, 60, 80, 100, 120, 140, and 160 cm), while the Mayoumula station also has 9-layer observations of soil temperature and moisture (at 0-10, 40, 60, 80, 100, 120, 140, 160, and 200 cm) but extends down to 2 m.

According to observations obtained in 2019 (Figure 10), GSTs at Mila Mountain remain well above 0 °C, and therefore this locality is unlikely to have permafrost, despite it having the highest altitude. Only a small proportion of GSTs measured at Xuegela Mountain and Saga County are below 0 °C, and thus permafrost is also unlikely to occur there. The Mayoumula Mountain monitoring region is more likely to have permafrost, since half of the observed GSTs are below 0 °C. In addition, the GSTs in Saga County have the largest daily variation, which may be related to its relatively dry environment. However, we note that these are merely preliminary analyses and more data is required to accurately interpret these observations.
To date, the construction of 34 GST monitoring stations, and two observational stations of frozen-ground water and heat transfer process systems have been completed in the UB basin. Further, to understand the long-term change of basin-wide frozen ground, the temporal and spatial distributions of frozen ground and maximum frozen soil depth in the UB basin from 1901 to 2016 have been calculated, based on the frost index model and the Stefan equation as well as reanalysis datasets (see Liu L et al., 2020).

5) SUPPLEMENTARY WATER LEVEL/DISCHARGE OBSERVATIONS

We chose several previously ungauged cross-sections of the main stream and large tributaries to supplement existing operational runoff observations in the UB basin. Based in the Motuo Observation and Research Center (MORC) of ITPCAS, our team has carried out water level/discharge observation at the downstream of the Nuxia gauge (on the main stream). In addition, we plan to select further tributaries and main stream sections which are largely supplied by glaciers and thawed frozen ground to carry out discharge observations; this will provide datasets to assess the impact of glaciers, frozen ground, and vegetation on runoff.

In the poorly-gauged upper UB basin (before the Nuxia discharge gauge; see Figure 1), two river cross-sections of discharge observations have been built to monitor discharge changes (R1 and R2, as shown in Figure 6), combined with associated soil–vegetation observations (Figure 7). To consider the runoff derived from typical glaciers, a runoff observation point at the Parlung Zangbo River has been built with the support of the SETS of ITPCAS. Additionally, two water level/discharge gauges have been built downstream of the Nuxia gauge in the UB mainstream, supported by the MORC of ITPCAS (Figure 6), to monitor water contributions from the Parlung Zangbo and Yigong Zangbo glacier-fed rivers.

As shown in Figure 6, the newly-built discharge gauge at Dexing (in Motuo County) captured the key processes of an extreme river-blocking flood event in the UB basin, which was triggered by a glacier avalanche and subsequent landslide in the autumn of 2018: (A) at 15:00 on 29 October, the blocking of the upstream portion of the UB river (at Milin County) caused the downstream water level (at Dexing) to begin to fall; it decreased by around 2.9 m and then stabilized; (B) at 18:00 on 31 October, the dammed lake at Milin County breached and the flood peak arrived at Dexing, where the water level rose by over 11.0 m; and (C) by 10:00 on 1 November, the water level at Dexing had dropped and returned to the level that was at before the upstream river blockage. An et al. (2021) pointed out that the river blocking
of UB in 2018 was mainly caused by the ice and entrained debris flows due to glacier collapse in the Sedongpu Basin at Milin County. Here, our new discharge gauge has successfully recorded the second downstream flooding event at Motuo County from 29 October to 1 November 2018, which was caused by the second of the two successive events of glacier collapse near the mainstream of UB, with the first glacier collapse occurred at 22:48 BST on 16 October 2018 while the second at 08:03 BST on 29 October 2018 (An et al., 2021).

6) Dataset Generation

Through the above observations, the project will generate the following basic datasets:

(a) A set of 10 × 10 km gridded surface meteorological data points (e.g., precipitation and temperature) that covers the whole UB basin from 1981 to 2019, to provide reliable source data for cryosphere–hydrology models.

(b) Glacier area datasets from four years (1976, 2001, 2013, and 2020) covering the whole UB basin, together with ice-storage-change datasets of typical glaciers (Namunani, Langadingri, Guren Estuary, Parlung No. 94), and the datasets of typical glacier ice-storage-change used to validate the cryosphere–hydrology models.

(c) Soil temperature and moisture observations (hourly data at four different depths, namely 10, 40, 80, and 120 cm) since 2017 in the UB basin, plus soil physical property data (including texture, porosity, saturated hydraulic conductivity, heat capacity, and thermal conductivity) obtained at the observation stations and measured in the laboratory, and vegetation indices (vegetation biomass and vegetation types).

(d) Based on the TTOP (temperature at the top of permafrost) model (Riseborough, 2002; Obu et al., 2019), and the Stefan equation, informed by near-surface air temperature from the reanalysis products, plus remote sensing and data assimilation-derived land surface temperature, combined with soil hydrothermal physical parameters, the characteristics of permafrost and the active layer in the UB basin will be simulated; this will enable the spatiotemporal distributions of permafrost and the thickness of the active layer in the UB basin to be obtained from 1981 to 2018.

b. Synergetic changes among climate, frozen ground, and vegetation
This task aims to investigate the synergetic changes in climate, frozen ground, and vegetation using process-based models, to lay a solid foundation for the further study of the impacts of these changes on streamflows (see Figure 11 for the roadmap).

The Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ; Smith et al. 2001, 2014) will be applied to reveal the synergetic change of permafrost and vegetation driven by climate over the entire UB basin. The LPJ has been widely used in ecological research; it can simulate plant functional types, soil temperature and moisture, plant photosynthesis and transpiration, soil organic matter and litter, as well as fire, on monthly and annual time scales. It can also simulate vegetation competition for water, light and nutrients, and vegetation tissue growth and community replacement on an annual scale. Firstly, the LPJ will be set up, based on a 0.25 × 0.25 ° DEM, and soil type data obtained from the HWSD (Harmonized World Soil Database; FAO/IIASA/ISRIC/ISSCAS/JRC 2012). Secondly, the existing 1:1,000,000 vegetation map of China (data from 1980 to 2001), MODIS NPP (Net Primary Production; Running et al., 2004) products, and in situ soil temperature/moisture observations, will be jointly utilized to verify the capability of LPJ in simulating changes in vegetation and soil temperature/moisture. Where necessary, the LPJ model will be further refined to enhance the simulations in alpine regions, and ensure the accuracy of the model in simulating vegetation types and soil temperature/moisture in the UB basin.

![Fig. 11. Roadmap of the synergetic change analyses among climate, glacier, frozen ground and vegetation in the UB basin.](image-url)
Furthermore, in order to study the synergetic change of permafrost and vegetation driven by climate change, a climate invariant scenario (i.e., removing the trend of temperature and precipitation with the initial year as the reference time; scenario 1) has been designed to drive the LPJ. In parallel, the LPJ model is also driven by historical climate data that reflects actual climate change (control experiment; scenario 2). The changes of simulated soil temperature/moisture, vegetation type, and NPP under the two scenarios (scenarios 1 and 2) will be compared to reveal the climate-driven spatiotemporal changes in frozen ground and vegetation across the UB basin. The in situ point-scale observations and spatial satellite images will be used to evaluate and ensure the reliability of the simulation results in representing the changes of basin-wide soil–vegetation status. Finally, the joint-EOF (Empirical Orthogonal Function; Lorenz, 1956; Kutzbach, 1967) statistical method will be used to reveal the synergetic transformation mechanisms in frozen ground–vegetation driven by climate change.

c. Impact of climate-driven synergetic changes of glaciers, frozen ground, and vegetation on streamflows

In the large but poorly-gauged UB basin, the missing information of basin-wide multi-sphere changes (e.g., precipitation, debris-covered glacier, permafrost) has brought much larger uncertainty (than model physics) to the hydrological simulations (e.g., Sun & Su, 2020; Wang Y et al., 2020). Therefore, in this study, we tended to investigate the applicability of the two models to the UB basin with complex topography, with a special focus on studying the impacts of the co-variations in climate, cryosphere, and vegetation on the river runoff. We also want to quantify and compare the uncertainty in results caused by individual physically-based cryosphere-hydrology models (with very different structure and parameters).

Therefore, the aims of this task are as follows: (1) to calibrate and validate physically-based, distributed cryosphere–hydrology models that incorporate glacial, frozen ground, and vegetation processes; (2) to quantify the co-variations among glaciers, frozen ground, and vegetation and their influences on streamflows using thoroughly-verified cryosphere–hydrology models; (3) to identify the uncertainties in the cryosphere–hydrology modeling through dual model simulations and inter-comparisons (see Figure 12 for the roadmap).
Fig. 12. Roadmap of the impact studies of climate-driven synergetic changes among glacier, frozen ground, and vegetation on the river runoff.

Using the verified VIC-Glacier (a variable infiltration capacity hydrology model coupled with an energy balance glacier melt scheme; Liang et al., 1994; Ren et al., 2018; Sun & Su, 2020) and WEB-DHM (water and energy budget-based distributed hydrological model; Wang et al., 2009, 2017; Shrestha et al., 2010, 2015; Qi et al., 2019; Wang Y et al., 2021), driven by the 10 km gridded meteorological forcing (1981–2016) generated by the project, the runoff change of the real surface environment in the historical period (the control run) was simulated to reveal the changes of glacier and snow melting in the basin, and the dynamic changes of soil moisture during the freeze–thaw cycles in the frozen ground. Combined with the verified model, the respective runoff effects of the glacier (glacier melting), frozen soil (change of active layer thickness), and vegetation are discussed, and the impacts of synergetic glacier–frozen ground–vegetation change on streamflows can be discussed by eliminating single or double factors (Figure 12). The sensitivity runs can be carried out to simulate the runoff variation under different scenarios. Different sensitivity tests are compared with the control run, to reveal the influence and contributions of different factors to the change in runoff. By comparing the output results of VIC-Glacier and WEB-DHM, the uncertainty of runoff effects owing to different changing variables (glacier, frozen ground, and vegetation) can be quantified.
Fig. 13. Comparison of the simulated runoff components by the WEB-DHM (a, b) and VIC-Glacier (c, d) at the upper area of Nuxia gauge (see Figure 6 in this study). Where, (a) and (c) show the contributions of simulated rain-runoff, snow melt, glacier melt, and groundwater flow to the total annual discharge from 1981 to 2016; while (b) and (d) are the mean contributions during 1981-2016. The calibration and validation of WEB-DHM and VIC-Glacier with long-term discharges can be found in Wang Y et al. (2021; at Fig S6) and Sun & Su (2020; at Fig S1), respectively.

Up to now, as given in Figure 13, with verified models of WEB-DHM and VIC-Glacier we have quantified the contributions of rain runoff, snow and glacier melt, as well as groundwater flows to the annual streamflows from 1981 to 2016 at the upper area of Nuxia discharge gauge (see Figure 6 for its location). Our initial results show that, regarding the long-term mean ratio of contributions to the total streamflows during 1981-2016, the two models have output comparable runoff components, e.g., the dominated role of rain-runoff (both greater than 60%), almost same amount of contributions from snow melt and groundwater flows (21.2% + 3.3% comparing to 20.8% + 4.6%), and slight difference in the simulated glacier melt (7.7% vs. 10.7%). We also notice that the simulated annual components by the two models are different at individual years, which still needs further investigations. Additionally, the study of the impact of frozen ground on the UB streamflows is still ongoing.
There have been some previous studies about the historical runoff simulation in the UB basin (e.g., Zhang et al., 2013; Lutz et al., 2014; Chen et al., 2017; Xu et al., 2019; Armstrong et al., 2019; Khanal et al., 2021), which have examined the runoff contributions of glacier and snow melting as well as rain-runoff (Table 2). It can be seen that, most of these studies have confirmed the dominant role of rain-runoff contribution to the total discharge (e.g., mostly >60%), with only one exception (26.0%) by Armstrong et al. (2019). It is not surprising since the UB basin is largely dominated by the Indian summer monsoon (Yao et al., 2019), and the monsoon precipitation (usually from June to September) provides abundant water input to the basin. However, there are large differences across various studies regarding the simulated results of runoff contributions from glacier (ranging from 1.0% to 15.9%) and snow melting (ranging from 9.0% to 73.0%). Although the different study area and study periods have been considered in various studies, the discrepancies can be largely attributed to the various precipitation inputs and different methods in glacier melt modeling.

Firstly, due to a very limited number of available CMA standard meteorological stations in the UB basin (Zhang et al., 2013), most of previous hydrological modeling studies were carried out with the precipitation inputs from a single reanalysis product directly (that may contains large uncertainty in the poorly-gauged basin), only with an exception of Chen et al. (2017) that used a merged product of reanalysis (CGDPA; see Table 2 for all the abbreviations in this section, hereinafter) and satellite data (TMPA). Different from these previous literatures, our team has performed hydrological simulations with the newly reconstructed precipitation products that incorporate more gauge observations (see Sun & Su, 2020; Wang Y et al., 2020), which have merged reanalysis, satellite, and ground-based observations that are from both the CMA (< 10 meteorological stations that have long-term observations) and the MWR of China (> 160 rain gauges; available during 2014-2016). These efforts have largely reduced the uncertainty in the simulated results by hydrological modeling.

Secondly, the lack of physically-based glacier melt modeling makes the results having large difference. It is known that the glacier melting at Himalaya and Nyainqêntanglha Mountains can be an important water source to close the water balance in the UB basin (e.g., Wang Y et al., 2021). But, for the model simplification and the available scares observations, most of the literatures have utilized existing hydrological models linked with a simple temperature-index model (or day-degree model) for the simulation of glacier melting in the
UB basin (see Table 2). Further, these day-degree models can be very sensitive to the input empirical parameters (e.g., day-degree factor) that need careful calibration with observed runoff at the study river basin. However, due to a lack of available discharge observations at the UB basin, some previous regional studies (e.g., Lutz et al., 2014; Armstrong et al., 2019) have directly applied the empirical factors (that were calibrated/obtained at other TP river basins) into the UB basin. All of these simplifications in glacier melt modeling and parameters may result in considerable uncertainties in simulating the total discharges, particularly in distinguishing the runoff components in the UB basin.

With the increasingly knowledge of the basin-wide distributions and changes in the glacier and permafrost as well as more and more available in-situ and satellite observations of multi-sphere hydrology at the UB basin, there are pressing needs for development and application of physically-based cryosphere-hydrology models (that includes energy-balance based glacier and permafrost simulations) for improving the accuracy of runoff simulations under the climate change (e.g., WEB-DHM in this study). This is particularly important for the future projections, as the empirical day-degree parameters obtained in the historical periods may not be applicable to the future conditions.
<table>
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Table 2. Comparison of the major studies in historical runoff simulations at the UB basin. Here, APHRODITE: Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (Yatagai et al., 2012); MWR: Ministration of Water Resources, China; CGDPA: China Gauge-based Daily Precipitation Analysis (Shen and Xiong, 2015); TMPA: TRMM Multi-satellite Precipitation Analysis, where TRMM is Tropical Rainfall Measuring Mission (Huffman et al., 2007); WFD: WATCH Forcing Data, where WATCH is Water and Global Change (Weedon et al., 2014).
4. Data storage and management

Following the data policy of China, we will establish and share the integrated cryosphere–hydrology datasets for the UB basin. These include: gridded precipitation data (10 × 10 km, 3 hourly) from the period 1981–2019; glacier area datasets from four years (1976, 2001, 2013, and 2020); soil temperature and moisture observations, as well as measured soil properties, from 9 stations (hourly, at depths of 10, 40, 80, and 120 cm) since 2017; and the spatial maps of permafrost and active layer thickness from 1981 to 2018 (annually). The metadata detail the geographical locations, area, altitudes, precipitation, glacier coverage, soil moisture, soil temperature, soil texture, soil porosity, saturated soil hydraulic conductivity, soil heat capacity, soil thermal conductivity, permafrost area, and thickness of the active layer, which are all strictly quality-controlled. Relevant data will be processed and stored according to the data format requirements of the National Tibetan Plateau Data Center in China (TPDC; http://data.tpdc.ac.cn/en/). To date, we have published high-resolution basin-wide precipitation data (5 × 5 km, 3 hourly; Wang Y et al., 2020) from the period 1981–2016 (and an updated version that covers 1981-2019 at https://doi.org/10.5281/zenodo.3711154), together with point-scale soil moisture and temperature observations from 2017 in the TPDC, and users can obtain data through online registration or by contacting the lead author directly. Datasets from this project will be updated annually, with a two-year restriction period for any in situ cryosphere–hydrology observations.

5. Summary

Since 2017, this project, supported by the National Natural Science Foundation of China (NSFC), has established an integrated meteorology–cryosphere–hydrology observational network in the UB basin, the largest basin in the TP, to monitor and quantify the impacts of synergetic changes in glaciers, frozen ground, and vegetation on streamflows, under the influence of climate change. Ground-based observations, remote sensing, and numerical simulations, were jointly used to detect and quantify the synergetic changes among climate, glaciers, frozen ground, and vegetation in this large basin, and the impact of these changes on river discharges at various cross-sections.

In the past four years, we have constructed a ground-based meteorology–cryosphere–hydrology observational platform for the UB basin. This has enabled observations of
precipitation and temperature gradients (12 stations), water levels and discharge (5 cross-sections/stations), shallow soil vegetation (9 stations and 4 layers), frozen-ground surface temperatures (34 stations), and water and heat transfer processes in frozen ground (2 stations with 9 layers). Furthermore, long-term (1981–2016) high-resolution surface precipitation data have been generated and published in open access journals (e.g., Wang et al., 2020), to facilitate relevant climatic and environmental analyses, as well as numerical modeling studies. With the continued operation of the meteorology–cryosphere–hydrology observational platform established by this project, progressively more in situ basin-wide observations will be quality-controlled and archived, and then published in the National Tibetan Plateau Data Center in China (TPDC; http://data.tpdc.ac.cn/en/). This will contribute to research communities, by adding more ground-truthed observations for improved understanding of multi-sphere interactions (atmosphere–biosphere–cryosphere–hydrosphere) in this large river basin.

To fully accomplish the aims of this UB project, future work will include:

(a) Quantification of the glacier ice storage changes between the four measurement periods (1976, 2001, 2013, and 2020), and clarification of the impact of collapsing glaciers in the east Himalaya and Nyainqêntanglha Mountains on river discharge in the downstream region of the UB.

(b) Mapping of the spatiotemporal distributions of frozen ground in the UB basin, and quantification of the synergetic change of frozen ground and vegetation under the influence of climate change.

(c) Identification of the contributions of synergetic changes in climate, glaciers, frozen ground, and vegetation to changes in basin-wide runoff, through cryosphere–hydrology modeling and uncertainty analysis.
Acknowledgments.

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Data Availability Statement.

All data needed to evaluate the conclusions in the study are present in the paper. In many cases external published data are used as input data for the calculations, and the literature references and links to the specific files are provided in the Table 1 of this study.
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