Quantifying changes in the Pan-Third Pole Water Tower

Final project report

An assessment of water-related climate change impacts on the Third Pole

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1. Introduction

The high mountains of Asia, including the Himalayas, Karakoram, Hindu Kush, Pamir, Tian Shan, and Tibetan Plateau, are crucial sources of water for downstream regions. These mountains play a crucial role in the hydrological cycle of the region, providing water for irrigation, domestic, and industrial uses to millions of people in Asia. The importance of these mountains for water resources has become increasingly clear in recent years, as the effects of climate change have become clearer (Immerzeel et al., 2020, e.g. 2010; IPCC, 2019; UN Environment Programme, 2021; Viviroli et al., 2007; Wester et al., 2019).

The region is also known as the Third Pole, because its mountain glaciers and snowfields hold more frozen water than any other place on Earth, except for the polar caps located in the Arctic and Antarctic. The buffering capacity of the ice makes this area the water tower for the entire region, being the source of many of Asia's major rivers, including the Indus, Ganges, Brahmaputra, and Yangtze. These rivers support the livelihoods of millions of people downstream, from the arid regions of Central Asia to the fertile plains of Southeast Asia.

This so-called Asian Water Tower (AWT) is, however, facing a range of threats that could undermine its role as a water resource. Climate change is causing glaciers to retreat (Hugonnet et al., 2021), leading to changes in the timing and amount of river flow (Khanal et al., 2021; Lutz et al., 2014; Wijngaard et al., 2017). This is leading to increased variability in water supply, which could lead to water shortages and increased competition for water resources. Additionally, the mountains are facing increasing pressure from human activities, including deforestation, mining, and agriculture, which can lead to soil erosion and water pollution.

To ensure the continued availability of water resources on the Third Pole, it is key to understand the complex interactions between climate, water, and human activities in the region. This will require a combination of continued scientific research into the climate impacts on the region with coordinated efforts from governments, researchers, and other stakeholders to monitor and sustainably manage water resources in the region.

To improve our understanding of the region and its complexities, the Pan-TPE program's project "**Q**uantifying Changes in the Pan-Third Pole **Wa**ter **Tow**er and Impacts for a Green Silk Road" (QWA-

TOW) has been aimed at understanding specific components of the AWT to elucidate upon the bigger picture. The project, funded by the Chinese Academy of Sciences (CAS) and led jointly by Utrecht University and FutureWater in collaboration with the Institute for Tibetan Plateau Research (ITP), has been concluded after running from September 2018 to February 2023. This report presents the outcomes of the activities that were conducted within the scope of the project.

This introduction will first revisit the aims and scope of the project and gives a brief account of the activities that were performed. Conducted research activities and outcomes will subsequently be presented on a theme-by-theme basis in separate chapters. Finally, project-related outreach and publications, attended events, and training workshops are discussed.

1.1 Project background, aims and setup

The QWATOW project falls under the Pan-TPE program's main objective "To illuminate changes in the Water Tower of Asia and its impacts on the Silk Road associated with climate change and earth system interactions". Specifically, it is positioned within the Pan-TPE theme "Westerly-monsoon interactions and changes in the Asian Water Tower and their impacts". The project therefore aims at unravelling changes in climate, water supply and demand in the Asian Water Tower (AWT) to ultimately provide the knowledge that allows to better inform scientists and policy makers on suitable adaptation measures for green development in the river basins that originate in the region, thereby impacting the entire surrounding region, i.e. the Pan Third Pole Environment.

In general, the climate on the southeastern side of the AWT is characterized by the East-Asian and Indian monsoon systems. The precipitation intensity in the region shows a strong north-south gradient caused by orographic effects (Galewsky, 2009). Precipitation patterns in the western mountain ranges are also characterized by westerly and southwesterly flows, causing the precipitation to be more evenly distributed over the year compared to the eastern parts (Bookhagen and Burbank, 2010). Consequently, the AWT has a very complex climate characterized by large spatio-temporal variations over relatively short distances.

To be able to illuminate changes that occur in the AWT, it is therefore required to unravel the dynamic interaction between the westerly and monsoon climate systems, and to quantify the influence of changes in the climate system on the environment and vice versa. The intricate feedbacks between the climate and surface processes, both physical and ecological, need to be understood before predictions of future changes to the system can be made accurately. To put our research into a logical and streamlined framework that allows us to tackle the related overarching problems targeted by the QWATOW project, the following four main work packages (WPs) were defined (also see Figure 1):

1. Observed and projected Pan-TPE climate change
2. Impacts on the present and future Water Tower of Asia
3. The Green Silk Road and changes in water demand
4. Adaptation for green development

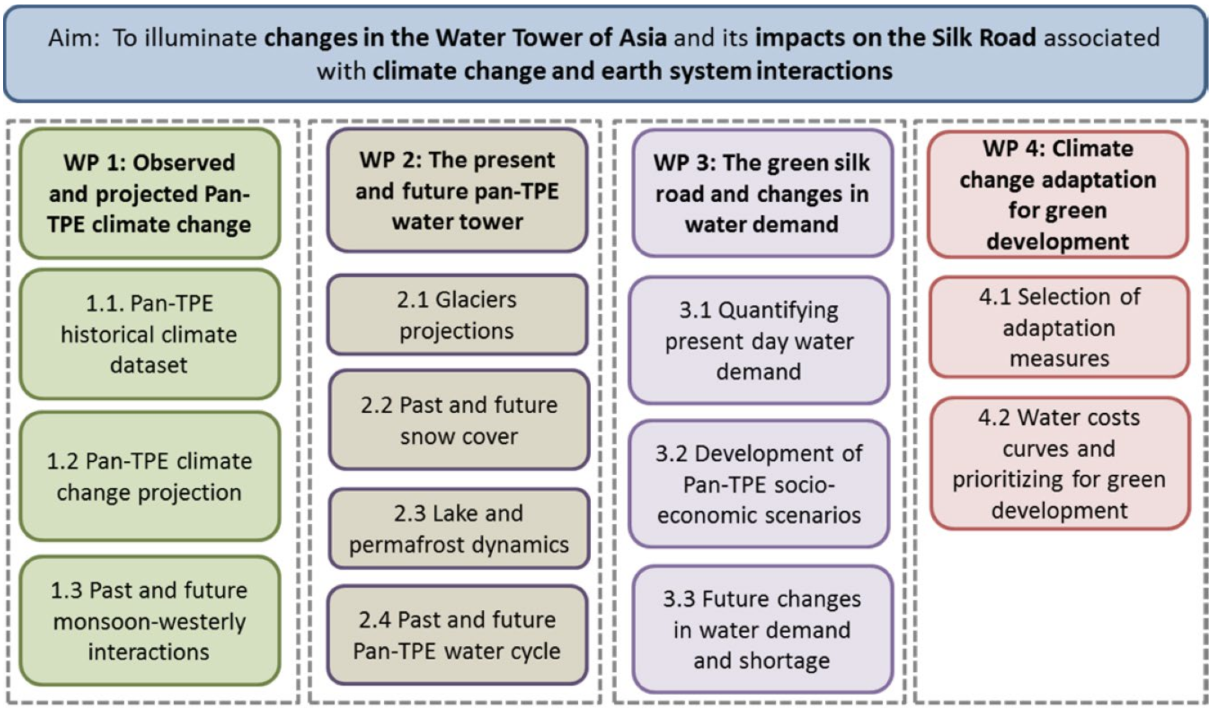

Figure 1. Diagram with the main work packages as presented in the QWATOW project proposal.

1.2 Project schedule, activities, and achievements

The project ran for five years in total, from 2019 to 2023, with most of the activities and work planned for the first four years. Year 1 (Y1) has encompassed most work of WP1, i.e. defining optimal gridded dataset(s) to use, looking at historical and future trends in climate variables and preparing an accompanying publication (Section 3.1). Activities of WP2 were spread over the first four years, with the first period mainly focusing on snow and glaciers (Section 4), and on lake changes on the Tibetan Plateau (Section 6). Subsequent years focused more on an integration of all components that affect AWT change from a hydrological perspective (Section 7).

WP3 and WP4 were scheduled for Y2–Y5 of the project, focusing on the socio-economic and demand sides of the water balance changes across the Third Pole. Due to COVID-19 restrictions and issues during these years progress on these work packages has been limited, unfortunately. At present we are still in collaboration with Chinese researchers to generate output (see Section 8.2). This collaboration will be continued after the end of the project, and we expect publication of results in early 2024. Trainings, workshops, and conference attendances were spread throughout the entire project period.

Considerable project time has been allocated to the setup and development of a tailored high-resolution implementation of the hydrological model Spatial Processes in Hydrology (SPHY) (Terink et al., 2015) (Section 7.1). The model encompasses the entire region and was aimed to ultimately act as a bridge between the different components studied within QWATOW. This way supply side changes, such as changes in snow, glaciers and permafrost (Section 4; Section 6), can be linked to changes in the demand side, such as increased population or developing societal needs (Section 8).

The activities that have been performed have been largely aimed at the specific work packages defined in the project schedule as outlined above. However, several other valuable components were added to better understand and quantify the changes that occur in the Pan-Third Pole region. To characterize the region, we have been working on identifying the state of our natural water towers (Section 2), on understanding changes in the climate of the Tibetan Plateau specifically (Section 3), and on unravelling anomalous glacier behavior in the Karakoram mountain range (Hewitt, 2005) (Section 5). Moreover, we have worked on analysis of unmanned aerial vehicle data of debris-covered glaciers to ultimately be able to better quantify the future implications of glacier change in the region (Section 4.4). A more comprehensive account of the work performed within the scope of the project is presented in the separate chapters of this report (Section 2–8).

1.3 Report contents

The chapters in this report provide a comprehensive summary of the output generated by the QWATOW project and with that an assessment of the current state of the Third Pole environment. The output is aligned along seven chapters (see contents section) covering different main themes, each important for understanding the regions past changes, current state, and (potential) future in terms of mountain water resources:

- **The state of our natural water towers.** Understanding the relevance of mountains starts with comprehension of current state of the mountain water supply system, its relevance and climate change vulnerabilities.
- **Climate change across the Third Pole.** Presents an assessment of the past changes in climate across the entire region, which is the cornerstone in understanding future climate changes.
- **Past and future changes in snow and glaciers.** Results of comprehensive modelling past and future snowpacks for all major river basins associated to the Asian Water Tower.
- **Understanding the Karakoram Anomaly. A**n account of potential causes and consequences of the anomalous response of Karakoram glaciers with respect to the rest of the Third Pole region.
- **Tibetan lake changes. L**arge-scale and small-scale studies trying to unravel the causes of the observed changes of the lakes on the Tibetan Plateau.
- **Streamflow from the Third Pole.** Integral analysis of changes in (future) streamflow in the region performed using self-developed Asian Water Tower Model
- **Impacts of a changing mountain water supply.** A first attempt at understanding the implications of changes in water supply for downstream areas in terms of socioeconomics.

2. The state of our natural water towers

Mountain ranges play a critical role in the global water cycle, providing water resources to millions of people and sustaining diverse ecosystems. In many regions of the world, mountain ranges act as natural water towers, capturing and storing precipitation as snow and ice before releasing it downstream during drier seasons. However, climate change is rapidly transforming mountain hydrology, with rising temperatures leading to glacier melt, changes in precipitation patterns, and altered river flows. Understanding the complex dynamics of mountain water systems is crucial for developing sustainable water management strategies and adapting to the impacts of climate change.

2.1 Importance and vulnerability of the world's water towers

Many of Asia's large rivers have their headwaters in the mountains of the Third Pole, and as such many people that live downstream in this densely population part of the world depend on the larger AWT to a certain degree (Biemans et al., 2019; Immerzeel et al., 2010). However, the importance of the upstream water resources varies greatly per river basin and mountain range. It depends, among other things, on (i) the relative area of a basin located in mountainous parts, (ii) the amount of water stored as snow and ice, (iii) the distribution of precipitation between the upstream part and downstream part of the basin, and (iv) the downstream socioeconomic water demands. Improving our understanding of the spatial distribution of the importance of mountain water resources can help to unravel and pinpoint the most critical areas in the AWT and beyond.

The Utrecht University team has therefore led a broad team of researchers from around the globe in a study aimed at understanding the importance of the world's natural water towers and to identify the most important ones (Immerzeel et al., 2020). To do so, a metric called the Water Tower Index (WTI) was defined, which ranks water towers (i.e., specifically defined Water Tower Units (WTUs)) in terms of their water-supplying role and downstream dependence of ecosystems and society (Figure 2). For each WTU, vulnerability related to water stress, governance, and future climatic and socioeconomic changes was assessed additionally (Figure 3).

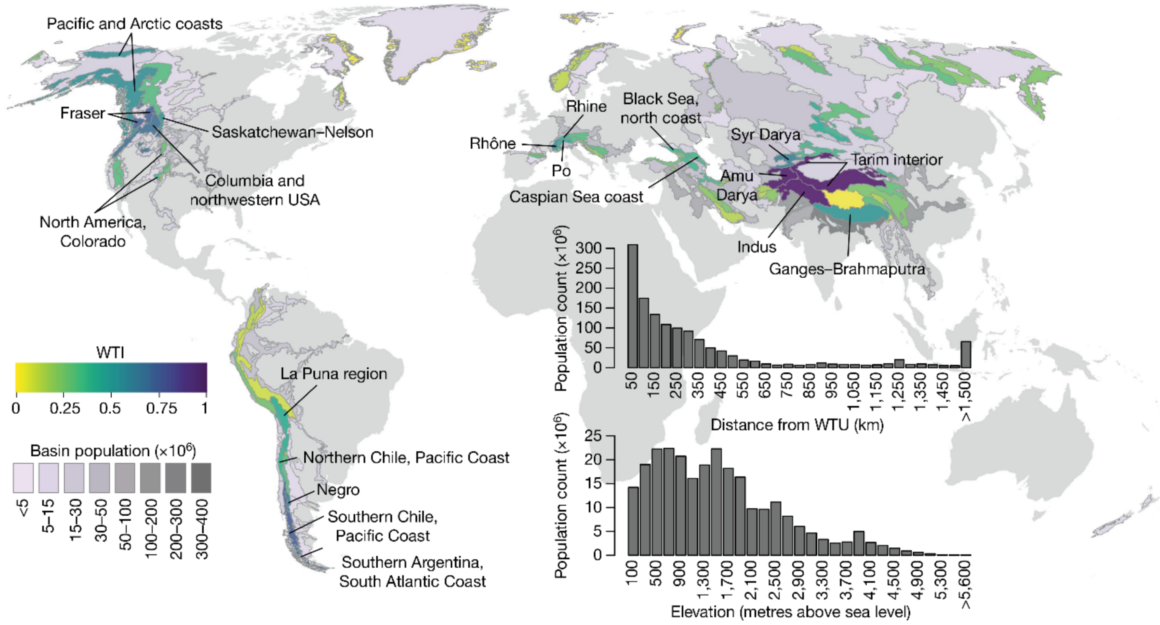

Figure 2: Ranking of the world's water towers by Water Tower Index (from Immerzeel et al., 2020). Labels indicate the five water towers with the highest WTI value per continent.

We found that the most important water towers are also among the most vulnerable, and that climatic and socio-economic changes will affect them profoundly. Unsurprisingly, the most important water towers in the world were found to be located in the Third Pole region, because of the vast ice reserves in the region and the large population downstream (Figure 2). The Indus, which is globally the most important water tower, was found to be particularly vulnerable due to its transboundary basin with considerable hydro-political tension. The population and economic development in the basin are expected to rise exponentially, increasing the demand for fresh water. Coupled with increased climate change pressure on the Indus head-waters, an already high baseline water stress, and limited government effectiveness, it is uncertain whether the basin can fulfil its water tower role within its environmental boundaries. Other water towers in this region are also among the more vulnerable, largely for the same reasons: high population and economic growth rates and, in many cases, ineffective governance in combination with a strong transboundary nature of the water resources (Figure 3). Given this general setting across the AWT, the water towers here are considerably more vulnerable than those in North America and Europe.

Our study highlights the critical importance of identifying and addressing the vulnerabilities of water towers in different regions of the world to ensure their sustainability in the face of growing population, economic development, and climate change. Conservation of water towers is essential to decrease vulnerability, and this can be achieved through transboundary cooperation and the efficient use of scarce water resources. Effective conservation measures would be preserving the buffering capacity of mountain ranges, increasing the buffering capacity with reservoirs, and conserving water by improving the water-use efficiency of irrigation and industry downstream.

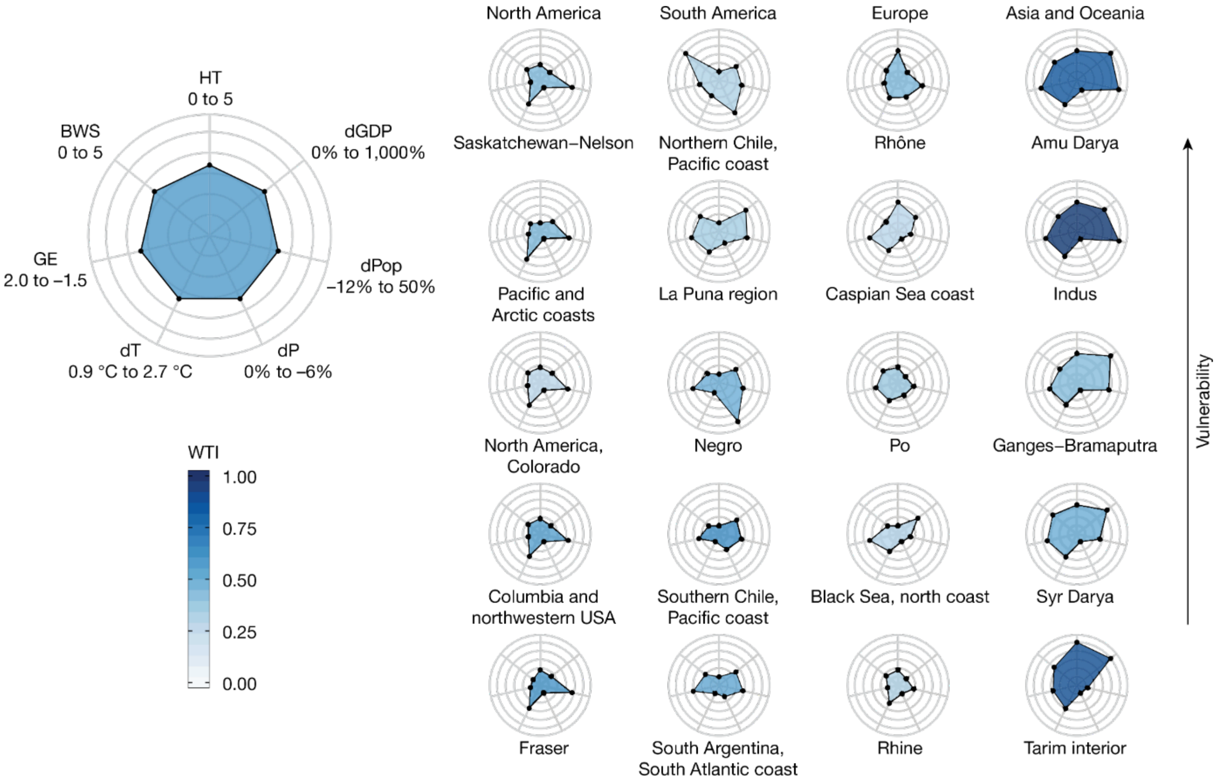

Figure 3: The vulnerability and projected change of the top five WTUs of each continent (from Immerzeel et al., 2020). The total vulnerability (indicated by larger polygons), and projected change indicators of the five most important WTUs on each continent.

The future vulnerability of water towers is dependent on the trajectory of change that a water tower and associated downstream basin will follow. The recent assessment for the Hindu-Kush Himalayan region (Wester et al., 2019) concluded that there is no single likely future, and each future pathway will result in systematically different demands for water. Therefore, international, mountain-specific conservation and climate-change adaptation policies must be developed to safeguard the mountain ecosystems and people while ensuring water, food, and energy security downstream under all possible future scenarios.

The results of the study clearly indicate that research of the water resources in the greater AWT region is of high importance, and that understanding processes and future changes at both the water supply and demand sides is key in defining an optimal strategy to tackle future water-related issues in the region.

Our study on water tower importance and vulnerability was published in *Nature* early 2020:

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., Elmore, A.C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.S., Koppes, M., Kraaijenbrink, P.D.A., Kulkarni, A.V., Mayewski, P.A., Nepal, S., Pacheco, P., Painter, T.H., Pellicciotti, F., Raja-ram, H., Rupper, S., Sinisalo, A., Shrestha, A.B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., Baillie, J.E.M., 2020. Importance and vulnerability of the world’s water towers. *Nature* 577, 364–369.

2.2 Third Pole's changing water resources

The Third Pole is a major source of fresh water for Asia, with snow, glaciers, and rainfall feeding major river systems that provide water for millions of people. However, recent climate change has led to uncertainty about water availability in the region and the future water supply from the Asian Water Tower (AWT). The region is the largest reserve of frozen water after the polar regions, but global warming has caused an imbalance in the Asian Water Tower, resulting in alteration of the water resources in downstream countries (Biemans et al., 2019; Immerzeel et al., 2020, 2010; Lutz et al., 2022; Yao et al., 2022; Zhang et al., 2019).

2.2.1 Water availability on the Third Pole

Although previous studies have assessed the impacts of climate change on water resources in sub-regions of the Third Pole, there is still a need for an integral focus and understanding of the entire region. To provide a guide to Third Pole scientists and identify important missing links in our understanding of the current state of water supply by the Third Pole, Prof. Dr. Fan Zhang from the Institute for Tibetan Plateau research led a review study on the water availability on the Third Pole with contributions of QWATOW project team members Prof. Dr. Walter Immerzeel and Dr. Arthur Lutz. The review summarizes the major components of water resources in the Third Pole and evaluates the impacts of current and future climate change on these resources. The study also examines the adequacy of observations and uncertainty of future climate change projections.

The study found that precipitation patterns in the Third Pole region are highly variable, owing to the complex processes that govern precipitation and the partitioning between snowfall and rainfall, further contributing to variability. Snow cover varies greatly among different river basins, with the maximum snow cover occurring in early spring, mid-autumn, late autumn, or winter depending on the basin. The melting of glaciers has led to excess river discharge in the basins where glaciers are located. Groundwater depletion has been observed in the Indian plains and Nepal, with springs drying up and/or become seasonal across the region. However, a severe lack of observational data hinders proper understanding of the region's groundwater hydrology.

Analysis of hydrological modeling studies revealed that rainfall is the primary contributor to runoff across all river basins, followed by snow and glacial melt. However, the relative contribution of these components varies greatly across different basins. Projected future changes suggest that water availability is likely to increase in various river basins and sub-basins due to increased precipitation and additional meltwater from retreating glacier, with shifts in seasonal patterns in some basins. Extreme hydrological and climatic events are also expected to increase in some basins, with an increase in precipitation extremes leading to more discharge extremes. Nonetheless, these projections are subject to significant uncertainty arising from climate model uncertainties.

The review on water availability on the Third Pole was published in *Water Security* in 2019:

Zhang, F., Thapa, S., Immerzeel, W., Zhang, H., and Lutz, A. (2019). Water availability on the Third Pole: A review. *Water Security* 7, 100033.

2.2.2 Imbalance of the Asian Water Tower

To better understand the magnitude and breadth of the imbalance of the AWT and its (potential) consequences for downstream water availability and to provide future focus for scientists and policy makers, Prof. Tandong Yao led another review effort with contributions from Utrecht University team leader Prof. Walter Immerzeel (Yao et al., 2022). In this review study the team combined observational data and model projections to illustrate the imbalance in the AWT resulting from the accelerated transformation of ice and snow into liquid water, mainly caused by the regions warming of 0.42 °C per decade since 1980, which is twice the global average rate. Consequently, since 2000, glacier mass in the AWT has decreased, while total water mass in lakes increased.

Annual precipitation in the AWT increased in both endorheic and exorheic basins, despite decreased precipitation in some large river basins. Yet alterations in freshwater resources in endorheic or exorheic basins were demonstrated to have spatial imbalance, as many phase changes in the region are associated with a south-north disparity caused by the spatiotemporal interaction of the Westerlies and the Indian monsoon. Global warming is anticipated to magnify this imbalance, relieving water scarcity in the Yellow and Yangtze River basins but exacerbating scarcity in the Indus and Amu Darya River basins.

Despite this study being able to pinpoint several of the major changes that have occurred or are expected on the Third Pole, the future of the AWT remains highly uncertain. To make precise predictions of future water supply, we stress that it is critical to set up comprehensive monitoring stations in data-scarce regions and develop advanced coupled atmosphere-cryosphere-hydrology models. These models are required to create policies for sustainable management of the available water resources. To succeed, collaboration between upstream and downstream regions and countries is necessary for sustainable water management.

The review on AWT's imbalance was published recently in *Nature Reviews: Earth and Environment*:

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G., Zhao, P., 2022. The imbalance of the Asian water tower. *Nat Rev Earth Environ* 3, 618–632.

2.2.3 Projected changes in the Third Pole

Prof. Walter Immerzeel has further contributed his knowledge about the state of and future projections for the AWT as a lead author of the chapter "Projected environmental changes in the Third Pole" in the recent report by United Nations Environment Programme. In this chapter several outcomes of the QWATOW project are integrated:

UN Environment Programme, 2021. A Scientific Assessment of the Third Pole Environment (No. DEW/2439/NA). United Nations, Nairobi.

3. Climate change across the Third Pole

The climate in the Third Pole region has changed in recent decades. While the temperature is consistently increasing at a higher rate as compared to the global warming rate, precipitation changes are inconsistent, with temporal and spatial variation in recent decades. Previous work has indicated that there are contrasting trends in historical precipitation changes over the Third Pole, and changes in the strength of the monsoon and westerlies (Yao et al., 2012), which can affect their interaction. Analysis of trends in the historical and future climate is hampered by the absence of a uniform dataset covering the entire AWT. Station data is sparse and mostly difficult to access. Recent efforts have focused on the generation of high-resolution gridded climate datasets covering entire river basins for a historical and future period (Immerzeel et al., 2015; Lutz and Immerzeel, 2015) to facilitate climate change analysis and forcing high-resolution hydrological models. These efforts take existing gridded climate products as a basis and correct them for biases with respect to available station data, and correct for the underestimate of high-altitude precipitation (Immerzeel et al., 2015, 2012).

3.1 Climate trends and indicators

In an effort to evaluate historical climatic trends for the entire Third Pole, the FutureWater team analyzed historical climate trends in the region using the novel and state-of-the-art ERA5 reanalysis dataset over the period 1979-2018 (ECMWF, 2017). The ERA5 data are available for 1979–present at hourly time scale and 31 km spatial resolution. The daily aggregated precipitation sums and mean temperature were used in this study to derive historical climate indicators. Each climate indicator was analyzed on an annual scale and seasonal scale. The five climate indicators analyzed for this study are consecutive dry days (CDD), heat wave duration index (HWDI), five-day precipitation amount (RX5), percentage of wet days (R95P) and compound indices (COMP95) (Table 1). The first five indices that are used are defined and described in Zhang et al. (2011). Additionally, we define COMP95 as the number of days when both precipitation and temperature are greater than the 95^{th} percentile values of their distributions.

Table 1: Climate indices used in this study.

Indicator	*Definition*	*Unit*	*Related hazard*
Consecutive Dry Days (CDD)	Largest number of consecutive days the daily precipitation is lesser than 1mm	days	Drought
Heat Wave Duration Index (HWDI)	Number of days, in intervals of at least 6 consecutive days, when the maximum temperature is greater than TXnorm[1] + 5	days	Drought
R10	Heavy precipitation days (precipitation >10 mm)	days	Floods
RX5	Highest five-day precipitation amount	mm	Floods
R95P	Wet days precipitation (precipitation >1 mm) when daily precipitation is greater than 95th percentile of all wet days.	mm	Floods
COMP95	Number of days when both precipitation and temperature are greater than 95th percentile of their distribution.	days	Floods

We focused our analysis on the data-sparse, high-altitude upstream parts of each river basin (Figure 4). The upstream region used in this study includes all areas above 2000 m and is delineated using HydroSHEDS (Lehner et al., 2008a). We categorize river basins in HMA by climate: monsoon dominated southern basins (Brahmaputra, Ganges and Irrawaddy), monsoon dominated eastern basis (Mekong, Salween, Yellow and Yangtze), westerly dominated western basins (Amu Darya, Balkash, Helmand, Indus and Syr Darya), northern basins (Alaguy, Junggar, Jo-Shui and Pai-t'a Ho) and the interior basins (Plateau of Tibet Interior, Tarim interior east and Tarim interior west).

Our results indicate consistent warming patterns over the entire AWT (Figure 5; Figure 6). The annual standardized temperature anomaly (STA) trends are statistically significant across the region. For some regions, especially on the Tibetan Plateau, we found warming trends to be mostly predominant in winter. Moreover, warming trends calculated from ERA5 at high altitudes do not show any evidence of enhanced warming. While the temperature trends are coherent, a general regional drying or wetting precipitation trend is harder to establish. The annual standardized precipitation anomaly (SPA) over the entire interior part shows increasing trends. This contrasts with all the other regions, which show a significant decrease in precipitation.

Our findings demonstrate the changes have a variable spatial and interannual variability. Our results indicate winter warming and summer wetting is dominant in the interior basin, whereas the western and eastern basins are coherently drying. A coherent significant increasing tendency in heat waves is observed across all regions in HMA. Results revealed that heavy precipitation days have higher variability in southern and eastern basins as compared to other regions in HMA. Consecutive dry days showed a distinct demarcation at lower and upper regions and are generally increasing for most basins. While the precipitation and temperature showed variable tendencies, their compound occurrence showed coherent tendencies, though smaller, especially in the monsoon dominated basins.

[1] TXnorm is the mean of maximum temperatures of a five-day window centred on each calendar day of a given climate reference period, here, 1981-2010.

A paper about the the climate trends and indicators has recently been published in the *Journal of Applied Meteorology and Climatology*:

Khanal, S., Tiwari, S., Lutz, A.F., Hurk, B.V.D., Immerzeel, W.W., 2023. Historical Climate Trends over High Mountain Asia Derived from ERA5 Reanalysis Data. *Journal of Applied Meteorology and Climatology* 62, 263–288.

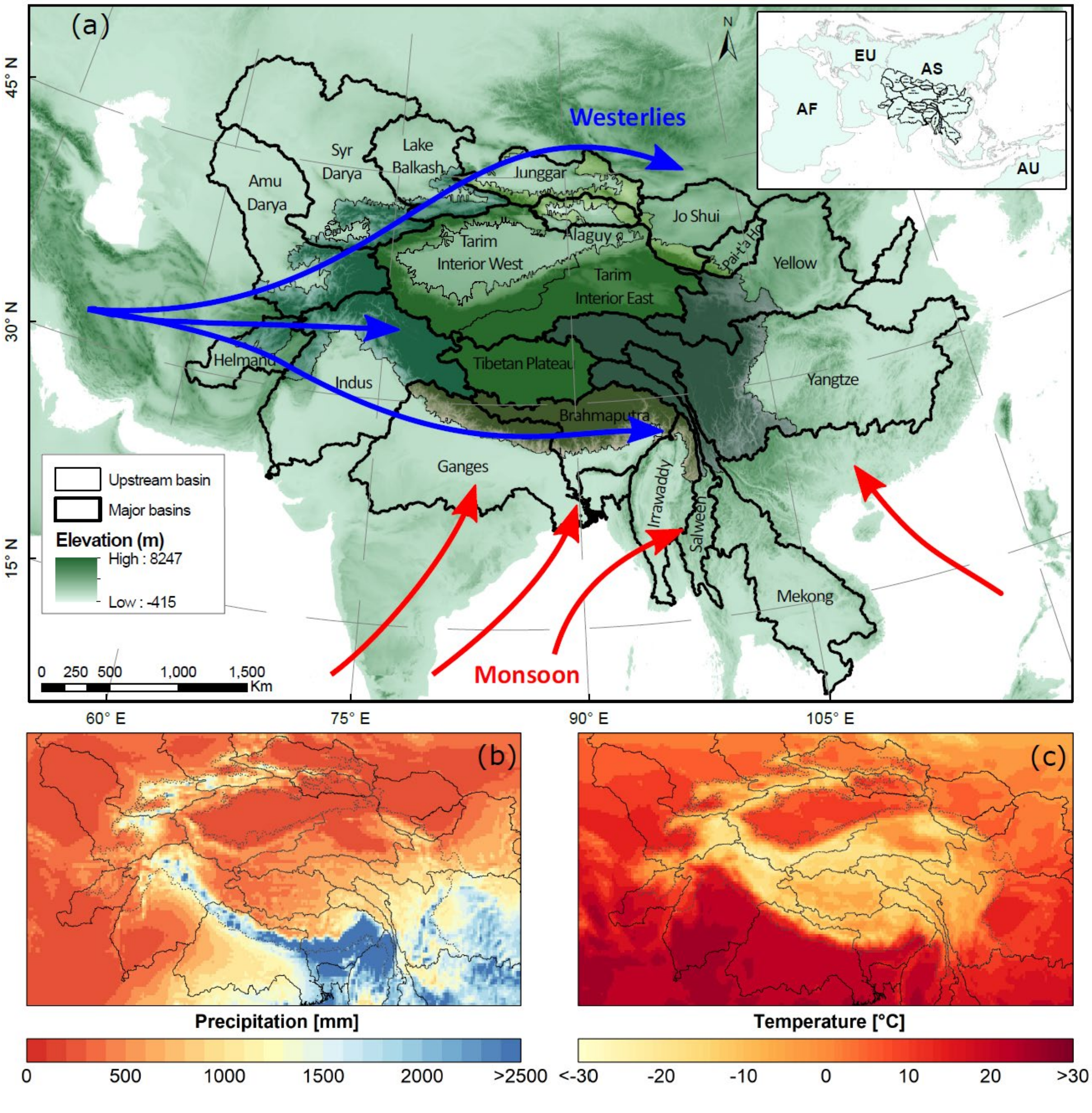

Figure 4. The major mountainous basins of the AWT analyzed in our climate indicator study (black boundaries). Gray lines represent the outline of the upstream region of each basin. The background represents the elevation of the region. Panels **b** and **c** denote 1979–2018 averaged annual precipitation and temperature fields across the region. The arrows represents the major atmospheric circulation systems, red for monsoon and blue for westerlies, in HMA (adapted from Yang et al. (2014)).

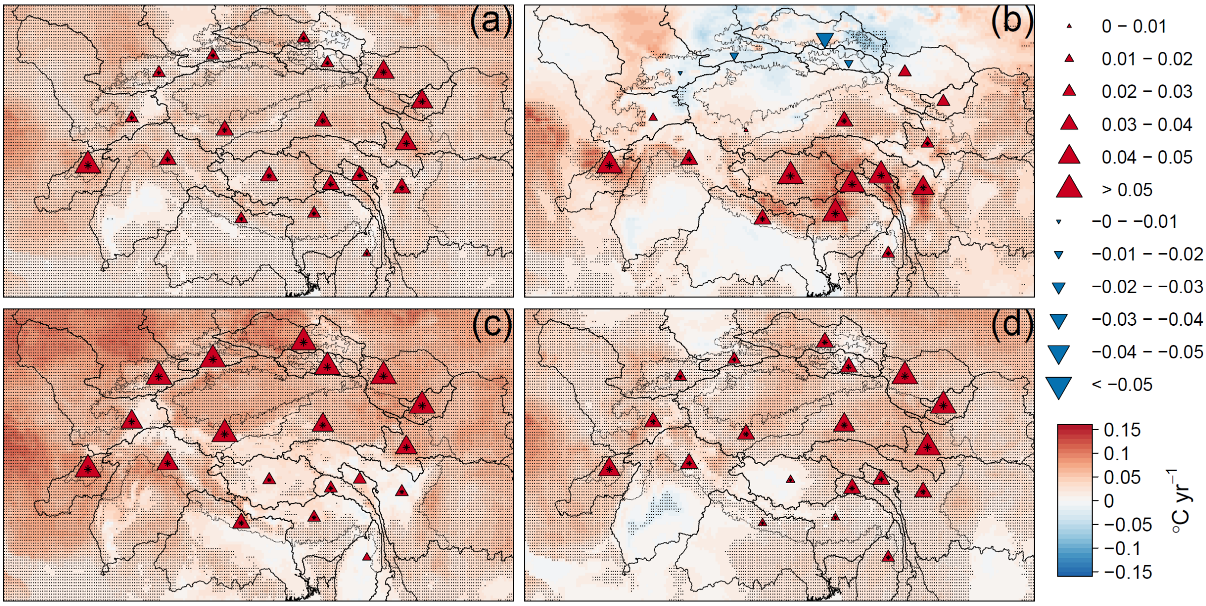

Figure 5. Average daily mean temperature over the entire TP during 1979–2018, and (b) winter, (c) summer, and (d) monsoon trends of mean temperature (8C yr21) estimated using Sen's slope. Dots represents areas with Kendall's significance at p<0.05. The triangles, red upward for an increase and blue downward for a decrease, represent the upper-basin-averaged temperature trends. The presence of a black asterisk in the triangle indicates areas with Kendall's significance at p<0.05 for upper-basin-averaged temperature trends.

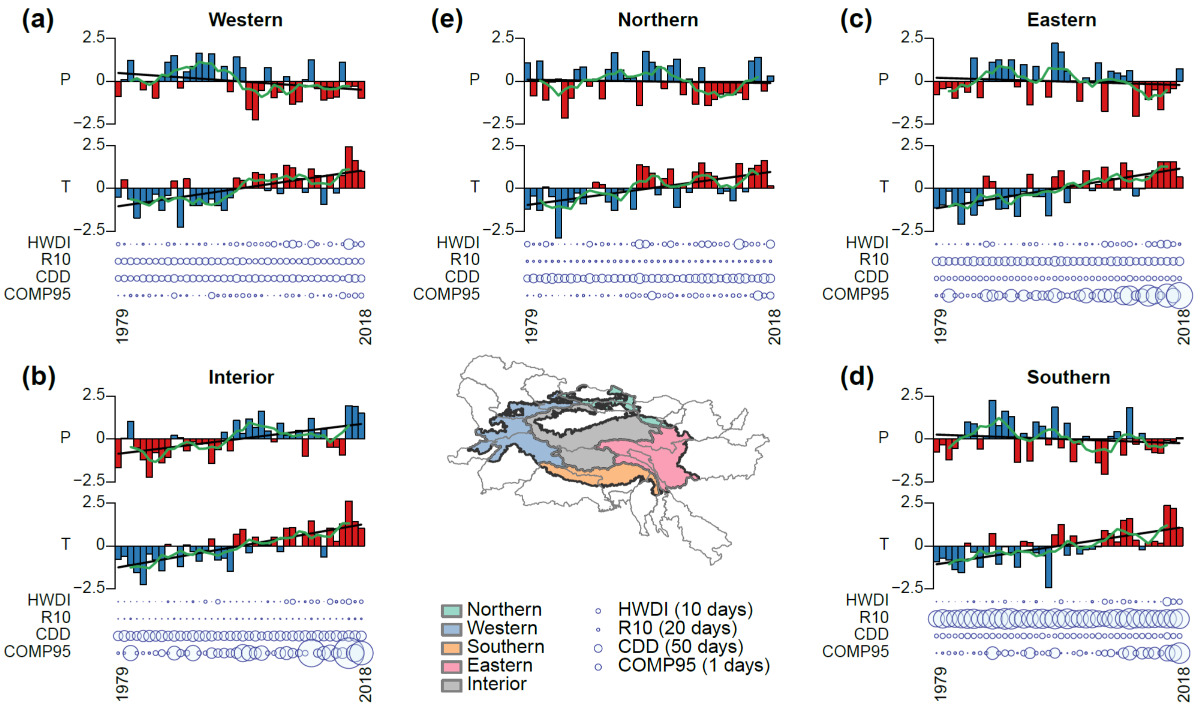

Figure 6: Area aggregated trend and extreme occurrences for different regions as shown in the central base map (**a–d**). The bar plot rows in each panel represent standardized precipitation and temperature anomalies, respectively. The blue (red) fill color represents increasing (decreasing) anomaly for precipitation (temperature). X-axis represents years over the period 1979–2018. The black line denotes the linear trend and the green line the five-year moving average. The bubbles indicate the annual occurrences of each extreme index. Bubble scaling is varied over the indices, which is specified in the legend.

3.2 Tibetan plateau temperatures

3.2.1 Corrected gridded air temperature

Air temperature is a key variable to properly model environmental processes in high-elevation areas of the Tibetan Plateau (TP). For example, they are crucial to accurately model snow and glacier melt. However, observations in the western part and at high elevation are very sparse. To acquire better spatially distributed maps of air temperature, advanced methods that combine currently available climate and satellite products are required.

To improve series of air temperature over the Tibetan Plateau, the Utrecht University team has collaborated on a study led by Dr. Hongbo Zhang, a visiting scientist at our Utrecht University Mountain Hydrology Group. In the study, we propose a novel machine-learning based method to efficiently integrate observations from high-elevation stations and eight popular reanalysis air temperature datasets (Table 2). The reanalysis datasets were downscaled using remote sensing-based temperature lapse rates in order to generate a 1 km resolution daily air temperature dataset over the period 1980–2014.

Table 2: Description of the eight reanalysis datasets used in the study.

Dataset	Full Name	Available	Resolution (Lon/Lat)	Temporal resolution
NNRP-2	NCEP/DOE Reanalysis 2 Project	1979–Current	2.5/2.5	daily
20CRV2c	20th Century Reanalysis Version V2c	1851–2014	2.0/2.0	6-hourly
JRA-55	Japanese 55-year Reanalysis Project	1958–Current	1.25/1.25	6-hourly
ERA-Interim	Interim version of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses of the global climate	1979–Current	0.75/0.75	6-hourly
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2	1980–Current	0.625/0.5	3-hourly
CFSR	NCEP Climate Forecast System Reanalysis	1979–2010	0.5/0.5	hourly
#CFSR-2	NCEP Climate Forecast System Version 2	2011–Current	0.5/0.5	hourly
GLDAS-2	Global Land Data Assimilation System Version 2	1948–2010	0.25/0.25	3-hourly
*GLDAS-2.1	Global Land Data Assimilation System Version 2.1	2001–Current	0.25/0.25	3-hourly
ERA5	Fifth generation of ECMWF atmospheric reanalyses of the global climate	1979–Current	0.25/0.25	hourly

#: CFSR-2 is used only for 2011–2014 for extending the CFSR data
*:GLDAS-2.1 is used only for 2011–2014 for extending the GLDAS-2 data.

To overcome potentially unreliable lapse rates derived from a limited number of observations, a new method to estimate spatially continuous monthly lapse rates from MODIS satellite imagery was developed. The MODIS-estimated lapse rates were used to downscale daily mean air temperature from eight reanalysis datasets to 1-km resolution. Machine learning techniques were used to integrate the eight downscaled reanalysis products and five other auxiliary variables, trained and validated using observations from 100 common stations (i.e. China Meteorology Administration stations) and 13 independent high-elevation stations (4 on glaciers).

The results show that the proposed lapse rate estimation efficiently reduces errors while maintaining acceptable downscaling accuracy. The downscaled temperature from JRA-55 was found to be the best among the eight downscaled datasets, followed by ERA-Interim, MERRA-2, CFSR and others. Finally, air temperature estimation driven by machine learning outperformed the direct lapse rate downscaling approach, especially for high-elevation stations. Both the MODIS-estimated lapse rates (Figure 7) and the high-elevation training observations are demonstrated to significantly improve the air temperature estimation accuracy of the machine learning model. The study provides a framework for integration of multiple reanalysis datasets integration with elevation correction in mountainous regions, which is not only restricted to use on the Tibetan Plateau.

Our study on lapse rates on the Tibetan plateau was published in 2021:

Zhang, H., Immerzeel, W.W., Zhang, F., de Kok, R.J., Gorrie, S.J., Ye, M., 2021. Creating 1-km long-term (1980–2014) daily average air temperatures over the Tibetan Plateau by integrating eight types of reanalysis and land data assimilation products downscaled with MODIS-estimated temperature lapse rates based on machine learning. *International Journal of Applied Earth Observation and Geoinformation* 97, 102295.

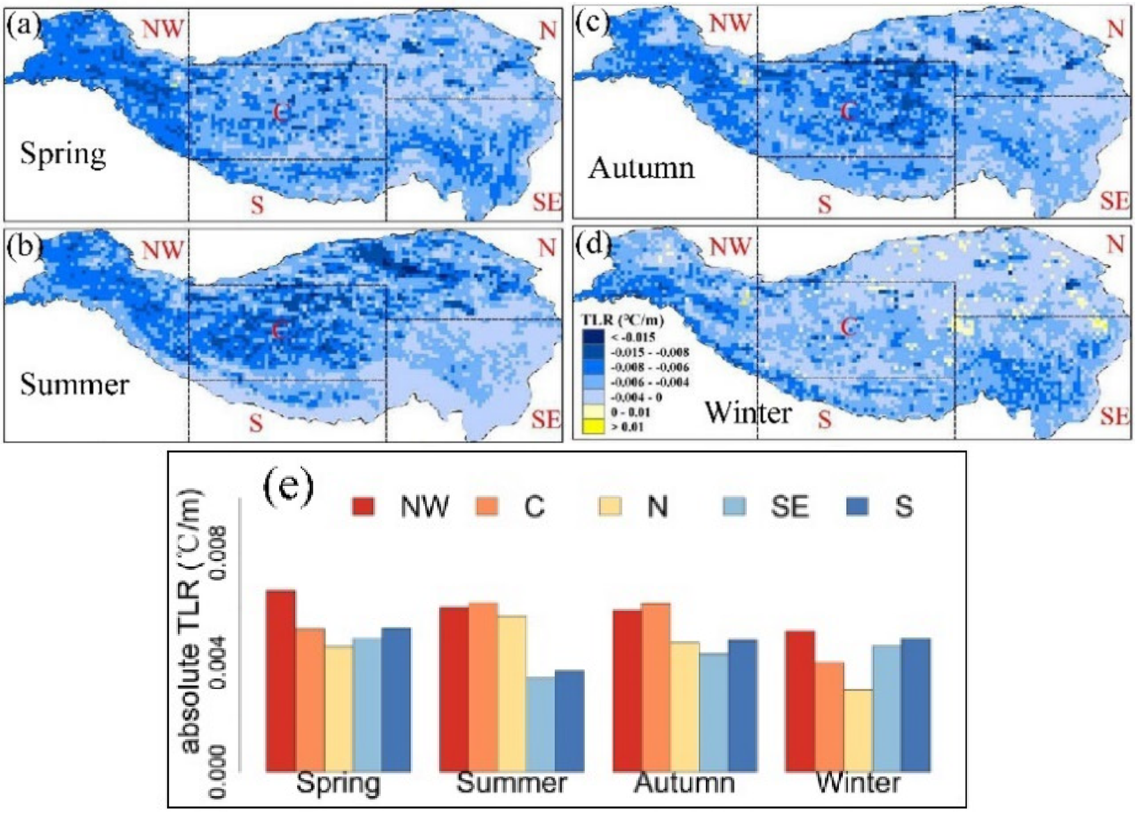

Figure 7: Spatial distribution of seasonal temperature lapse rates from MODIS (**a-d**), and their averaged values in five regions (**e**): “NW”: Northwestern TP; “C”: Central TP; “N”: Northern TP; “SE”: Southeastern TP; “S”: Southern TP.

3.2.2 Ingesting high-altitude meteorological data

The Tibetan Plateau (TP) is recognized as a hotspot for global warming, although our understanding of warming patterns at high elevations (>5000 m) remains limited due to sparse observational data. In this study, we analyze spatial patterns of warming rates on the TP using the newly developed near-surface air temperature dataset spanning from 1980 to 2014. This dataset incorporates high-elevation observations and downscaled reanalysis datasets (Section 3.2.1) to provide a more comprehensive view of the TP's warming status.

Our high-resolution temperature dataset allowed us to confirm with high confidence that most major TP basins warm rapidly (Figure 8), in particular in winter (Figure 9). Notable stepwise warming in annual temperature change is detected in 1997 although the seasonality is rather complex (Figure 9). Such abrupt warming can explain some observed sudden environmental changes starting in the late 1990s.

Overall, elevation dependent warming is only valid up to about 5000 m above which the persistent snow cover prohibits an increase of warming rate with increasing height, making the altitudinal patterns of elevations below and above 5000 m reversed (Figure 10). For the first time, the new data covers elevations above 5000 m with the best accuracy reached so far, which made it possible for us to conclude that the well-established snow-albedo feedback is less important at high elevations than in low-middle elevation areas, because of the persistent existence of snow covers at high elevations. The snow covered and glacierized areas over high elevations that have hardly changed so far, effectively constrain the warming rates. There is an important positive feedback loop and warming rates are amplified when snow cover and glacier areas are reduced.

This study highlights the potential implications of decreasing snow cover and glacier extent at high elevations on amplifying the warming of the TP. The negative feedback mechanism provided by the presence of snow and glaciers at high elevations suggests that they play a crucial role in regulating the TP's warming. As such, understanding the interactions between high-elevation snow and glaciers and the regional climate system is essential for accurately predicting future warming on the TP and its broader impacts on the Earth system.

Our study on altitudinal warming patters on the Tibetan plateau was published in 2022:

Zhang, H., Immerzeel, W.W., Zhang, F., de Kok, R.J., Chen, D., Yan, W., 2022. Snow cover persistence reverses the altitudinal patterns of warming above and below 5000 m on the Tibetan Plateau. Science of The Total Environment 803, 149889.

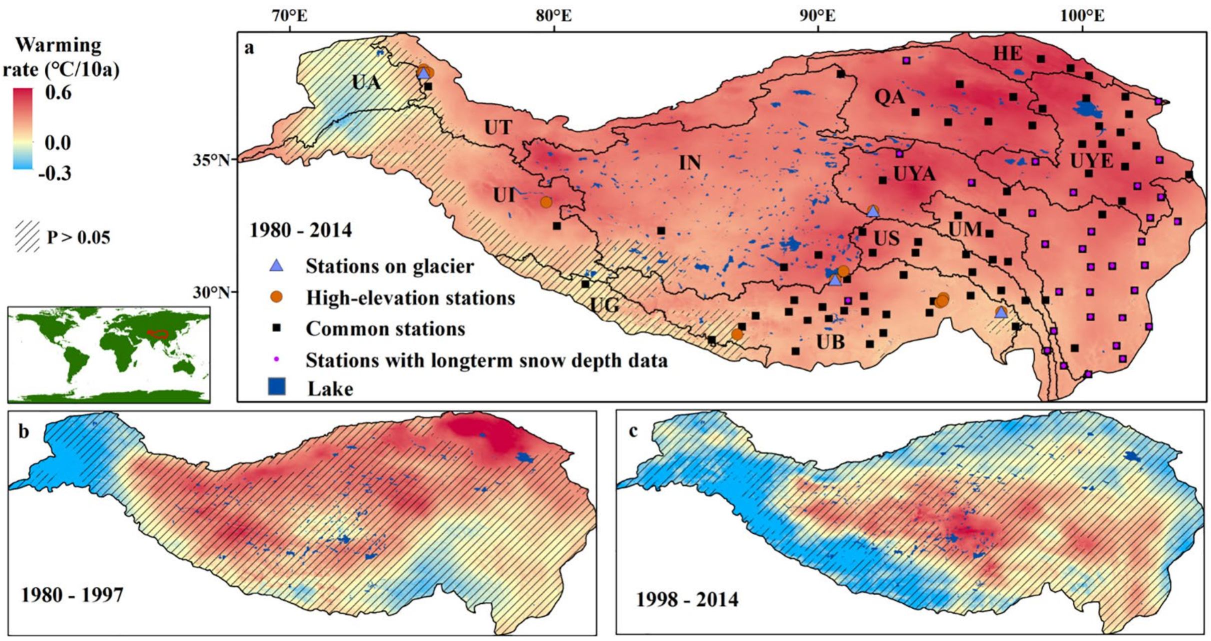

Figure 8: The all-year warming rates of the Tibetan Plateau. 1980–2014 (a). 1980–1997 (b). 1998–2014 (c). UA: Upper Amu Dayra, UB: Upper Brahmaputra, UG: Upper Ganges, HE: Hexi, UI: Upper Indus, IN: Inner, UM: Upper Mekong, QA: Qaidam, US: Upper Salween, UT: Upper Tarim, UYA: Upper Yangtse, UYE: Upper Yellow, TP: the whole Tibetan Plateau. Shadowed area means insignificant temperature trends (P > 0.05).

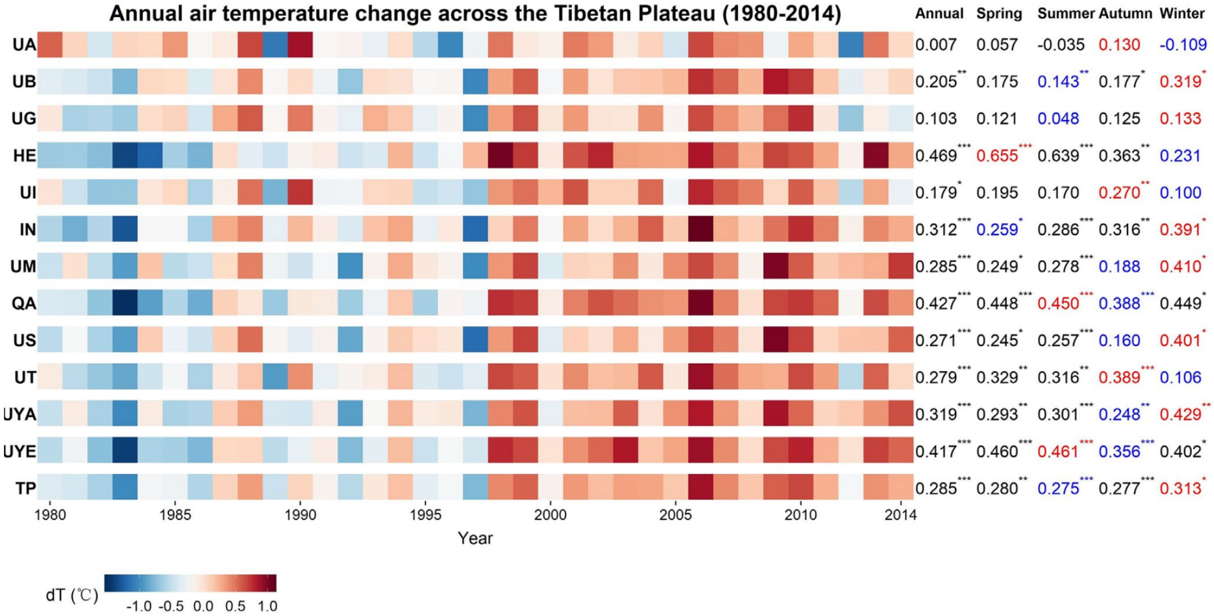

Figure 9: Annual air temperature variations (colors) and trends (numbers on the right) across the TP (1980–2014). dT is the temperature anomaly relative to the average temperature during 1980–2014 for the corresponding basin. The significance levels of the trends are indicated by ∗∗∗: P < 0.001; ∗∗: P <0.01; ∗: P < 0.05. Number in red indicates the season with the highest warming rate; number in blue means the season with the smallest warming rate.

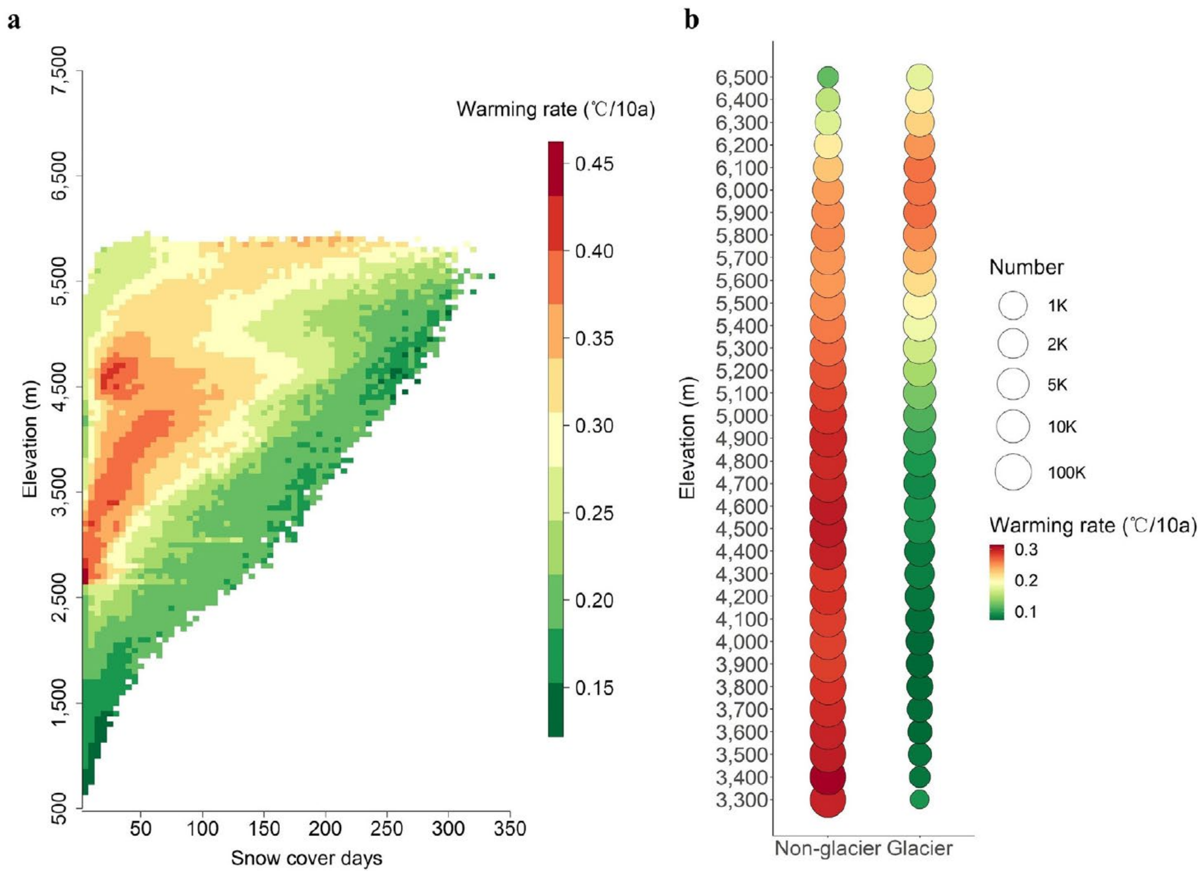

Figure 10: Elevation dependent warming affected by snow cover and glaciers. Warming rate of air temperature and as function of elevation and snow cover days with glacierized pixels excluded (a). Comparison of warming rates between non-glacierized and glacierized areas (b).

4. Past and future changes in snow and glaciers

Snow is an important component of the high-altitude water cycle, provides retention of precipitation on a seasonal scale, and changes in seasonality of snowfall and snowmelt can have large consequences for the timing of downstream discharge and water availability. Although melt water from seasonal snow provides a substantial amount of runoff in many river basins in and around the Third Pole, the importance of snow in the region, its past changes and future sensitivity to climatic changes are relatively unknown.

4.1 Modelling changes in Asia's snowpacks

To investigate the state as well as the past and potential future changes in snow water equivalent (SWE) in the Third Pole region in detail, we have developed a snow model at a spatial resolution of 0.05° (~5.7 km) for all grid cells in the Third Pole's major river basins that have on average at least four days of snow per year. We have implemented a sub-grid routine for each 100 m elevation band within a model pixel, to account for important small-scale altitudinal variability in snow. The model is run at a three-hourly time step for the period 1979–2019 and is fed with air temperature and precipitation data from the recent ERA5 reanalysis dataset (ECMWF, 2017), which we corrected for biases using satellite observations (Hall, 2015; Wan et al., 2015) and topography (Farr et al., 2007). The snow accumulation and melt model itself are based on a customized temperature-index melt model and includes additional components such as refreezing, rain-on-snow, albedo decay, and a snow loss scheme (sublimation) for high-elevation perennial snow packs. We validate the model results using *in situ* observations of SWE (Kirkham et al., 2019; Putkonen, 2004) and satellite-derived snowdepth (Lievens et al., 2019).

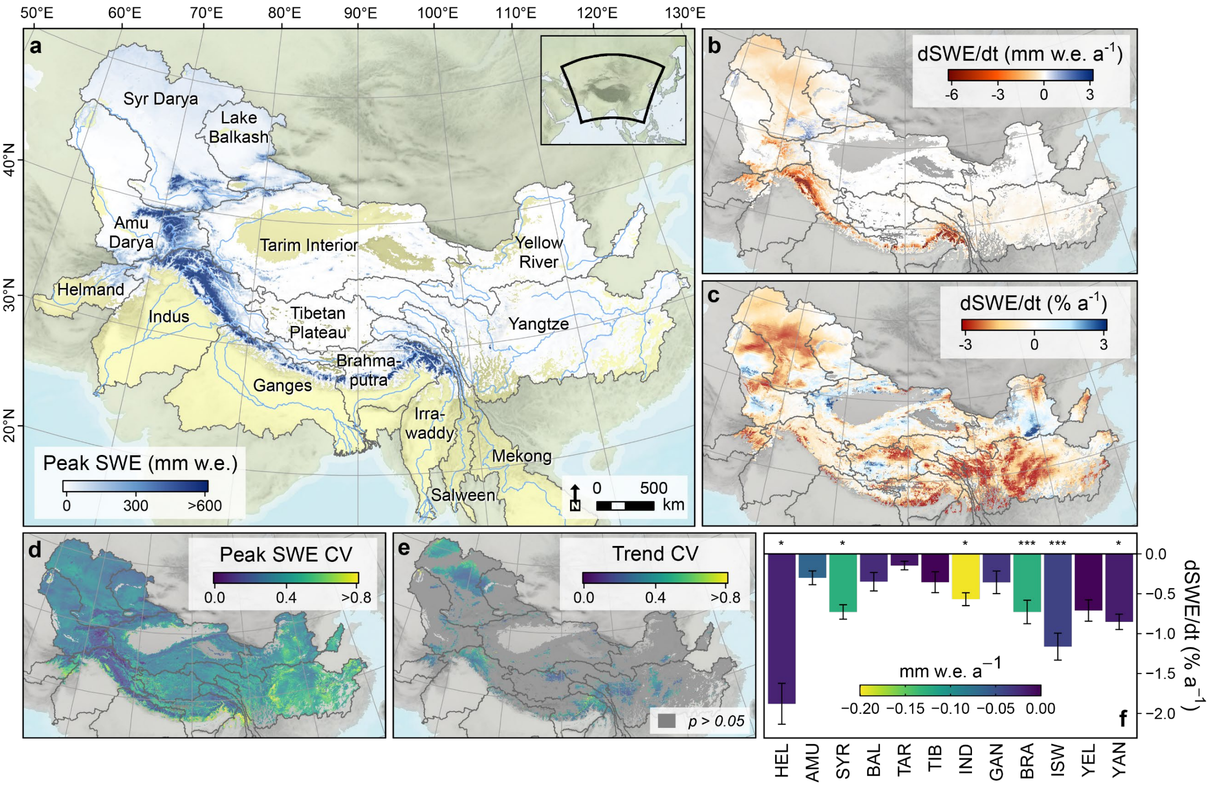

Figure 11: Snow water equivalent (SWE) and historical absolute and relative trends. Overview map of the AWT annotated with major rivers and basins and simulated mean annual peak SWE over the period 1979–2019 (a). Absolute (b) and relative (c) trends in the annual peak SWE over the same period. Model uncertainty in mean annual peak SWE (d) expressed as coefficient of variation (CV). Trend uncertainty expressed as CV (e), with areas of statistically insignificant trends (P > 0.05) masked out. Basin-wide aggregated relative trends (f) in mean annual SWE for snow years (September–August).

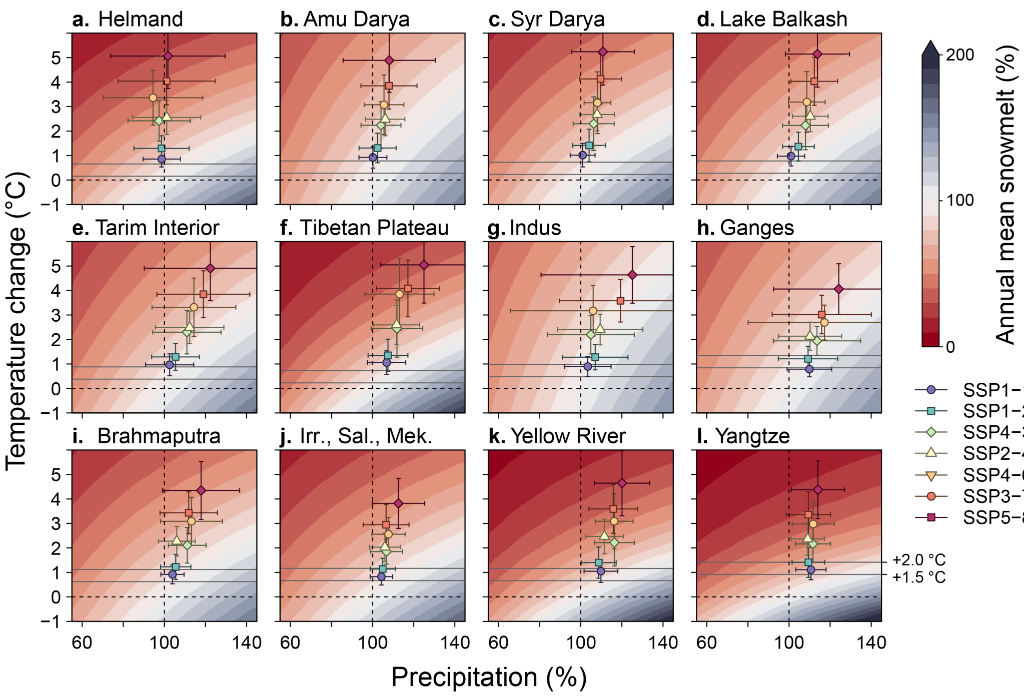

Figure 12: Response of snowmelt to changes in precipitation and temperature. Relative difference for all basins in climatological annual mean snowmelt between reference period 2000–2019 and the same period with superimposed changes in precipitation and temperature (a-l). The points and whiskers denote mean and standard deviation of the CMIP6 SSP-RCP model ensembles (Supplementary Table 1) for the end of the century (2071–2100).

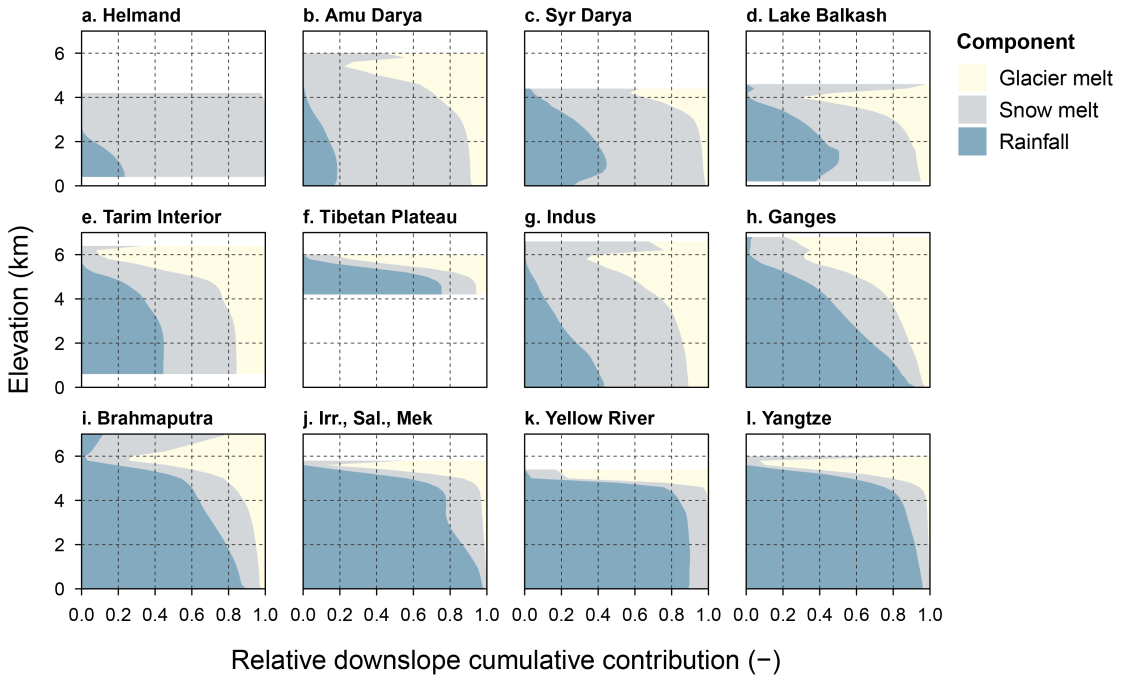

Figure 13: Relative contributions of rainfall, snowmelt and glacier melt for the period 1979–2019 over the entire elevation range of each river basin. The contributions are cumulated from high to low elevation.

Using our setup, we have simulated series of SWE, snow discharge and snow cover for the period 1979–2019. This allows us to evaluate general trends in snow (Figure 11), differences between basins, and shifts in seasonality of the snowpack and its melt water release. Furthermore, we assess the sensitivity of the snowpack in both a bottom-up approach by superimposing precipitation and temperature changes, and CMIP5 climate scenario ensembles (Figure 12). Results show that there have been substantial changes in timing of snow meltwater availability, and that snowmelt is a much more important contributor to streamflow than glacier melt (Figure 13). For the future, strong, but variable changes in snow melt water availability are projected (Figure 12). As a result of the climatic differences and basin hypsometry, the sensitivity of snowmelt to changes in precipitation and temperature is heterogeneous. The large importance of snow melt that we identify, the strong projected changes and the variable sensitivity reveal that snow is crucial to consider in future water balance studies in the region, and more so than previously thought.

4.2 Revised glacier projections

To estimate the importance of glacier melt to the water budget in the Third Pole, we performed new model runs for all glaciers larger than 0.4 km^2 using the mass balance gradient glacier developed by the Utrecht University team (Kraaijenbrink et al., 2017). The major advancements in these new model runs are the use of state of the art glacier mass balance input data (Shean et al., 2020), the most recent gridded reference climate of ERA5 (ECMWF, 2017) and the use of the most current ensemble of available future climate projections from CMIP6 (Eyring et al., 2016), which comprise a total of 143 individual General Circulation Model runs.

The new runs considerably improve upon the realism of the model outcomes and, importantly, enable better comparison with other studies in the coming years within the scope of the upcoming IPCC Assessment Report 6 (IPCC, 2014). Intentions to include a more accurate ice dynamics parameterization (e.g. Wijngaard et al., 2019) were unfortunately unachievable, as calculations were found to be computationally too costly at large scale.

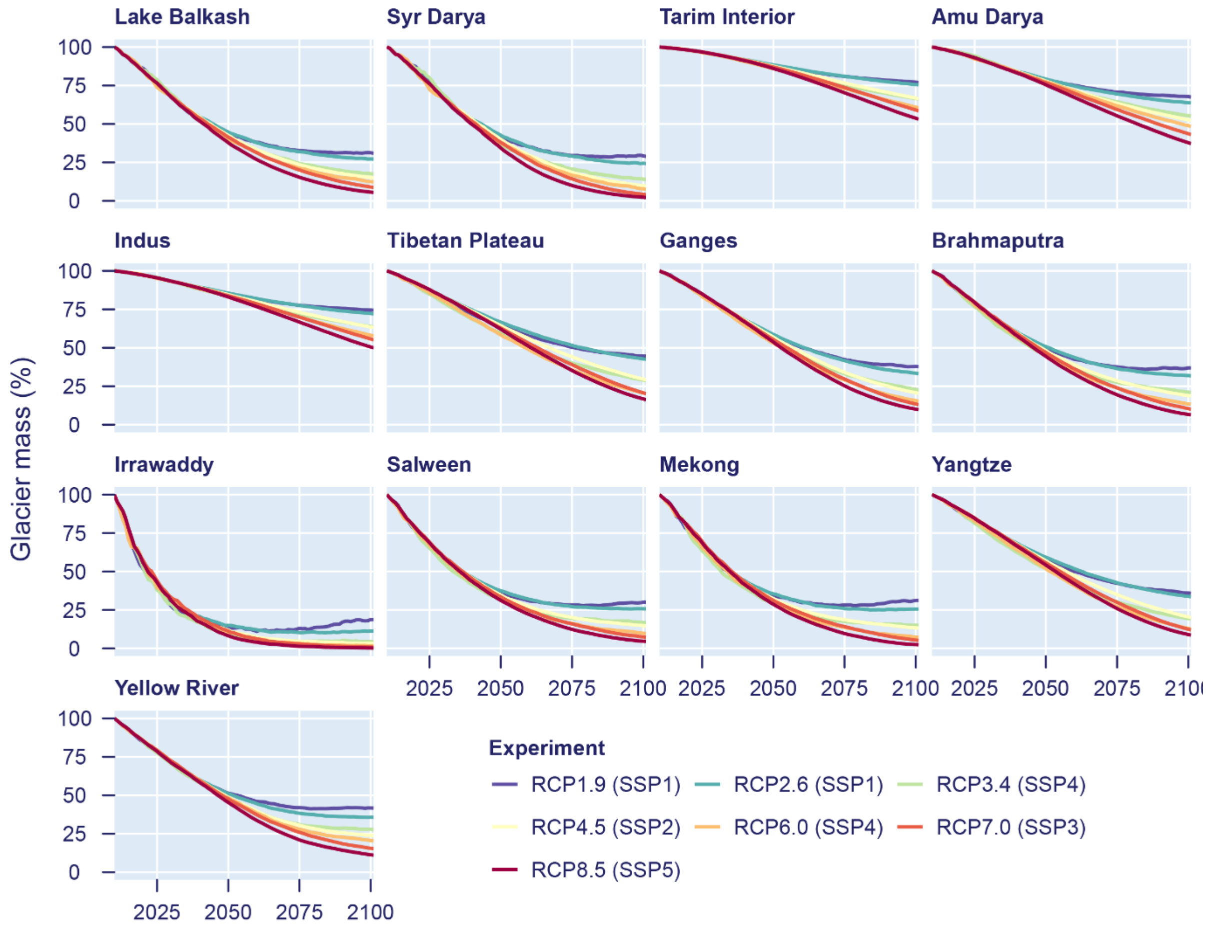

Figure 14: Relative changes in glacier mass for the major river basins of the Third Pole. Projections are made using a revised version of the glacier model by Kraaijenbrink et al. (2017), forced by the latest CMIP6 models (Eyring et al., 2016) and glacier mass balance estimations (Shean et al., 2020).

Similar to the results presented by Kraaijenbrink et al. (2017), the updated projections show large variability in relative glacier mass loss across the Third Pole region (Figure 14). Areas with large ice reserves and relatively stable mass balances at present (Brun et al., 2017; Shean et al., 2020), such as Amu Darya, Indus and Tarim Interior, show relatively modest losses of glacier mass. Other regions, in particular the monsoon-dominated eastern parts of the Third Pole, exhibit considerably larger losses. Overall, projected mass losses are slightly larger than those reported by previous projection, which may largely be attributed to the stronger warming projected by CMIP6 with respect to CMIP5 (Tokarska et al., 2020).

For future work, we aim to evaluate the possibility of increasing the temporal resolution of the glacier model from annual to a sub-annual time stepping, e.g. monthly. This is expected to improve the accuracy of the model on the smaller catchment scale, which allows better integration with the results from our snow cover study. This would enable the use of the model for smaller regions in the AWT domain, such as the Karakoram-Kunlun area (Section 5), or one of the super sites defined in the Pan-TPE program (see Section 9.3), and be combined with other results and models to improve our understanding of these specific sites and their dynamics. Besides further updates to the glacier model and studies of specific sites, we also intend to perform a new and separate large-scale analysis in which the importance of glacier runoff is determined for the entire Pan-TPE domain.

4.3 Future importance of snow and glaciers

The updated glacier model projections (Section 4.2) enable a direct comparison of changes in glacier meltwater availability and those in snow meltwater availability, as determined using our snow model (Section 4). While the projected future snowmelt shows distinct negative trends with an increasing radiative forcing for all river basins, losses of glacier melt are stronger on average and are often relatively constant or even decrease with an increase in forcing (Figure 15). This is caused by differences in the timing of increased glacial meltwater release (Huss and Hock, 2018; Immerzeel et al., 2013; Kraaijenbrink et al., 2017) caused by (i) stabilizing temperatures and small precipitation increases under low forcing (i.e. reduced excess melt due to stabilizing glacier mass balances and only small mass turnover increases), and (ii) continued temperature rise and strong precipitation increases under stronger forcing (i.e. sustained excess melt and increased mass turnover, despite decreasing glacier surface areas). As a result, the relative importance of snowmelt in HMA's rivers will increase with respect to glacier melt. Absolute reductions in snowmelt volume mostly exceeds those of glacier melt (Figure 15), however, and a decline of snowmelt therefore has larger impacts on downstream meltwater supply than that of glaciers.

It should be noted that glacier melt usually lags snowmelt and continues through summer when the snow storage has been largely depleted, i.e. the timing of the two meltwater sources is not the same. Glacier melt can be dominant for brief periods during the late melt season (Armstrong et al., 2019). However, rainfall runoff generally becomes an important part of the streamflow by that time, reducing the overall importance of snow and glacier meltwater for the water supply (Lutz et al., 2014; Wulf et al., 2016). Nevertheless, now and in the future, glaciers can be critically important in periods of drought (Pritchard, 2019) and further research is required to understand the intricate intra-annual streamflow dynamics, for example using the developed Asian Water Tower Model (Section 7.1).

Our study on the AWT's snow and glaciers has been published in *Nature Climate Change* in 2021:

Kraaijenbrink, P.D.A., Stigter, E.E., Yao, T., Immerzeel, W.W., 2021. Climate change decisive for Asia's snow meltwater supply. Nat. Clim. Chang. 11, 591–597.

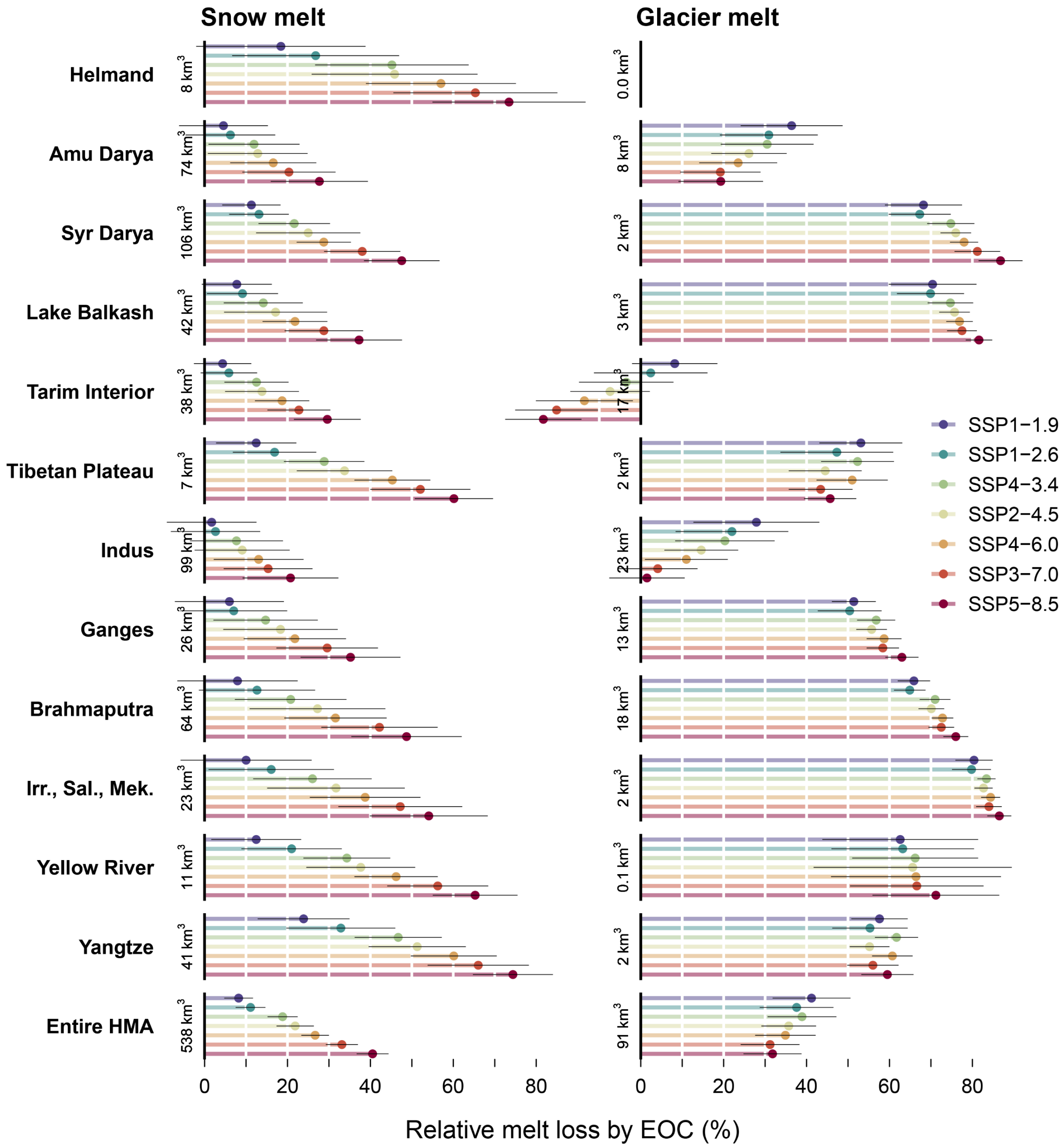

Figure 15: Projected losses in snow and glacier meltwater by the EOC. Simulated loss of annual snow (left column) and glacier (right column) meltwater by the end of century (2071–2100) for SSP-RCP ensembles with respect to present day (2000–2019) for all basins and the entire AWT (rows). Annual meltwater volume (km³) in the reference period is annotated in black left of the vertical bars. The errors bars indicate one standard deviation.

4.4 Unraveling debris-covered glaciers

A large fraction of glacier mass in the Third Pole is affected by supraglacial debris (Kraaijenbrink et al., 2017), which affects melt rates and causes high spatial heterogeneity in surface elevation changes. Understanding the processes, state and future of debris-covered glaciers is important in order to unravel the future cryospheric water supply. Over the last ten years Dr. Philip Kraaijenbrink and Prof. Dr. Walter Immerzeel have worked together on groundbreaking measurements of debris-covered glaciers in the Nepalese Himalaya using unmanned aerial vehicles (UAVs), and have revealed UAV data to be indispensable in mapping and monitoring this type of glacier (see Kraaijenbrink, 2018).

Although almost all data acquisition has been performed in previous projects, a final paper has been produced within the scope of the QWATOW project to combine data from all the UAV surveys that were performed. In this study, we present the results of a five-year UAV monitoring campaign in the Langtang Catchment in the Nepalese Himalaya in which we surveyed Lirung Glacier (9 surveys, 2013--2018) and Langtang Glacier (7 surveys, 2014--2018) (Figure 16). Optical UAV imagery was processed into high-resolution image mosaics and elevation data, accurately positioned using ground control data and co-registered using tie points. Derived glacier surface velocities and flow-corrected elevation changes were analyzed and used to evaluate supraglacial ice cliff evolution and glacier retreat.

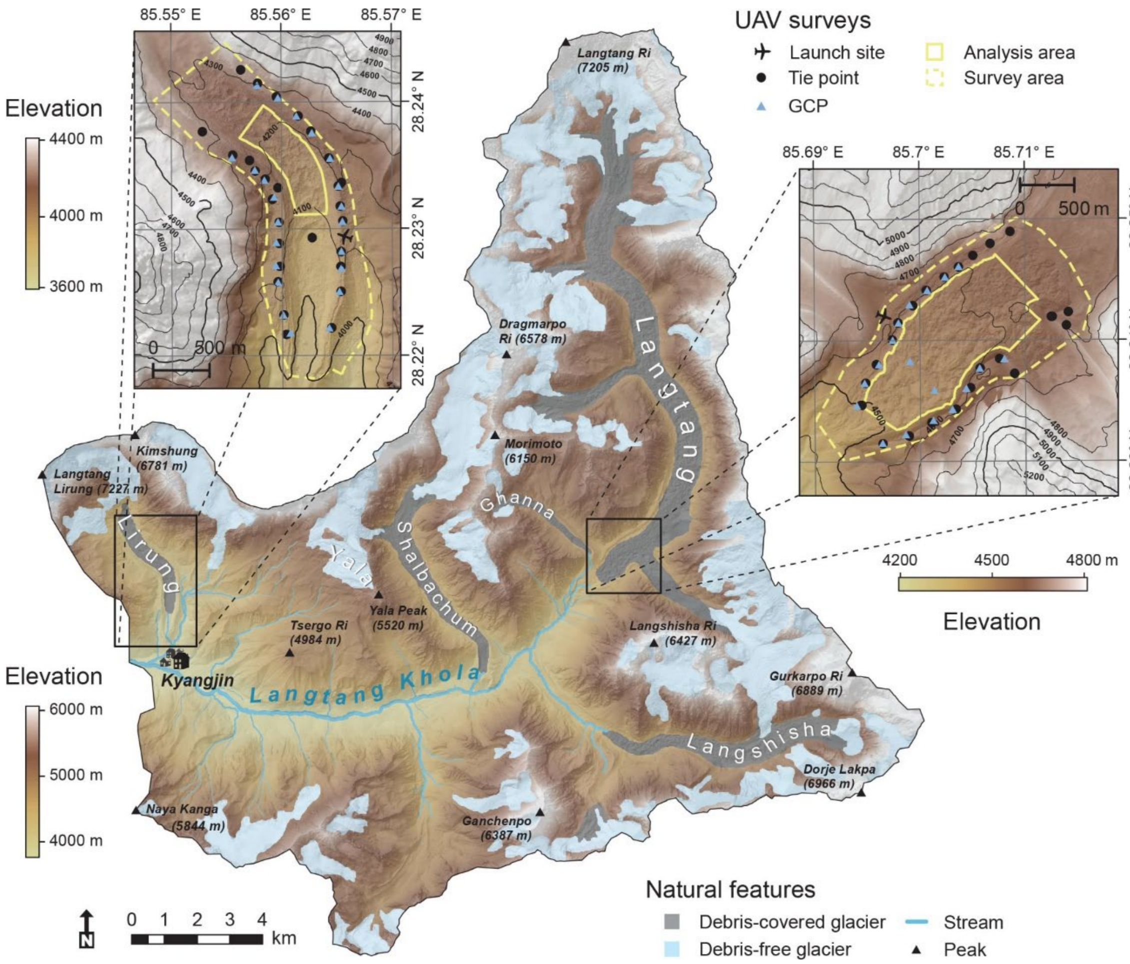

Figure 16: Overview of the upper Langtang Catchment, its glaciers and the location of the UAV surveys. The two inset maps show detailed views of Lirung Glacier and Langtang Glacier, the typical UAV survey areas and the area used for data analysis, as well as the ground control and tie points that were used during image processing.

Results show that on average the surveyed areas of both glaciers had comparable elevation changes of –0.76 and –0.83 m a^{-1}, respectively (Figure 17). Surface velocities of both glaciers were similar as well, ranging from 1.0 to 3.5 m a^{-1}. Higher velocities and anomalous glacier thickening were observed for Langtang Glacier in and after the period spanning the 2015 Ghorka Earthquake, which could be explained by a temporary change in glacier dynamics. Supraglacial ice cliffs on both glaciers exhibited variable responses irrespective of aspect. The terminal cliff of Lirung Glacier experienced incredibly fast retreat of 41 m a^{-1} (Figure 18).

These five years of UAV surveys have provided unique insights in surface changes of debris-covered glaciers and catalyzed new research focusing on process understanding of ablation processes at unprecedented detail. All our acquired UAV data will be released upon publication of this study and it is expected to be a paper that is of high interest in the debris-covered glacier and UAV communities.

At time of writing, the UAV study is being revised and we expect publication in 2023:

Kraaijenbrink, P.D.A., Immerzeel, W.W., 2023. Five years of unmanned aerial vehicle observations of two debris-covered glaciers. Journal of Geophysical Research: Earth Surface (in revision).

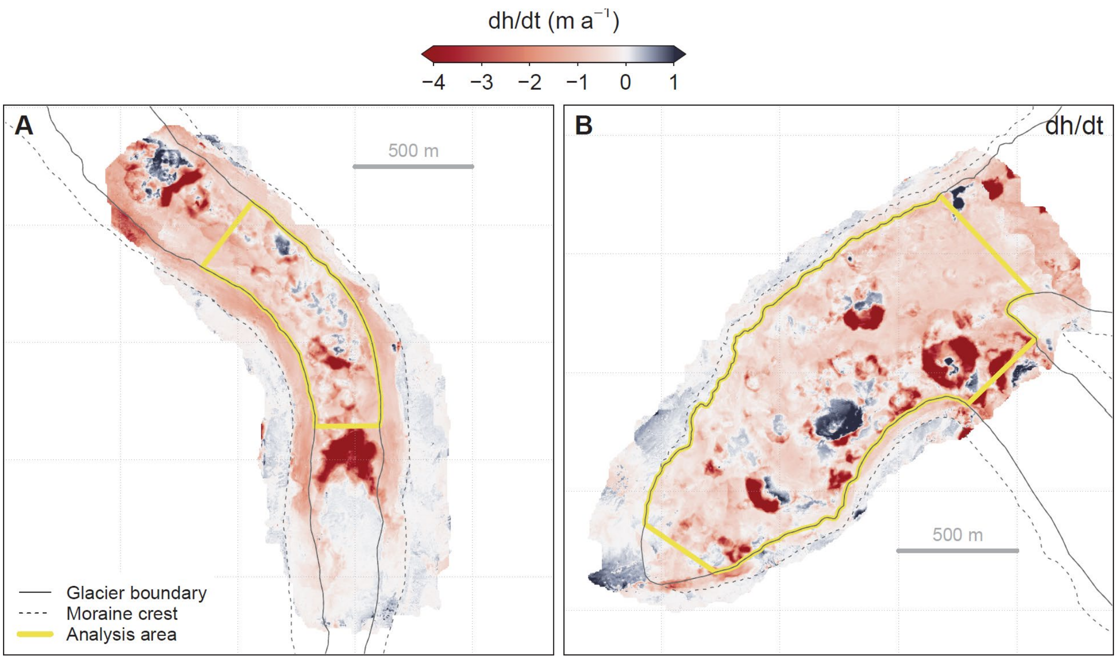

Figure 17: Elevation change as determined by pixel-wise linear regression of the DEMs of Lirung Glacier (A; 2013–2018) and Langtang Glacier (B; 2014–2017).

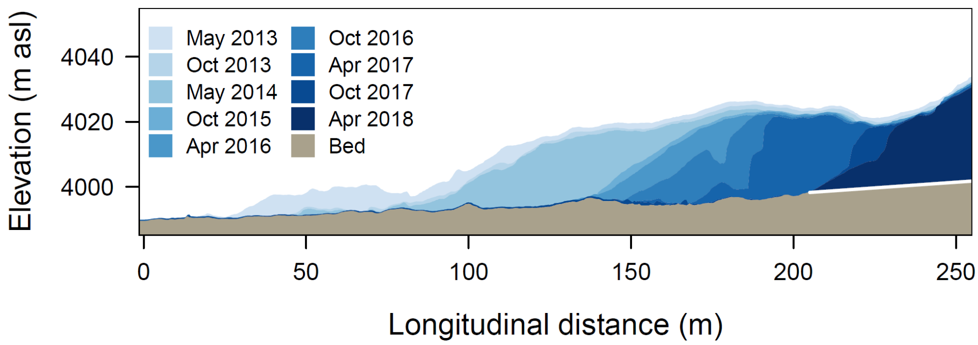

Figure 18: Longitudinal cross section of the terminus retreat of Lirung Glacier over the period of monitoring.

5. Understanding the Karakoram Anomaly

Glacier thinning and retreat is observed all around the globe and is indicative of the climatic changes that occurred over the last decades (IPCC, 2019). While the observed warming and spatiotemporal shifts in precipitation have generally resulted in negative glacier mass balances for most regions in the world the negative response is not universal. Of particular interest are the Karakoram and West Kunlun mountain ranges, which are home to the largest glacier ice reserves in the AWT region (Kraaijenbrink et al., 2017) and exhibit stable or positive glacier mass balances (Brun et al., 2017; Shean et al., 2020), despite the local climatic warming. This anomalous glacier behavior has been dubbed the Karakoram Anomaly (Hewitt, 2005). Since the Karakoram-Kunlun region represents the most important water tower of the world (Section 2.1; Figure 2), understanding the specific causes of this anomaly and their long term implications are important and a key component of unraveling the present and future Pan-Third Pole water tower.

5.1 Manifestations and mechanisms

In an effort to spark additional research and ultimately further our understanding of the anomalous situation in the Karakoram, the Utrecht University team has collaborated with ETH Zurich on a perspective study that discusses the manifestations of the Anomaly and the mechanisms at its cause that are suggested in scientific literature thus far (Farinotti et al., 2020). The perspective provides a good account of the current understanding of the extent of the anomaly, i.e. that both the change surface elevation (Brun et al., 2017) and ice flow velocities (Dehecq et al., 2019) are minimal or positive in the Karakoram-Kunlun (Figure 19).

Glacier mass balance is governed by meteorological forcing, and the explanation for the anomaly therefore must be of meteorological nature. Several potential explanations for changes in meteorological specifics in the region over the last decades are summarized in our perspective (see also the schematic of Figure 20). Examples of suggested explanations are (i) changes in the westerly-driven precipitation events, which are thought to have a strong control on glacier mass balance in this region (e.g. Forsythe et al., 2017; Kapnick et al., 2014), to (ii) modulations of the Karakoram/Western Tibetan Vortex (de Kok and Immerzeel, 2019; Li et al., 2018), and to (iii) increased evaporation in Northwest China during the twentieth century (de Kok et al., 2018). Note that several of the suggestions come from the Utrecht University team, and that we are committed to search for a definitive explanation for the Karakoram Anomaly in the future.

The most important – but yet unanswered – question is how long the Anomaly will sustain. Climate change will most likely continue in the coming decades, and meteorological drivers will do so accordingly at various scales. There have been studies that project glacier melt in the region (e.g. Kraaijenbrink et al., 2017; Rounce et al., 2020), but forcing of these models have not yet fully included the complex meteorological conditions and physical processes that define the Karakoram climate. To better understand future of the Karakoram glaciers, future research should therefore focus on model parameterizations that do include the specific meteorological drivers that are important in this region.

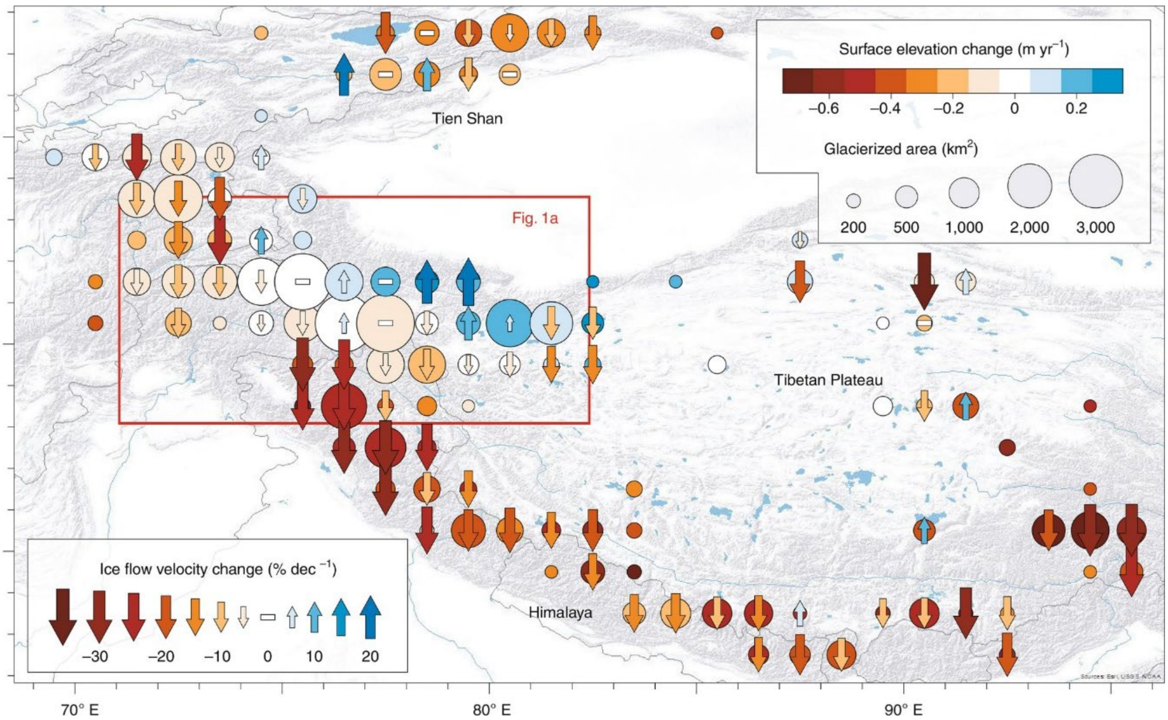

Figure 19: Recent glacier changes in High Mountain Asia (from Farinotti et al., 2020). The rate of glacier surface-elevation change (Brun et al., 2017) is shown together with changes in ice flow velocity (Dehecq et al., 2019).

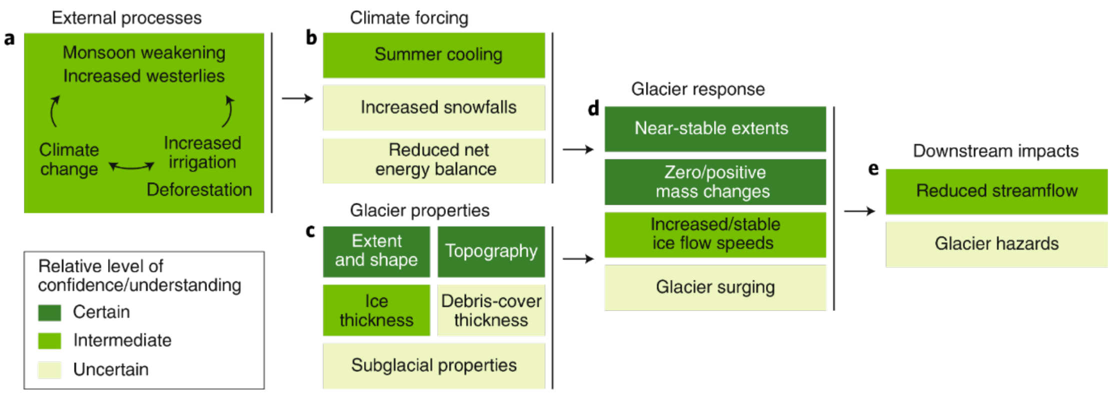

Figure 20: Schematic of the process chain leading to anomalous glacier evolution. **a**, External processes. **b**, Climate forcing. **c**, Glacier properties. **d**, Glacier response. **e**, Downstream impacts. For every element, a relative level of confidence in its characterization or understanding is indicated by the shading (from Farinotti et al., 2020).

The perspective on the Karakoram Anomaly was published in *Nature Geosciences* in January 2020:

Farinotti, Daniel, Walter W. Immerzeel, Remco J. de Kok, Duncan J. Quincey, and Amaury Dehecq. 2020. "Manifestations and Mechanisms of the Karakoram Glacier Anomaly." *Nature Geoscience* 13 (1): 8–16.

5.2 Snowfall controls on glacier mass balance

To further investigate the effects of changes in snowfall in the Karakoram-Kunlun region as a result of increased irrigation (Section 5.1), the Utrecht University team has performed another study (de Kok et al., 2020) that combines dynamical downscaling using WRF (de Kok et al., 2018) and glacier modeling (Kraaijenbrink et al., 2017) to understand the spatial variability of glacier mass balance in High Mountain Asia.

Our simulations, based on ERA-Interim and GLDAS reanalysis data, indicate that an increase of snowfall (Figure 21) and a low temperature sensitivity are the main reasons why glaciers in the Karakoram-Kunlun are stable or growing. Using a moisture tracking technique (Tuinenburg et al., 2012), we show that the growing irrigated area in the arid region of Northwest China (primarily the Tarim Basin) results in increased snowfall in the Karakoram-Kunlun region. Previous studies have already indicated existence of this process (Cai et al., 2019; de Kok et al., 2018), but we now show that this process is also important when compared to other atmospheric changes that have occurred over the last decades. In fact, the increase in snowfall due to irrigation is necessary to replicate the observed spatial patterns of glacier mass balances (Brun et al., 2017) (Figure 22). Future evolution of snowfall in this part of the AWT is therefore partly linked to how the irrigated areas develop in the future.

It should be noted that the increase snowfall from irrigation is most likely unsustainable. Irrigation in Northwest China may come from glacier meltwater originating in the Tien Shan (Dong et al., 2018). This meltwater runoff will reduce when Tien Shan glaciers continue to shrink under climate change (Immerzeel et al., 2010; Kraaijenbrink et al., 2017), thereby potentially reducing irrigation volume and the increased snowfall, resulting in negative glacier mass balances. If the primary source of water for irrigation is local groundwater, the glaciers in the Karakoram-Kunlun will receive less snowfall once the groundwater is depleted, having a similar effect. The relative importance of groundwater extraction, glacier melt from Tien Shan, and recycling from the Karakoram-Kunlun for the water availability in the Tarim Basin is yet unknown and will require future study.

If climate warming in the region continues, which is highly likely (Wester et al., 2019), the resulting increase in melt will likely counteract any glacier growth that is due to increased precipitation in the long term. It is clear that the coupling between glacier mass balance, runoff, and irrigation in different regions creates a complex problem of water availability, which requires further research to inform decision makers on irrigation policies.

The study on snow fall controls on AWT's glacier mass balance was published in *The Cryosphere* in 2020:

de Kok, R.J., Kraaijenbrink, P.D.A., Tuinenburg, O.A., Bonekamp, P.N.J., Immerzeel, W.W., 2020. Towards understanding the pattern of glacier mass balances in High Mountain Asia using regional climatic modelling. *The Cryosphere* 14, 3215–3234.

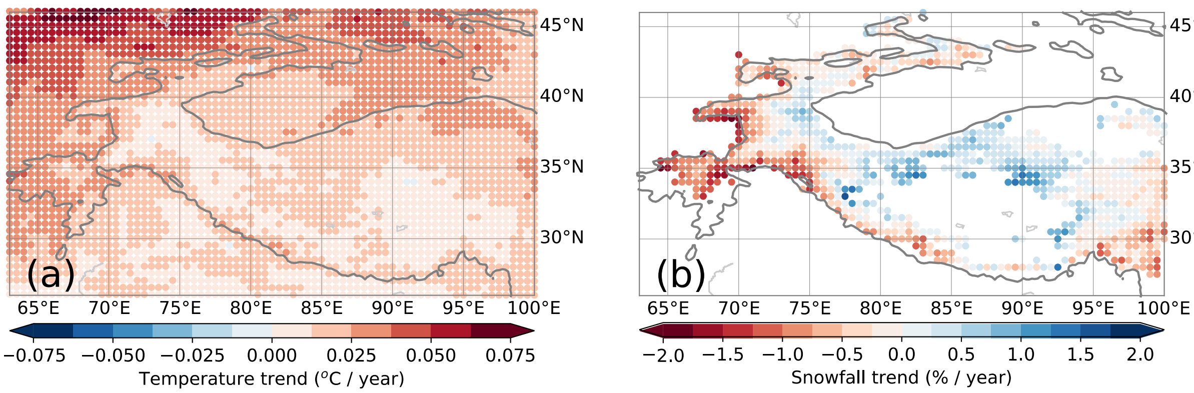

Figure 21: Trends over 1980–2010 of temperature in the melt season (**a**) and annual snowfall (**b**), averaged over 0.5° bins for clarity. Regions with monthly snowfall of less than 10 mm were masked out. The 2000 m elevation contour is indicated by a solid line (from de Kok et al., 2020).

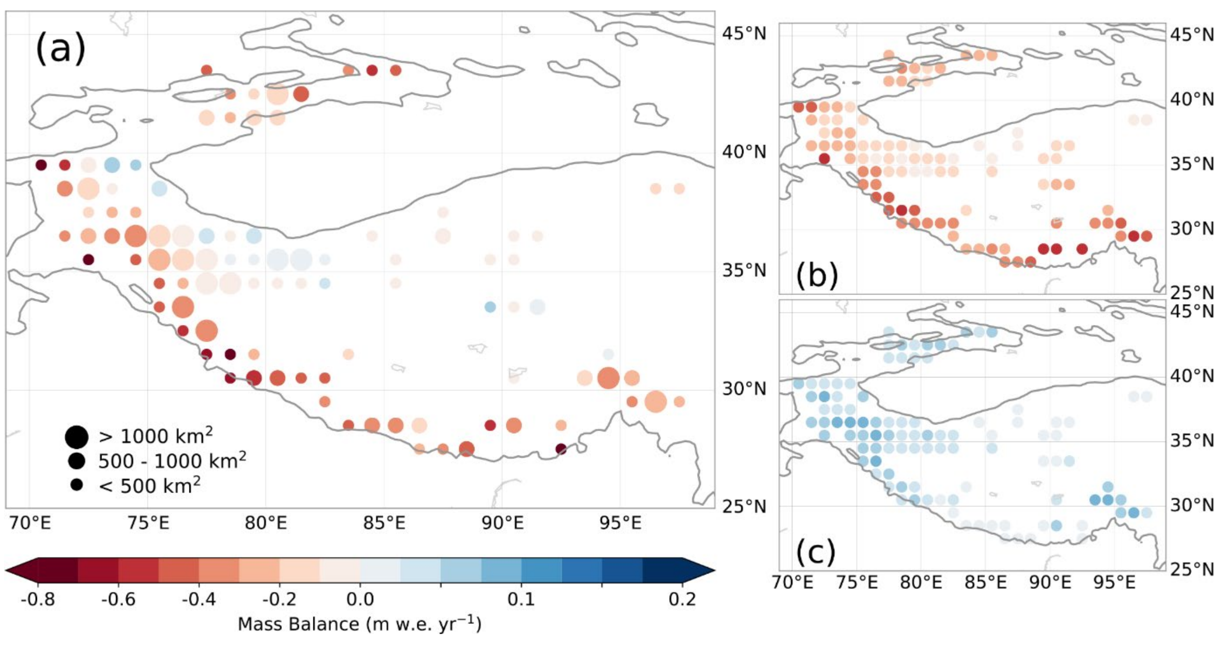

Figure 22: Simulated glacier mass balance between 2000-2010 when forced by changes in temperature and snowfall from WRF (**a**), only changes in temperature from WRF (**b**), and only changes in snowfall from WRF (**c**). The 2000 m elevation contour is indicated by a solid line (from de Kok et al., 2020).

6. Tibetan lake changes

One of the unique features of the water cycle in Third Pole region is the presence of a large number of (endorheic) lakes on the Tibetan Plateua (TP), many of which have grown rapidly in the last decade (Wan et al., 2016). The TP plays an essential role in the water supply to Asia's large river systems and, as the largest and highest mountain plateau in the world, it drives the Asian monsoon and influences global circulation patterns significantly. The increase in TP lake level since the mid-1990s is well documented in the literature, however the drivers of these changes remain largely unexplained. The reason for the growth of the lakes could potentially be attributed to permafrost degradation, increased precipitation and/or melting glaciers, but the exact mechanisms remain unknown.

6.1 Contributors to lake changes on the Tibetan Plateau

In collaboration with the University of Oslo and NASA, the Utrecht University team has investigated three potentially important contributors to lake level rise: glacier mass loss, and changes in the precipitation and evaporation regimes.

By combining recent observations of lake (Treichler et al., 2019) and glacier (Shean et al., 2020) volume changes across the TP, we show that glacier mass loss has a limited contribution to the lake volume increase (Figure 23), i.e. 19±21% for the whole TP. The increase in surface water storage is largest on the southeastern edge of the TP, which is also where the precipitation increase is largest. We observed a considerable additional May precipitation since the mid-1990s. The underlying reason for the (pre)monsoon wetting of the TP may well be related to global warming patterns, but the exact mechanisms for this intensification remain largely unclear.

Overall, we do not manage to close the TP water budget, but we show that the increase in precipitation minus evapotranspiration after 1994 is three to five times larger than the increase in water stored in lake and glacier volume (Figure 24). We suggest that the remaining difference could be attributed to enhanced evaporation from the lakes due to warming and increased surface area, to enhanced evaporation from the ground due to greening of the land surface and/or to changes in the seepage to the deep groundwater.

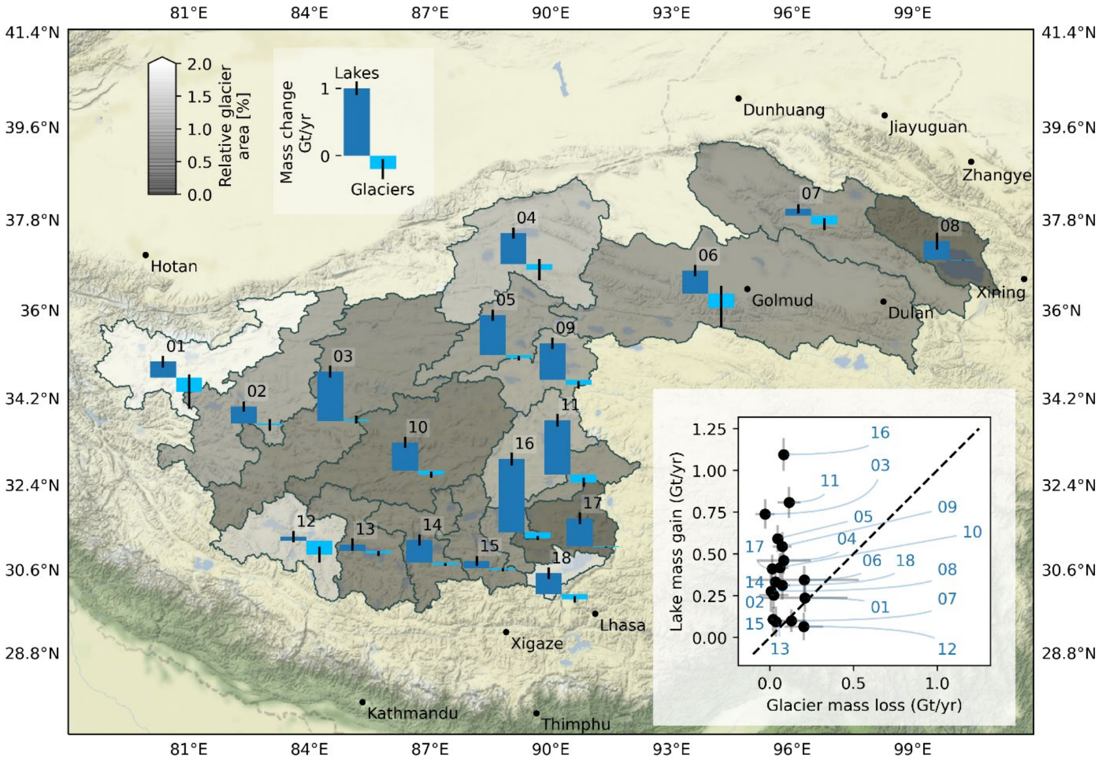

Figure 23: Lake and glacier mass change for the eighteen endorheic basins considered in this study. The colored bars represent the total mass changes and the black lines the uncertainties, all the bars are plotted with the same scale. The basins are colored according to the ratio between the glacier area and the basin area.

Although it appears that the recent increase in volume of Tibetan lakes is likely due to increased precipitation rather than glacier mass loss, the reasons behind this increase in precipitation are not yet fully understood and could be linked to changes in moisture sources or the influence of Westerlies. To gain a better understanding of these mechanisms, it is important to accurately represent evapotranspiration processes in reanalysis products. We also need to better understand the role of snow and sublimation in the Tibetan plateau water cycle, especially in dry conditions. Additionally, changes in lake level might be affected not only by the total amount of precipitation but also by the intensity, frequency, and seasonality of rainfall and snowfall. For example, the highest lake level increase coincided with an increase in May precipitation in the southeast edge of the plateau, possibly due to an earlier onset of the South Asian monsoon.

In conclusion, TP lakes are extremely sensitive to changes in the water balance because they are sinks of large endorheic basins. Global-scale reanalysis and precipitation products show changes that are qualitatively, but not quantitatively in agreement with the lake changes. We therefore advocate for the need of catchment-scale studies with local observations to better understand the water budgets of the TP lakes.

This work has been published in *Frontiers of Earth Science* in late 2020:

Brun, F., Treichler, D., Shean, D., Immerzeel, W.W., 2020. Limited Contribution of Glacier Mass Loss to the Recent Increase in Tibetan Plateau Lake Volume. Front. Earth Sci. 8.

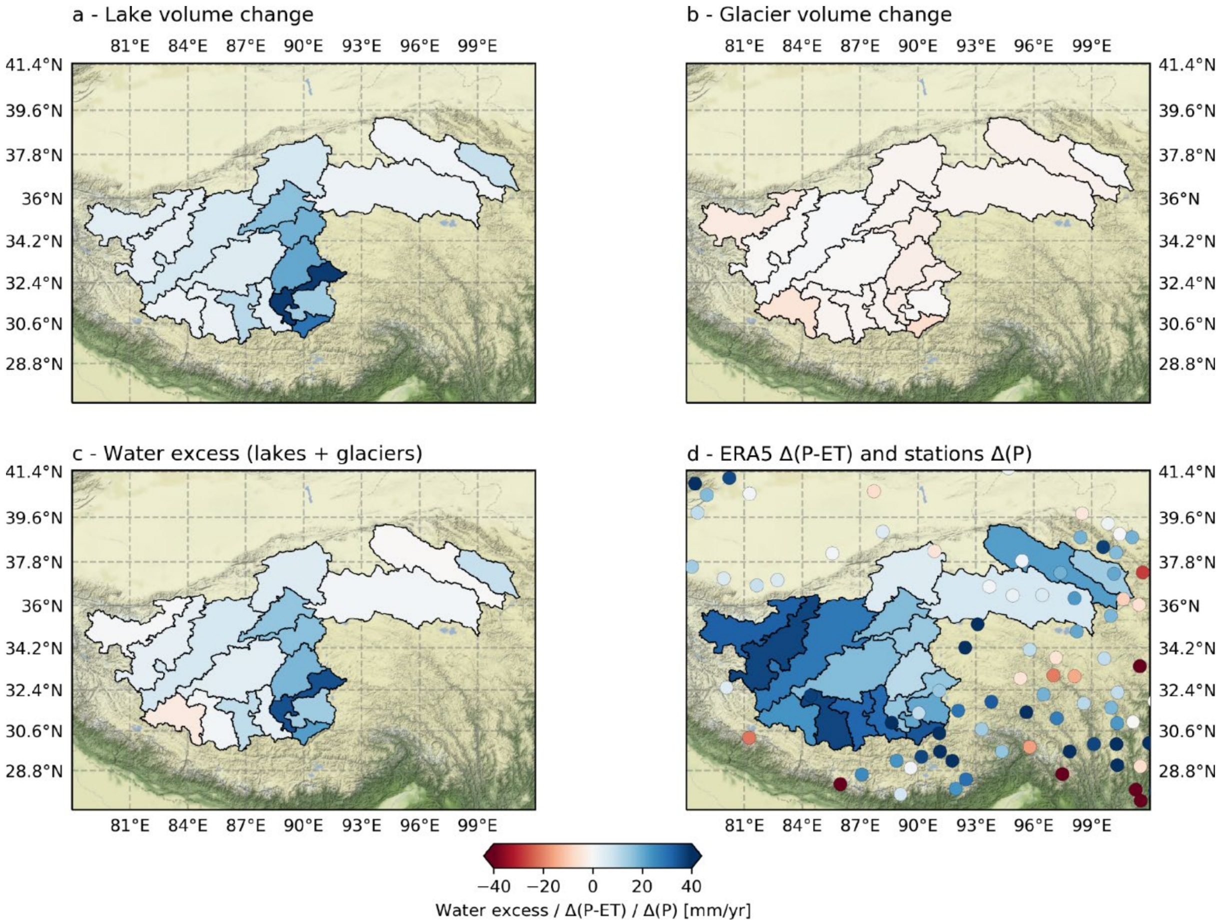

Figure 24: Lake (**a**), glacier (**b**) and lake + glacier (**c**) rate of water volume change distributed over the basin area (in mm a^{-1}). Δ(*P*-ET) from ERA5 reanalysis, and Δ*P* from the meteorological stations (dots) for the period 1994–2015 relative to 1979–1993 (**d**).

6.2 Paiku Co fieldwork

To achieve our aims to better understand the current state of the Pan-Third Pole water tower to allow for better future predictions of environmental change, a better understanding of the dynamics of the Tibetan Plateau (TP) is important. Many components, processes and feedbacks on the TP are not yet completely understood, e.g. the changes in endorheic lakes and the potential thawing of vast stretches of permafrost (Zou et al., 2017), and their effects are largely unquantified. Modeling and remote sensing studies have shed light on some aspect of the system, such as our work on TP lake change (Section 6), but also reveal that more specific knowledge is required that can only be acquired through *in situ* monitoring of the system. In a joint effort with researchers (Dr. Yanbin Lei) and field assistants (Lothar, Tsere and Phortse) from the Institute of Tibetan Plateau Research (ITP), Utrecht University team researchers Dr. Fanny Brun and Dr. Maxime Litt have therefore performed fieldwork in the endorheic Paiku Co basin.

6.2.1.1 Fieldwork aims and tasks

Paiku Co basin is a closed hydrological basin of ~2400 km^2 located on the southern edge of the Tibetan Plateau (TP) (Figure 25), just north of the extensively monitored Langtang Hydrological basin in Nepal. Field investigations and remote sensing data have previously shown that the sink of the basin is a large alpine lake (Paiku Co; 270-280 km^2), which underwent continuous volume loss during the last 30-40 years (Lei et al., 2018). The main objective of this work is to equip the upper part of the basin with various scientific instruments in order to:

- Monitor and provide better estimates of the vertical dependence of meteorological main variables inside the hydrological basin.
- Monitor and assess the contribution of proglacial lake outflow to the water balance of Paiku Co, and their role in buffering the glacier runoff.

We deployed a number of sensors in order to reach this goal, divided over four distinctive tasks:

Task 1. Installation of one full Atmospheric Weather Station (AWS) on solid ground

Task 2. Installation of two Compact AWSs at high elevation inside the proglacial lake sub-basins

Task 3. Installation of water pressure-temperature sensors into two high pro-glacial lakes

Task 4. Installation of water pressure-temperature sensors into rivers emanating from these pro-glacial lakes

To install all equipment a total of seven field days were required, excluding travel and acclimatization (

Table 3). The location of the study area and the installed instruments are shown in the overview map of Figure 25 and in the detail map of Figure 26. A brief description of each of the performed tasks is provided in the following subsections.

Table 3: Schedule of the Paiku Co fieldwork in October 2019.

Date	Location	Activities
21-10-2019	Lhasa	Arriving in Lhasa
22-10-2019	Lhasa	Shopping in Lhasa
23-10-2019	Lhasa	Shopping in Lhasa
24-10-2019	Trip from Lhasa to Lhatze	
25-10-2019	Trip from Lhatze to Paiku Co	
26-10-2019	Paiku Co	Acclimatization / Paiku Co check-up of ITP's installed equipment
27-10-2019	Paiku Co	Work on the full AWS (task 1)
28-10-2019	Paiku Co	Work on the full AWS (task 1)
29-10-2019	Paiku Co	Work on the full AWS (task 1)
30-10-2019	Upper Paiku Co basin	Work on compact AWS 1 (task 2)
31-10-2019	Upper Paiku Co basin	Work on Golo Co (task 3) and compact AWS 1 (task 2)
1-11-2019	Upper Paiku Co basin	Work on Golojang Co + rivers (task 3 and 4)
2-11-2019	Upper Paiku Co basin	Work on compact AWS (task 2)
3-11-2019	Trip from Paiku Co to Xigaze	
4-11-2019	Trip from Xigaze to Lhasa	

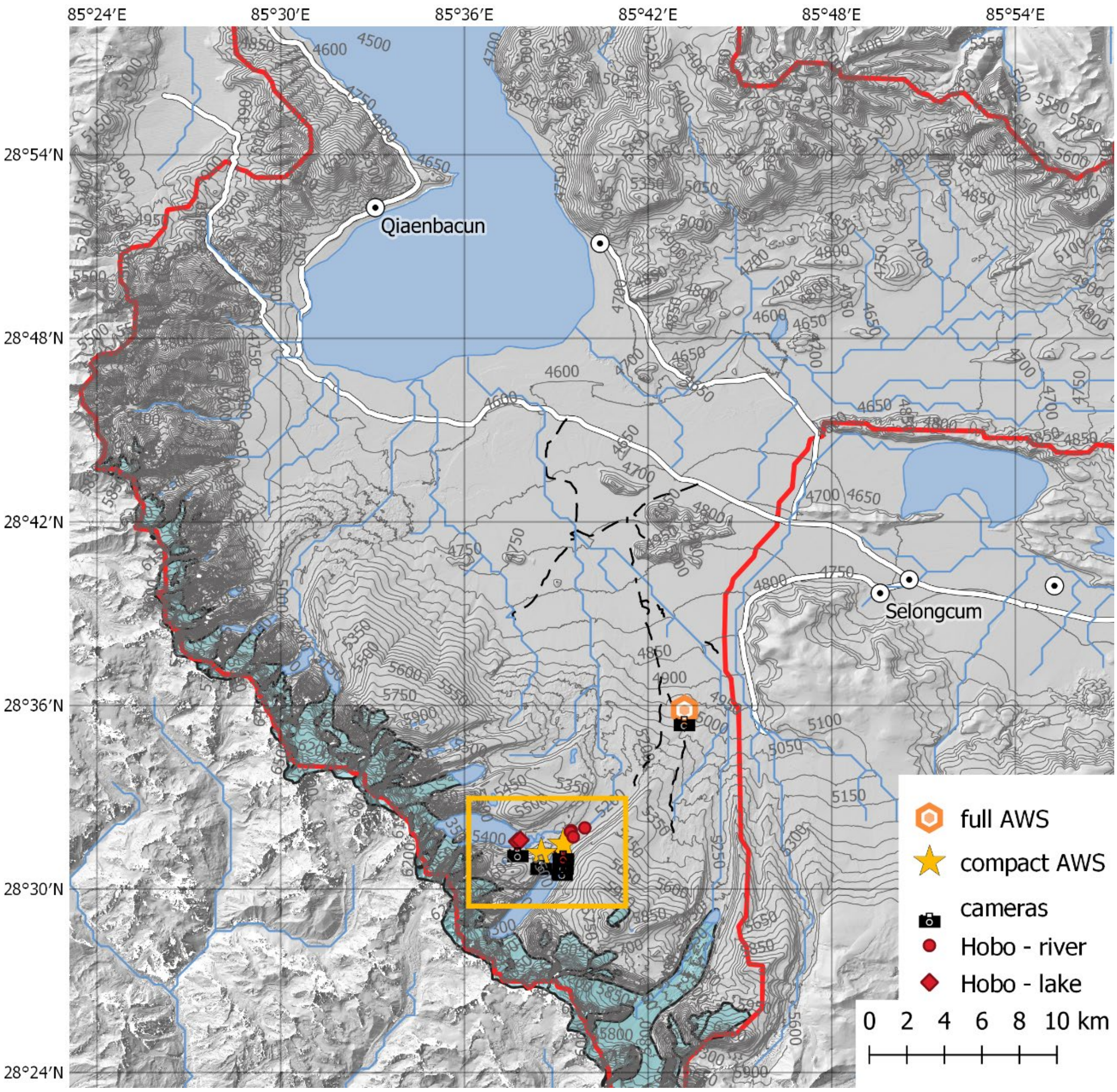

Figure 25: General map of Paiku Co basin. The red outline represents the basin boundary. The background is an hillshade derived from the High Mountain Asia DEM (Shean, 2017) contour lines are shown with a 50 m interval. The yellow inset corresponds to the map provided in Figure 26, which focuses on the investigated proglacial lakes.

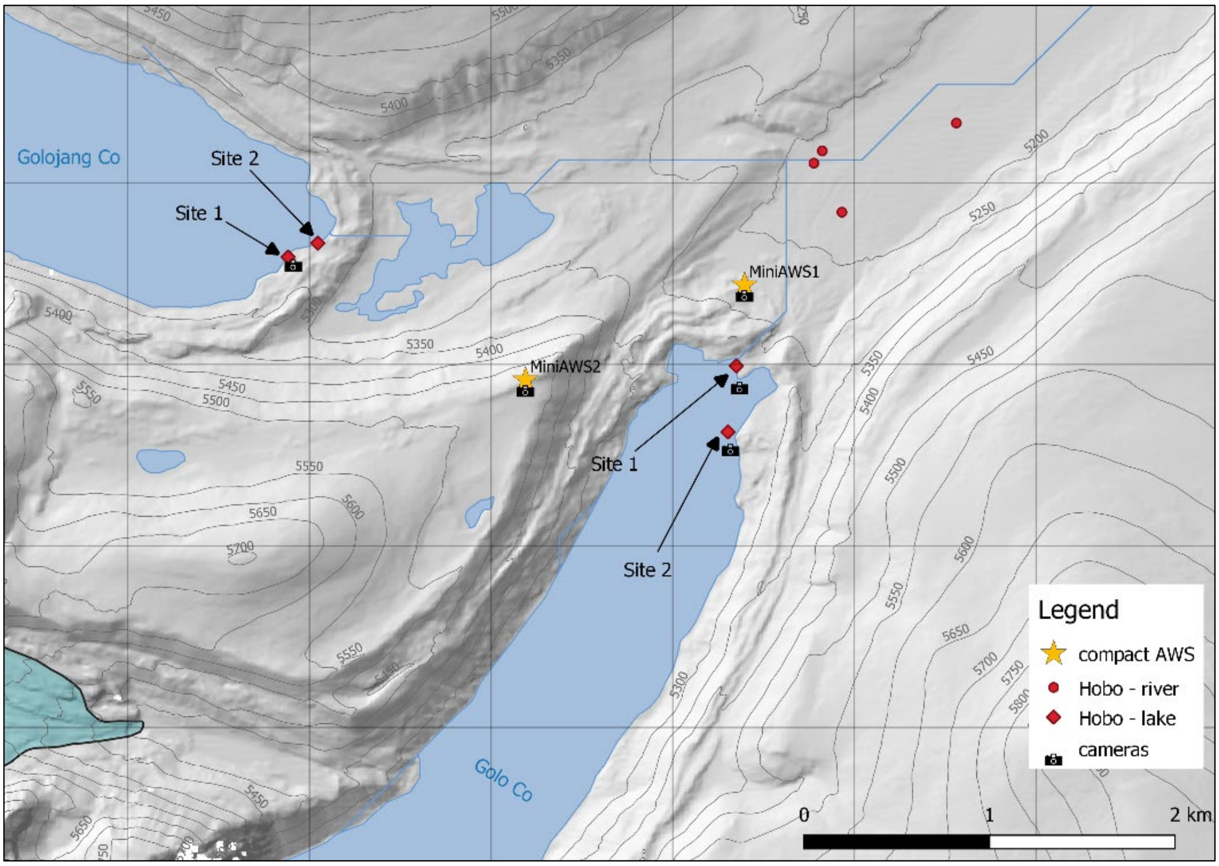

Figure 26: Detailed map of the two investigated proglacial lakes.

6.2.1.2 Description of performed tasks

Task 1: Installation of an Automatic Weather Station

We installed a full AWS on a relatively flat ridge at ~5030 m asl (see Figure 25). The site can be reached by a dirt road, the river has to be crossed a few kilometers down the basin. The AWS comprises (i) an 3 m high aluminum tower holding a data-logger box and the whole set of scientific instruments, and (ii) an OTT pluvio2, which is set up separately as a secondary tower. The aluminum mast and the OTT pluvio2 pedestal are bolted to the ground with 10 mm bolts drilled in solid rock. Both structures are firmly attached with guy wires, which are anchored with 14 mm bolts in large rocks. A time-lapse camera is fixed on the pole of the pluviometer facing southwards towards the aluminum mast. It is taking pictures of the site automatically every hour during daytime. shows the list of sensors and material installed, their specifications, when relevant the height at which they are fixed above ground, and the connection used on the data logger. A picture of the finished installation is shown in Figure 27.

Table 4: List of instruments installed on the full AWS.

Material-Instrument descriptor	Location/Height
Iridium transmission modem+antenna	Removed and transported back
CR1000 data-logger	Inside the logger box
75 Ah Battery	Inside the logger box
Solar Panel	On the Pluvio set up
Time-lapse camera	On the Pluvio set up
OTT Pluvio2	On the Pluvio set up (2.50 m, top of the housing)
SR50A	North facing arm (1.88 m)
HMP155 T/RH T plug	On the Aluminium tower (2.09 m, bottom of the instrument)
Young 05103-45	North facing arm (2.46 m)
CS106 barometer	Inside the logger box
Kipp and Zonen CNR4 Net radiation	South facing arm (2.10 m)
Kipp and Zonen CNR4 Temperature	Inside the CNR4 box

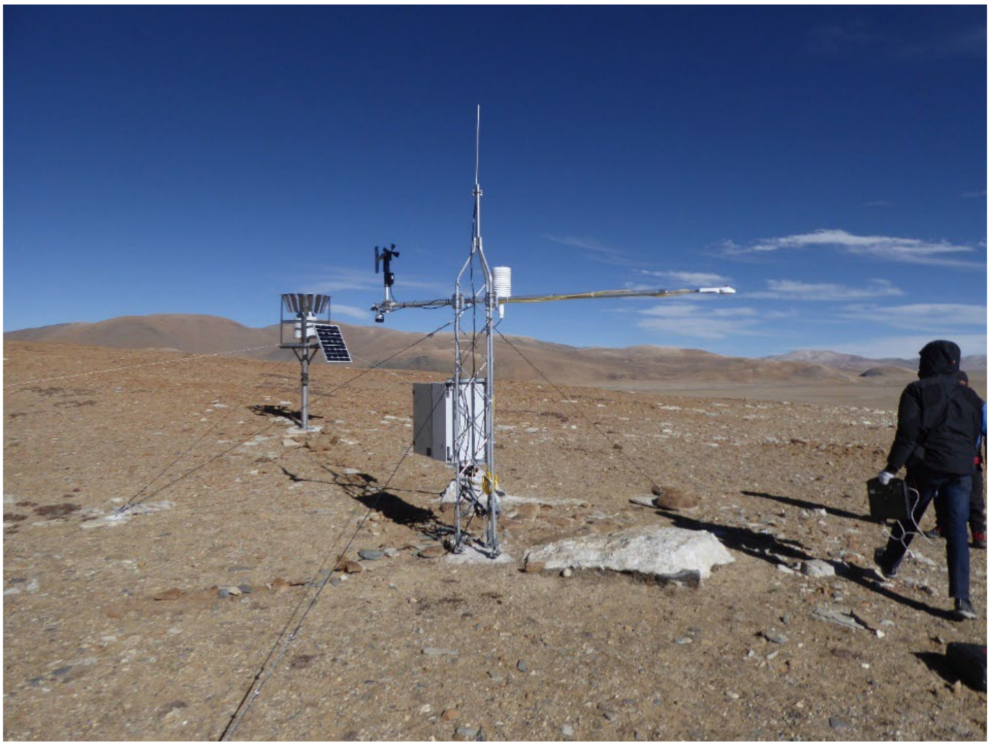

Figure 27: Picture of the full AWS, consisting of one aluminum mast (front) with instruments and a secondary pole supporting the OTT pluvio2 (in the back). The large rock visible beneath the CNR4 was later removed in order to homogenize and flatten the surface below the sensor.

Task 2: Installation of two compact AWS

We installed two compact AWS at elevations of 5200 m (miniAWS1) and 5500 m (miniAWS2) in the sub-catchments of the proglacial lakes Golo Co Golojang Co (see Figure 26). The compact AWSs are made of a steel pipe holding a metal box, which contains a CR200x Campbell logger, a 12V battery and a combined wind and T/RH sensor (WS500-UMB Smart Weather Sensor). The sampling frequency was set to one measurement every 10 minutes. The 12 Volt batteries are not recharged by any system and will have to be replaced during a next visit. The two AWSs were mounted on 1.5 m steel pipes, which were stuck in large boulders. They are reinforced by guy wires attached to pegs inserted in the ground.

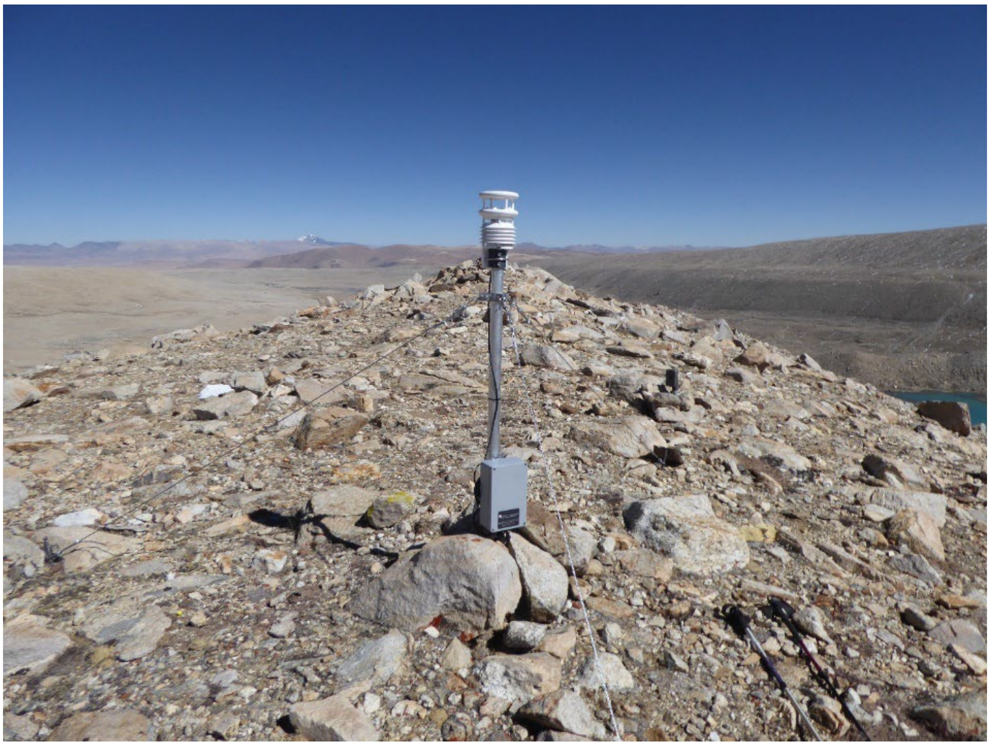

Figure 28: Picture of the compact AWS (miniAWS2) installed in the catchment at 5500 m elevation.

Task 3: Installation of pressure transducers in proglacial lakes

We installed a total of 8 pressure transducers (Hobo U30) in two proglacial lakes Golo Co and Golojang Co (Figure 26). For each lake, one atmospheric pressure reference transducer was installed on rocks, in locations that do not seem to be covered by water anytime of the year (same instrument to compensate for atmospheric fluctuations). The three other pressure transducers were placed in the water at depths ranging from 15 to 80 cm. All the sensors were placed inside a steel pipe of ~15 cm length for protection. The sampling frequency was set to one measurement per hour (*P* and *T*).

Task 4: Installation of pressure transducers in rivers

We installed five Hobo sensors (one reference and 4 sensors in water) in the streams coming from the two lakes. The river sensors were launched and parametrized similarly to the lake sensors. We installed them in the large plain at 5200 m, where the rivers are well channelized. The river flowing from Golojang Co basin is separated into two branches at the location of the measurement. There are evidences of dry channels that are very likely inundated during monsoon. A rating curve (if possible) should be established in the future. All the Hobos are tightened to rocks, and cased in steel pipes. They are located in between small cairns built on both sides of the rivers to find them more easily.

6.3 Repeat fieldwork Paiku Co

A repeat fieldwork to the Paiku Co catchment is required to read out the data loggers and install additional equipment. Initially this was planned for spring and/or autumn 2020 but, due to the impacts of the COVID-19 pandemic it was not possible to perform this fieldwork. Luckily, our field work partner from

ITP, Dr. Yanbin Lei, has been committed to fieldwork and was able to visit the sites. He has read out the dataloggers of most of the stations we have installed, which has provided a good subset of data over the period 2019–2021.

6.4 Impact of thermo-hydrological changes on lake level

The Tibetan Plateau (TP) has experienced significant hydrological changes in recent decades, including puzzling lake level variations. Besides the clear influence of precipitation shown in our large-scale work (Section 6.1), we hypothesize that climate-driven modifications of the ground thermal regime also contribute to lake level variations. This hypothesis has been largely overlooked by modelers due to the lack of field data and difficulty in accounting for the spatial variability of the climate and its influence on the ground thermo-hydrological regime in a numerical framework.

To test this hypothesis, the Utrecht University team conducted a study on the cryo-hydrology of the catchment of Lake Paiku in southern Tibet (Figure 29) from 1980 to 2019. We used TopoSCALE and TopoSUB (Fiddes and Gruber, 2014) to downscale ERA5 data and capture the spatial variability of the climate in our forcing data. We used the CryoGrid community model (version 1.0) in a distributed setup to quantify thermo-hydrological changes in the ground during the period (Westermann et al., 2016). To validate our results, we compared our forcing data and simulation outputs with weather station data, surface temperature logger data, and lake level variations that we acquired in our field campaign (Section 6.2).

Our study reveals that both seasonal frozen ground and permafrost have warmed at a rate of 1.7 °C per century (Figure 30), increasing the availability of liquid water in the ground and the duration of seasonal thaw. These phenomena promote evaporation and runoff, but ground warming drives a significant increase in subsurface runoff, resulting in an increase in the runoff/(evaporation + runoff) ratio over time. We also found that summer evaporation is an important energy sink, and active layer deepening occurs only where evaporation is limited. Our results suggest that the presence of permafrost promotes evaporation at the expense of runoff, consistent with recent studies. However, we also show that this relationship is climate-dependent, and a colder and wetter climate produces the opposite effect.

The ambivalent influence of permafrost may help to understand the contrasting lake level variations observed between the south and north of the TP, opening new perspectives for future investigations. Our study underscores the importance of accounting for the spatial variability of the climate and its influence on the ground thermo-hydrological regime in numerical models to improve our understanding of the impacts of climate change on mountainous regions.

A paper on this study is under second round of review. Initial submission is available online as preprint:

Martin, L.C.P., Westermann, S., Magni, M., Brun, F., Fiddes, J., Lei, Y., Kraaijenbrink, P., Mathys, T., Langer, M., Allen, S., Immerzeel, W.W., 2022. Recent ground thermo-hydrological changes in a Tibetan endorheic catchment and implications for lake level changes. *Hydrology and Earth System Sciences Discussions* 1–45.

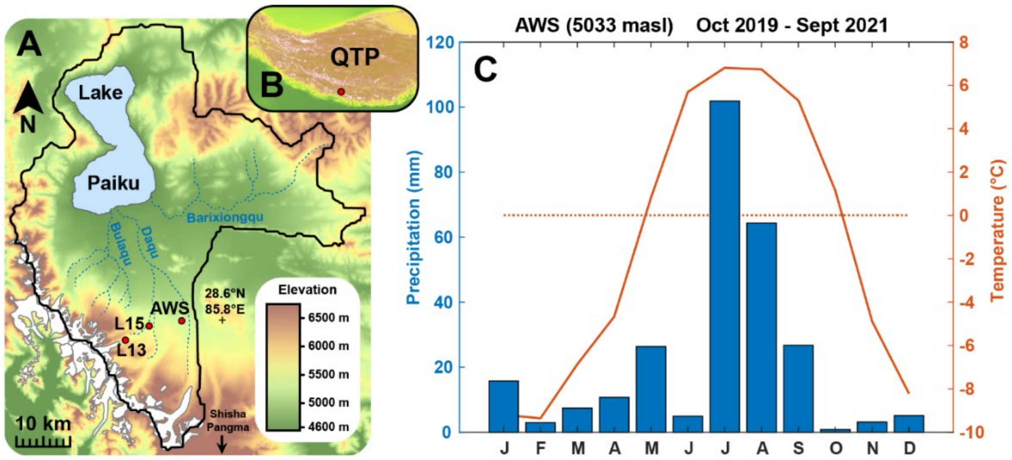

Figure 29: The Paiku Catchment. A: Topographic and hydrologic map of the catchment with the glaciers in white, the ephemeral rivers in dark blue and the lake in light blue. B: Localization of the catchment over the QTP. C: Monthly temperature and precipitation recorded at the AWS between October 2019 and September 2021.

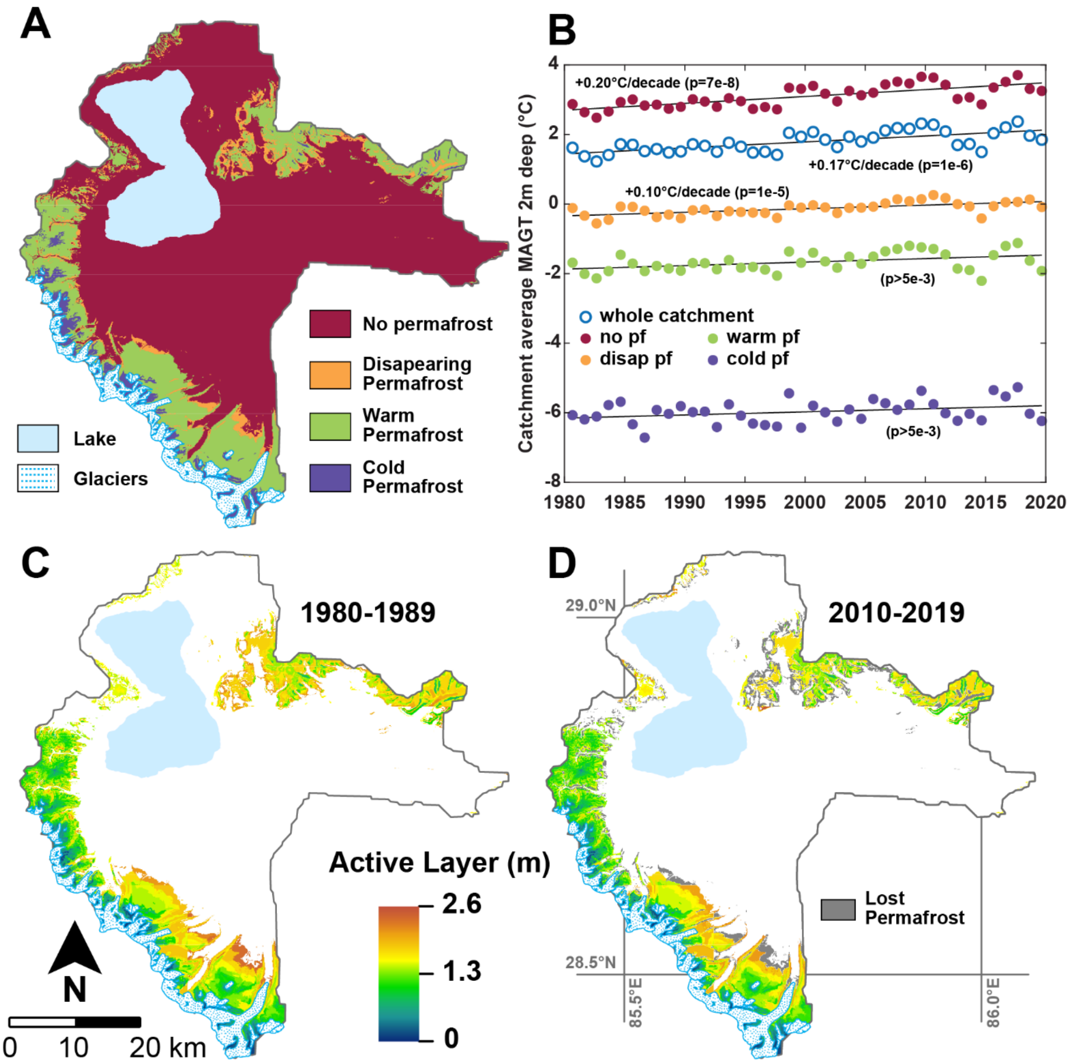

Figure 30. A: Different cryological states of the ground throughout the catchment for the 1980-2019 period (see Tab. 1). B: Annual 2 m deep ground temperature averaged for the whole catchment and for the different cryological states of the ground. C: Average active layer depth over the 1980-1989 period. D: Average active layer depth over the 2010-2019 period.

7. Streamflow from the Third Pole

The Third Pole is the source of many of the world's largest rivers, including the Indus, Ganges, and Brahmaputra, which provide water to millions of people downstream (Biemans et al., 2019; Immerzeel et al., 2020; Lutz et al., 2022). However, climate change is causing significant changes to the HMA region, particularly in terms of streamflow.

Recent studies have shown that climate change is causing increased temperatures and changes in precipitation patterns, which are leading to changes in streamflow in the region. Glacier melt and changes in snowmelt timing are altering the timing and magnitude of streamflow, which can have significant impacts on downstream communities, ecosystems, and water availability. Additionally, changes in streamflow and sediment transport can also impact hydropower generation, agriculture, and food security.

Despite the importance of understanding the impacts of changing streamflow in the river basins of the AWT, there are still significant gaps in our knowledge. One of the principal issues is that the effects of climate change on future meltwater contribution to streamflow and water supply across the region have been mostly reported for scattered river basins and catchments, in various studies relying on different approaches based on different data, thus hampering comparability (Armstrong et al., 2019; Biemans et al., 2019; IPCC, 2019; Kraaijenbrink et al., 2017; Lutz et al., 2014; Wijngaard et al., 2017). Addressing this issue is crucial to ultimately develop effective adaptation and mitigation strategies to manage the impacts of changing water supply in the region.

7.1 Asian Water Tower Model

7.1.1 Model setup

We have set up a large-scale distributed Spatial Processes in Hydrology (SPHY) model (Terink et al., 2015), dubbed the *Asian Water Tower Model* (AWTM) to conduct a comprehensive assessment of the present and future hydrology in the major river basins of the AWT. The SPHY model was developed by FutureWater to enable state-of-the-art simulations of cryospheric and hydrological processes and their interaction at large scale.

AWTM was set up at 5 km spatial resolution for the upstream basin areas, which includes glacier reserves of the water tower and most of its seasonal snowpacks. A threshold elevation of 2000 m was taken as a reference to divide the upstream and downstream areas (Figure 31). Further, we excluded the area downstream of the large man-made reservoirs using Global Reservoir and Dam Database (GRanD) (Lehner et al., 2011). The 1 km resolution HydroSHEDS digital elevation model (DEM) (Lehner et al., 2008b) was used to delineate the rivers in the region. Some manual adjustments were applied to the DEM to ensure correct river flow direction and basin delineation, particularly in the river basins of the Tarim, Alaguy and Ganges.

The outlets for the hydrological model for which we intend to calculate the hydrological trends later are created manually to ensure the entire upstream area that is covered by snow and glaciers is included for the basins. The HiHydroSoil 1 km database (Table 5) was used to obtain the soil properties such as hydraulic conductivity, field capacity, water content, dry and wilting point for the root and sub soil profiles.

We used Randolph Glacier Inventory 6.0 (RGI Consortium, 2017) to derive the glacier properties in the model. To prevent extreme computationally intensive model runs, we discard the glaciers with a surface area of less than 2 km^2 in our calculations, in line with Brun et al. (2017). A distinction between clean and debris-covered ice distinction is made according to a region-wide classification of 30 m resolution Landsat 8 satellite imagery (Kraaijenbrink et al., 2017). The ice thickness for the glaciers that we use are obtained from the most recent consensus estimate (Farinotti et al., 2019). The ERA5 historical precipitation (P) and temperature (T) data (ECMWF, 2017) were used to force the hydrological model.

To calibrate the AWTM, we implemented a three-step approach: (i) snow, (ii) glaciers and (iii) streamflow. Such an approach helps to ensure proper model calibration while minimizing equifinality issues that are often present in the mountain hydrology realm. We also filter for unrealistically high melt components from snow and glaciers in the water balance. Snow is calibrated in a first step by minimizing the difference between monthly snow persistence that results from the SPHY model run and that observed by MODIS (i.e. MOD10CM) for the period 2001–2017 (Hall and Riggs, 2015). We calibrate this by modulating a temperature bias value with respect to the ERA5 forcing data. This ensures that our modelled snow seasons optimally match observations on the grid cell level. In the second step, we calibrate the temperature bias grid for glacier pixels only, forcing the bias with consistent region-wide mass balance observations for the period 2000–2016 (Brun et al., 2017). This ensures proper behavior of the glaciers and their imbalance. In the last step, i.e. streamflow calibration, we will modulate discharge related parameters in the model to calibrate to river runoff data optimally.

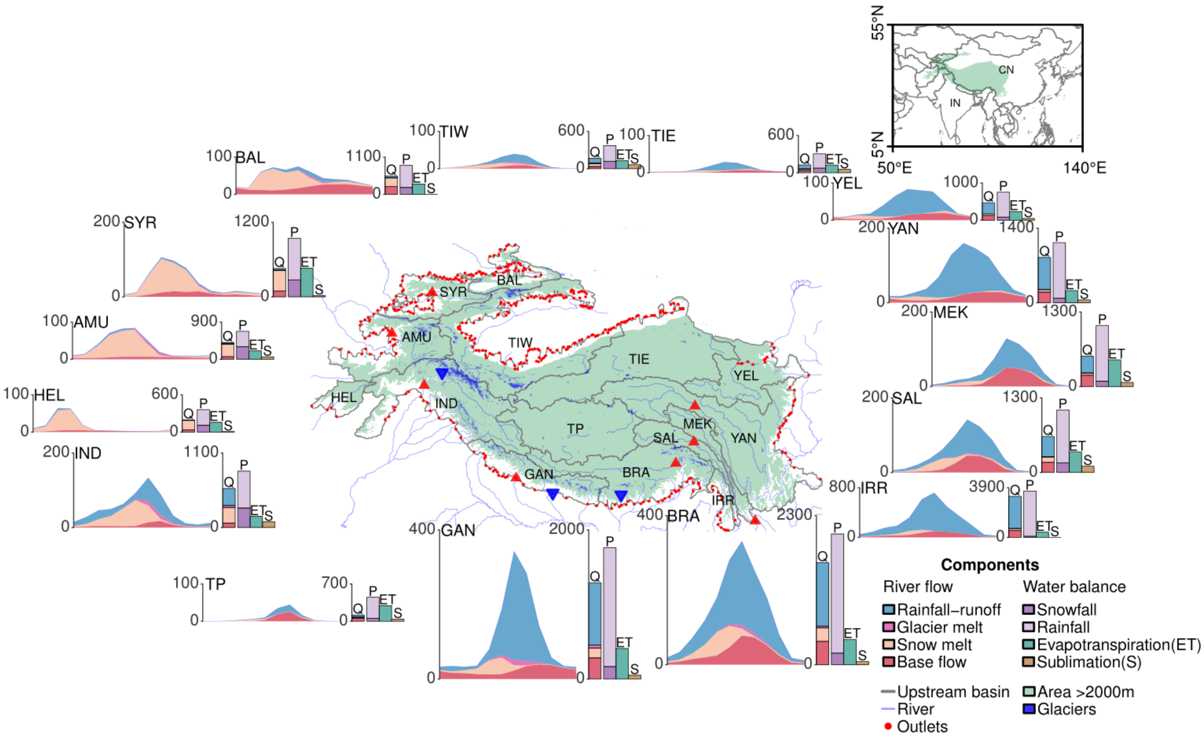

Figure 31. The upstream mountainous basins of HMA analyzed in this study (grey boundaries). The dark green color represents the area above 2000 m in the region. The stacked polygons on the left show monthly average discharge (Q, in mm a^{-1} from January to December) contributed by baseflow (red), snow melt (orange), glacier melt (magenta), rainfall runoff (blue) for the reference period (1985-2014). The first stacked bar plot shows the average annual contributions of discharge components, while the second bar plot shows the average annual precipitation (P) falling as rain (light purple) and snow (purple). The third bar plot (light green) shows the average annual actual evapotranspiration and the fourth bar plot the average annual sublimation (brown). The red triangles in the geographical map represent the station locations used for the calibration and validation of streamflow. The blue downward triangles represent the station locations where independent validation to observed discharge is performed. Note the difference in vertical scale for each of the catchments.

7.1.2 Gathered datasets

To accommodate our analyses and facilitate our hydrological model, we have gathered various datasets. To obtain better model results we continue data collection to construct a reliable and spatially comprehensive discharge data collection.

Table 5. Notable datasets collected for the studies within the QWATOW project.

Data	Source	Resolution	Time period
DEM	SRTM (Farr et al., 2007)	30 m	2004
	Hydrosheds (Lehner and Grill, 2013)	1 km	2005
Soil properties	https://www.futurewater.eu/2015/07/soil-hydraulic-properties/	1 Km	2015
Land use / land cover	ESA CCI land cover (ESA, 2017)	1 Km	1992– 2015
Glaciers			-
Outlines	Randolph Glacier Inventory v6 (RGI Consortium, 2017)	-	2017
Classification	Kraaijenbrink et al. (2017)	30 m	-
Mass balance	Brun et al. (2017)	-	2001–2016
	Shean et al. (2020)	-	2000–2018

Snow			
Cover	MOD10CM & MOD10A1 (Hall and Riggs, 2015)	5 km	2002–2018
Depth	Lievens et al. (2019)	1 km	2016–2019
Forcing	ERA5 (ECMWF, 2017)	25 km	1979–2019
	CMIP6 (Eyring et al., 2016)	variable	1850–2100
Discharge			
Devghat (Ganges)	DHM, Nepal	daily	1979–2014
Chisapani (Ganges)	DHM, Nepal	daily	1979–2008
Chatara (Ganges)	DHM, Nepal	daily	1979–2007
YANGCUN (Brahmaputra)	GRDC		
Toktogul inflow (Syr Darya)	CAWATER database	10 days	2001–2010
Nurek inflow (Amu Darya)	CAWATER database	10 days	2001–2010
Tarbela inflow (Indus)	IMWI Pakistan/WAPDA	daily	1990–2015
Xia La Xiu (Mekong)	GRDC	daily	1982–1987
ZHIMENDA (Yangtze)	GRDC	daily	1979–1997
LUNING (Yangtze)	GRDC	daily	1981–2000
HUANGHEYAN (Yellow River)	GRDC	daily	1979–1997
MINHE (Yellow River)	GRDC	daily	1979–1997
WUSHAN (Yellow River)	GRDC	daily	1979–1997
SARYTOGAI (Lake Balkash)	GRDC	daily	1979–1987

7.2 Asian Water Tower streamflow under future climate change

To robustly assess climate change impacts on the 21st century water supply in the entire Third Pole region, the FutureWater team has used their calibrated high-resolution model AWTM (Section 7.1) covering fifteen basins (Figure 31) to quantify the compound effects of future changes in precipitation and temperature.

To simulate future climate for our future AWTM runs, we use a “bottom-up” approach (e.g. Garcia et al., 2014). In contrast to the top-down methods, bottom-up approaches start in the vulnerability domain (Figure 32). Such a method is particularly useful as a vulnerability-oriented approach, and it limits the large overhead of performing separate model runs for many climate model realizations.

To generate transient future forcing from 2015 to 2100 for the entire region for a set of combinations of precipitation (P) and temperature (T) changes, we first established an end-of-century (2100) range of ΔP factors and ΔT values. The range for these delta changes were determined from the most recent set of General Circulation Models within CMIP6 (Eyring et al., 2016). Several studies have investigated the projected change in precipitation and temperature in the Asian and Tibetan plateau region with the available CMIP6 models (Almazroui et al., 2020; Na et al., 2020). The projected changes, based on a 27 CMIP6 model ensemble, of precipitation (ΔP) and temperature (ΔT), for the far future (2080 to 2099) over the entire South Asian region range from 3 °C to 7 °C and +15% to +40%, respectively (Almazroui et al., 2020). As some GCMs have indicated a potential decrease in precipitation in certain regions, we extended our range of ΔP accordingly to -30% to 40%. To study potential additional increases in T, we extended our range of ΔT to 3–8 °C.

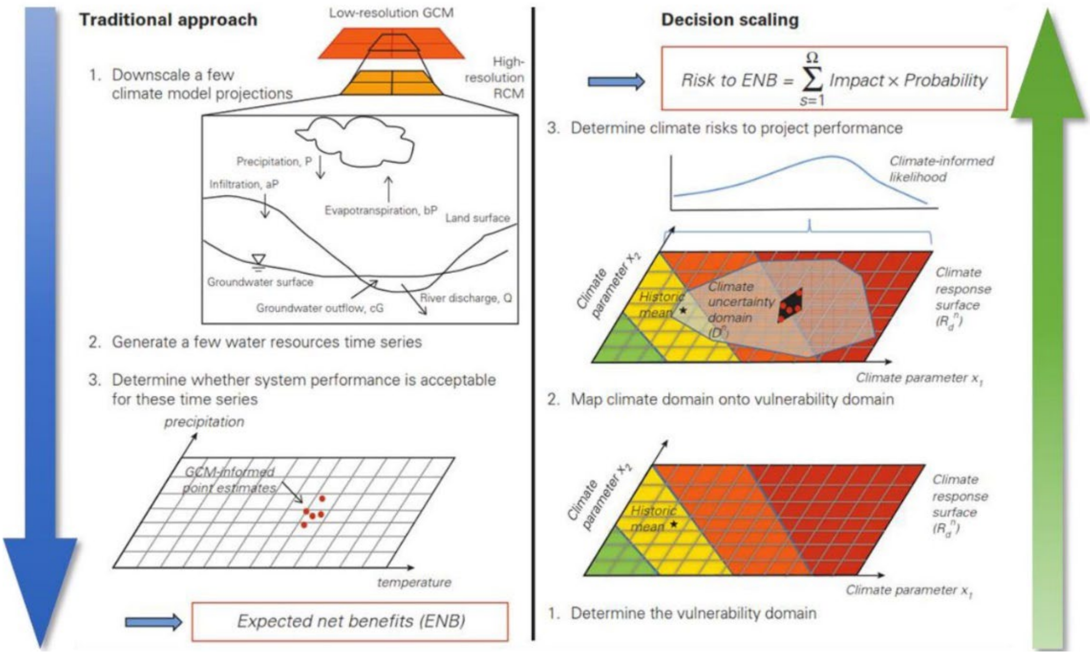

Figure 32: Top-down versus bottom-up risk assessment (Garcia et al., 2014).

The ranges, with an increment of 1 °C for ΔT and 10% for ΔP, expand into 48 different combinations of future climate change. The ΔT and ΔP in each combination were assumed to increase linearly between the start of the century (2015) and the end of the century (2100). Individual years of ERA5 data over the 1979–2018 ERA5 period were sampled randomly without replacement in three consecutive blocks of 40 years each to generate a sequence of 86 (2015–2100) random years. The linear change in climate is then superimposed on the sampled reference years, to generate the transient future forcing that is used to drive the calibrated AWTM.

Model results indicate that the hydrological regime of the western basins (Amu Darya (AMU), Syr Darya (SYR), Helmand (HEL), Balkash (BAL) and Indus (IND)) are dominated by snow melt processes). This snow melts in spring and summer and contributes to the flow when temperature is above freezing point (Figure 31). In AMU (46%), SYR (30%), HEL (31%), IND (36%) and BAL (25%), a considerable amount of annual *P* falls as snow. These basins are also characterised by vast glacierised areas in the upper high elevation regions, particularly in IND (4.77 %). The hydrological regimes in these basins are dominated by snow and glacier melt and characterised as glacio-nivial hydrological regimes. Conversely, the hydroclimate in southern (Brahamaputra (BRA), Ganges (GAN)) and interior basins (Plateau of Tibet interior (TP), Tarim Interior East (TIE) and Tarim Interior West (TIW)) is dominated by the Indian monsoon and is dominated by rainfall runoff. The large amount of monsoonal precipitation over GAN explains the relatively small contribution of melt to streamflow (13.8%) despite having a relatively large area covered by glaciers (3%). The endorheic basins on the interior of the Tibetan Plateau (TP) show a stronger monsoonal *P* pattern than other basins around the Himalayan arc. Even though the average elevation of TP is above 4500m, only 12% of annual *P* falls as snow in the region since most *P* falls during summer when *T* is above 0 °C even at such a high altitude. Consequently, a rainfall runoff regime, with 93% of the total annual flow occurring during the monsoon, is prevalent in the region. The hydrological regimes in southern and interior basins are dominated by rain with some contribution from snowmelt and thus characterised as nivio-pluvial hydrological regimes. A similar rainfall runoff dominated regime can be seen in the wet eastern HMA river basins (Yellow (YEL), Yangtze (YAN), Mekong (MEK), Salween (SAL) and Irrawaddy (IRR)). There is relatively small contribution from snow melt and almost insignificant glacier melt in these basins. Therefore, the hydrological regime of eastern basins is characterised as pluvial.

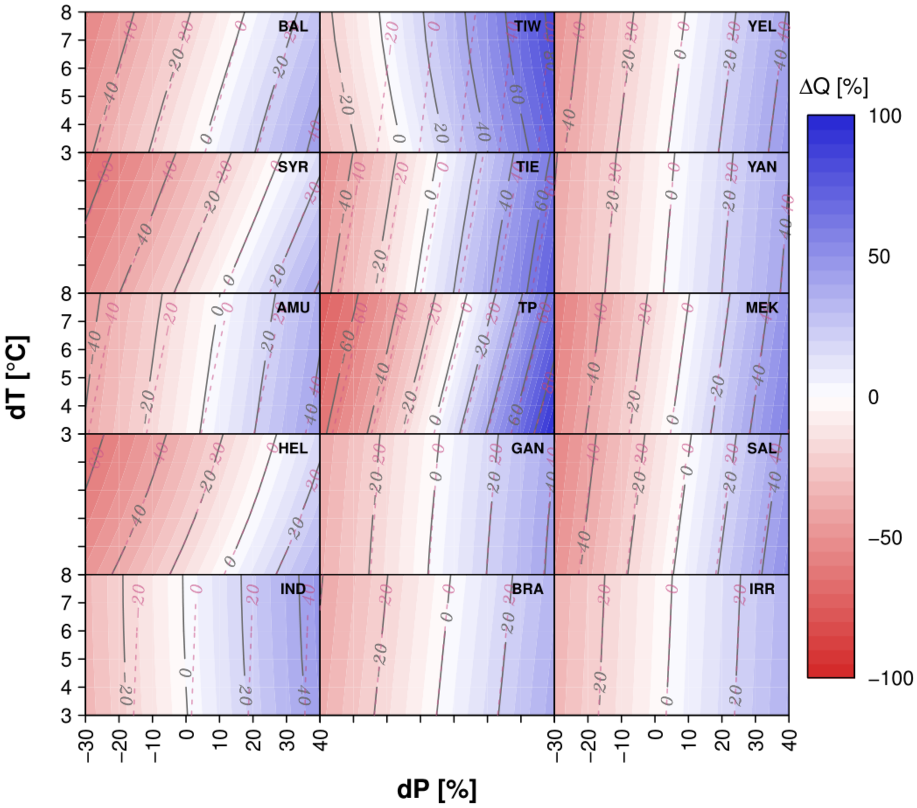

Figure 33: Relative change in total water supply for the end of the century period (2071–2100), expressed as the change in total annual mean discharge normalized by the value in the reference period (1985–2014). The dotted red contours represent the water supply change for a scenario run without glaciers. The horizontal and vertical axes represent the percentual change in precipitation and absolute change in temperature, respectively.

The total water supply in each region shows a strong sensitivity to changes in P (Figure 33). It is dominated by the rainfall runoff, which is positively correlated to P. In the western basins (e.g. AMU, HEL, SYR and BAL) a sensitivity to dT is also evident, which we attribute to the melt-dominated hydrological regime. Similar sensitivities are observed in the interior and northern basins. In contrast, Eastern and Southern basins (e.g. BRA, GAN, IRR, YAN and YEL) show almost no response to dT, because of a relatively small meltwater contribution to discharge in the monsoon-dominated basins. Results illustrate that the compound effect of changes in P and T in the future without glaciers has a larger impact on the water supply (Figure 33).

Changes to the water supply in case of glacier melt are predominantly found on longer time scales (i.e. multiple decades), whereas changes in rainfall runoff and snowmelt have a nearly immediate effect on streamflow. In a scenario in which we test the effect of glacier melt on total streamflow by omitting them from the model, we find that primarily in the western, northern, and interior basins glaciers are of importance and provide an important long-term buffering effect. The change to faster responding snow and/or rainfall runoff instead of slow and more gradual melt contribution from ice reserves as a result from glacier decline is a primary reason for the decrease in total water supply in those regions. Tarim Interior West, with having a large glaciated area, shows the largest difference. The monsoon dominated southern and eastern basins, show almost no change in total water supply in the future. It is mainly due to insignificant glaciated contribution and the dominance of the rainfall runoff regime.

This study has been published in *Water Resources Research* in 2021:

Khanal, S., Lutz, A.F., Kraaijenbrink, P.D.A., Hurk, B. van den, Yao, T., Immerzeel, W.W., 2021. Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at Seasonal to Decadal Time Scales. Water Resources Research 57, e2020WR029266.

7.3 Understanding change through sediment

The sediment flux of a river is important for transport of nutrients and pollutants and provides a key indicator of land degradation and environment changes. With climate change impacts in the Third Pole on the rise, particularly on the environmentally sensitive Tibetan Plateau, it is important to understand (changing) sediment fluxes coming from the region. In an effort to perform a first quantification of the variability and changes in sediment influx over the last decades, Utrecht University team member Prof. Dr. Walter Immerzeel has collaborated on a project led by Prof. Dr. Fan Zhang (ITP). In the project, the sediment fluxes over the last 30 years in the Tuotuo River, which forms a part of the upper reaches of the Yangtze River, have been analyzed (Zhang et al., 2020).

Annual time series of hydro-meteorological variables during 1986–2014 indicate significantly increasing trends of air and ground temperature, precipitation, discharge, suspended sediment concentration, and the total sediment flux (Figure 34). Double-mass plots indicated that both meltwater and rainfall contributed to the increased river discharge, while the increased sediment flux was mostly the result of increased erosive and transport capacity that follow from the increased discharge. Sediment flux was, however, buffered due to a decrease in sediment source that was the result of a shift of maximum monthly rainfall from June/July to July/August, which is a period with denser vegetation cover that prevents soil erosion (Zhang et al., 2020).

The study provides important insights into the controlling processes for sediment flux changes and gives guidance for water and soil conservation on the Tibetan Plateau and beyond, and reiterates that understanding the entire system follows from understanding its individual components.

The study was published in *Science Bulletin* in March 2020:

Zhang, F., Shi, X., Zeng, C., Wang, L., Xiao, X., Wang, G., et al. (2020). Recent stepwise sediment flux increase with climate change in the Tuotuo River in the central Tibetan Plateau. *Science Bulletin* 65, 410–418.

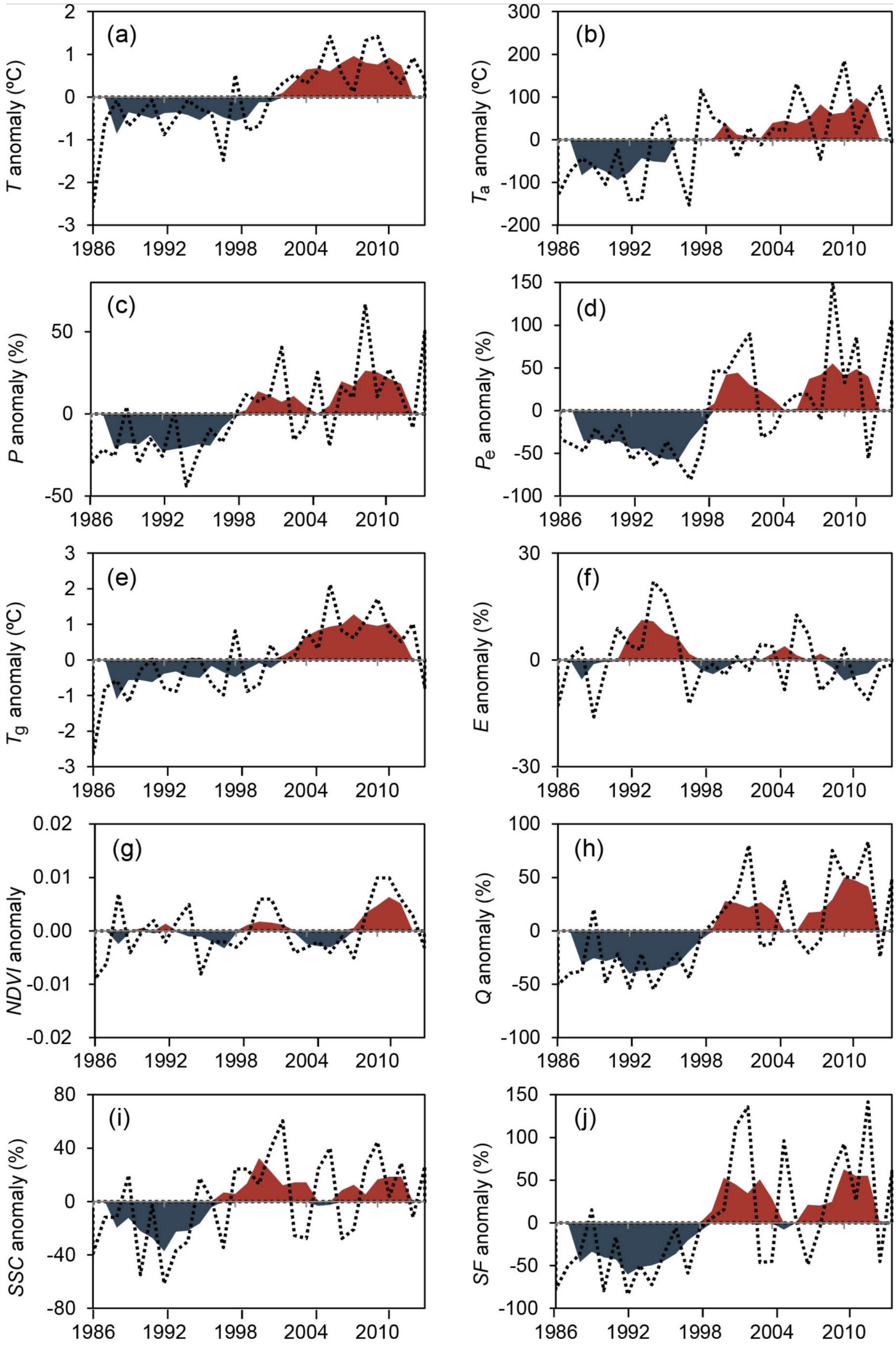

Figure 34: Time-series (1986–2014) of the Tuotuo River Catchment. (**a**) Air temperature (T); (**b**) accumulated positive temperature (Ta); (**c**) precipitation (P); (**d**) erosive precipitation (Pe); (**e**) ground temperature (Tg); (**f**) potential evaporation (E); (**g**) NDVI; (**h**) discharge (Q); (**i**) suspended sediment concentration (SSC); (**j**) sediment flux (SF). The dashed line represents the anomaly value; the red and blue shaded areas represent the positive and negative parts of a 5-year moving average, respectively.

8. Impacts of a changing mountain water supply

Population and economic growth in the Third Pole region will lead to increasing demands for water for agricultural, domestic, and industrial use. Changes in water supply and water demand are closely inter-linked and insufficient supply would hamper socio-economic development. On the other hand, changes in socio-economic development can severely affect the water demand and availability across sectors and thus many complex feedback systems exist in this domain.

8.1 AWT water supply and demand, a hydro-socio-economic perspective

To properly assess future changes in water demand we have commenced development of a model that will use both existing and novel socio-economic concepts and its feedbacks with the local water balance. Our vision is a model that:

- Has (online or offline) coupling with the (output of the) hydrological Asian Water Tower Model (Section 7.1; Section 7)
- Fits within the novel and promising natural-social interface model concept recently devised by Prof. Xiaoming Wang (State Key Laboratory of Cryospheric Sciences, Lanzhou, China) at the International Workshop on AWT (section 9.3)
- Can model cascading socio-economic effects that transcend the interface between the natural and social domains
- Integrates well with the Shared Socio-Economic Pathways (SSPs) (Riahi et al., 2017)
- Focuses on changes that happen in economic corridors of the Belt and Road Initiative (BRI) such as the Silk Road Economic Belt (SREB) (Figure 35), within their economic range of influence, or in their range of hydrological dependence (Figure 36)

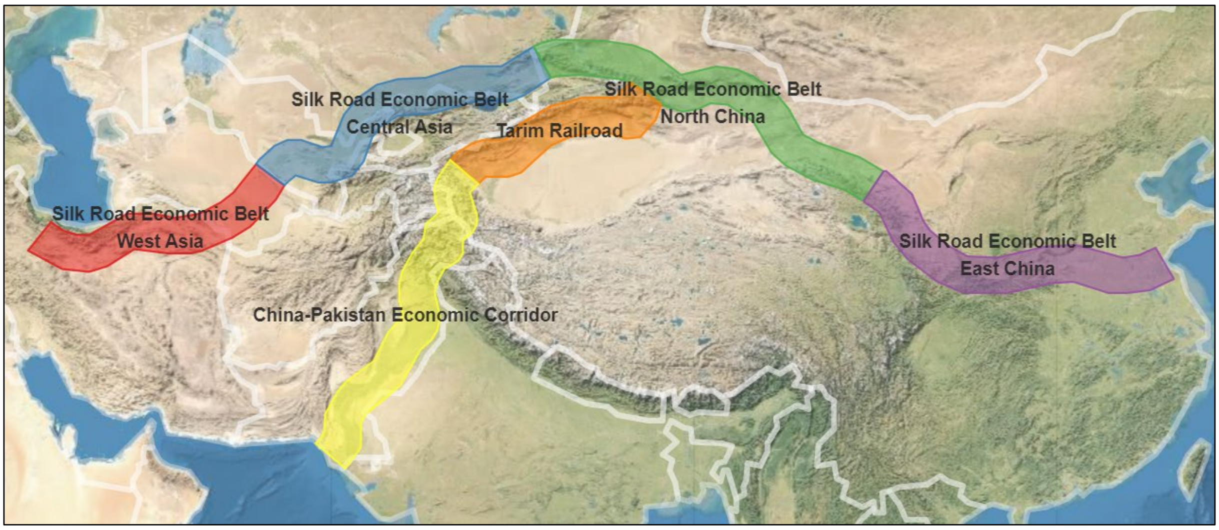

Figure 35: Map of the various economic corridors in the AWT region associated to the Belt and Road Initiative.

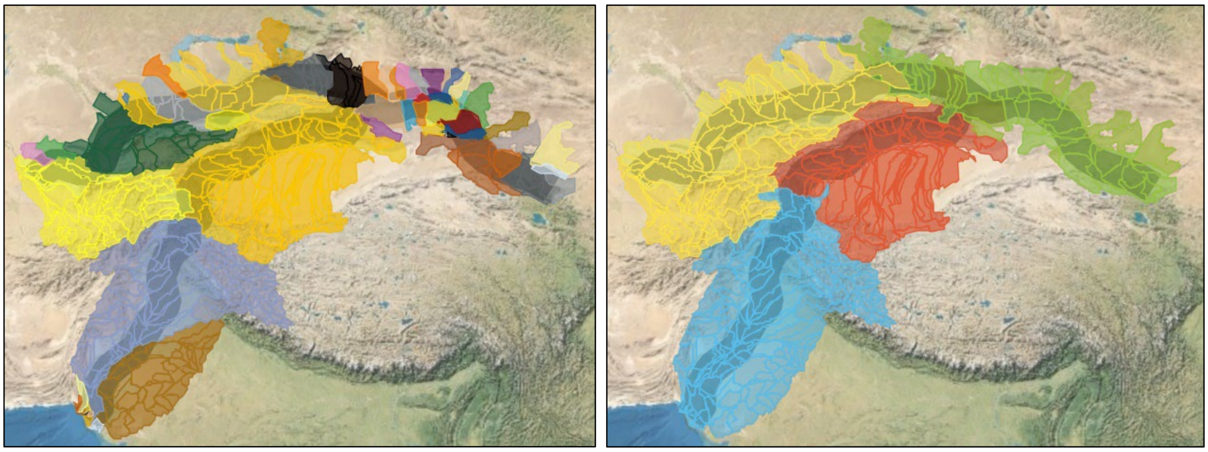

Figure 36: Map of hydrosheds subbasins (Lehner and Grill, 2013) that intersect or are upstream of the economic corridors in the AWT region that associated to the BRI. Fill colors show the main river basin to which the subbasins belong (left) or the specific economic corridor (right) (Figure 35).

To have optimal model performance, we utilize SSP data that was downscaled using China-specific datasets and policies by the research team led by Prof. Xiaoming Wang (Figure 37). If necessary, we will take effort to downscale them further to tailor them to the specific needs of our model and the QWATOW project goals. For example, spatiotemporal sets of e.g. population, gross domestic product (GDP), irrigation and industry could be produced using a spatial allocation modelling strategy, similar to an approach developed in a joint project by Wageningen University and Utrecht University in which our team is involved. Such downscaling could be driven by future narratives of socio-economic development that are linked to the SSPs (or SSP-RCP combinations), but tailored specifically to future potential developments related to the BRI's economic corridors. This would allow better integration of this study in WP4, as more region-specific model outcomes would improve our capability to devise effective adaptation strategies.

Using our model concept, we can determine the locations where and sectors in which economic growth could/should optimally be focused as to not reach the local ceiling of cryospheric water supply (Figure 38).

This allows us to provide narratives and adaptation strategies that yield green development (WP4), while retaining optimal economic growth. Specific focuses are infrastructural and urban developments within the economic corridors of the AWT region and optimal allocation of agriculture and industry. Direct or indirect coupling between water demand estimations and the hydrological model allows upstream water withdrawals to affect the downstream regions.

To determine indirect economic effects of changes in cryospheric water availability on entire countries, the results of the different scenarios or narratives of spatiotemporal changes in population, GDP, agriculture, and industry within the area of a country that is directly affected by the AWT water supply are extrapolated. To do so, smart connections and feedback systems between the direct and indirect parts are developed/parameterized. This is the expertise of Prof. Xiaoming Wang and we strongly collaborate with him and his research team on this part. Unfortunately, the progress on this study and the collaboration with Prof. Xiaoming Wang has experienced delays and is not yet finished. The COVID-19 pandemic enforced travel and office restrictions, making the (collaborative) efforts on this subproject difficult to sustain in full.

Nevertheless, beyond the QWATOW project, we intend to continue our collaboration and modelling efforts aimed at properly assessing changes in water availability by coupling (upstream) natural systems and (downstream) socioeconomic systems. At present, this specific concept requires further development and the integration of other modelling procedures and datasets.

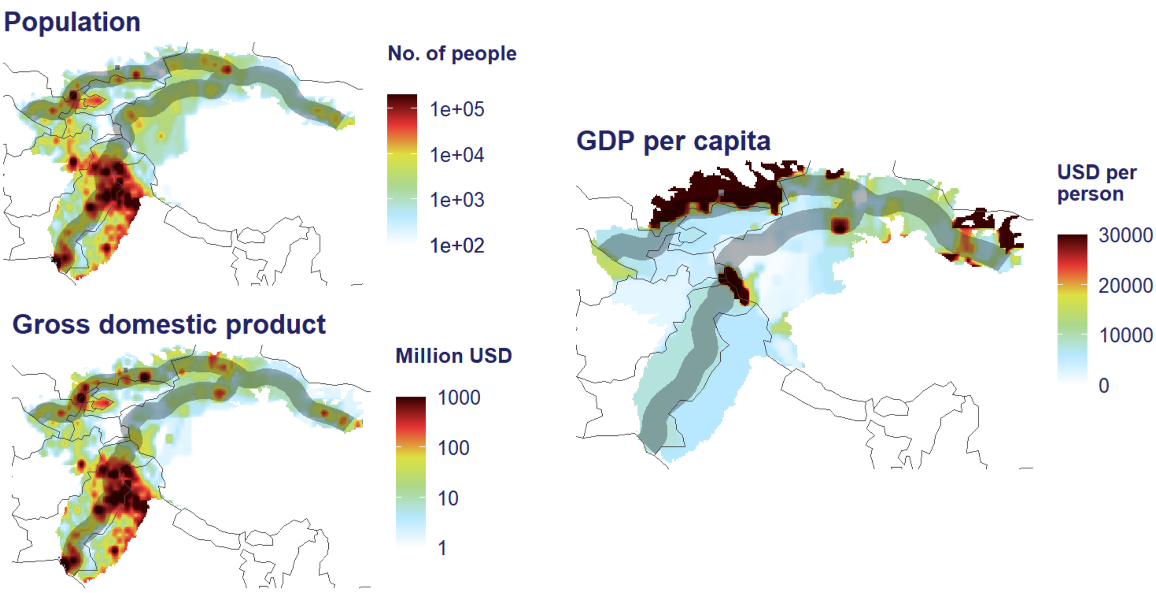

Figure 37: Population and GDP in 2010 from downscaled SSPs in the AWT subbasins associated to BRI's economic corridors (Figure 35), produced by researches from the State Key Laboratory of Cryospheric Sciences of the Chinese Academy of Sciences.

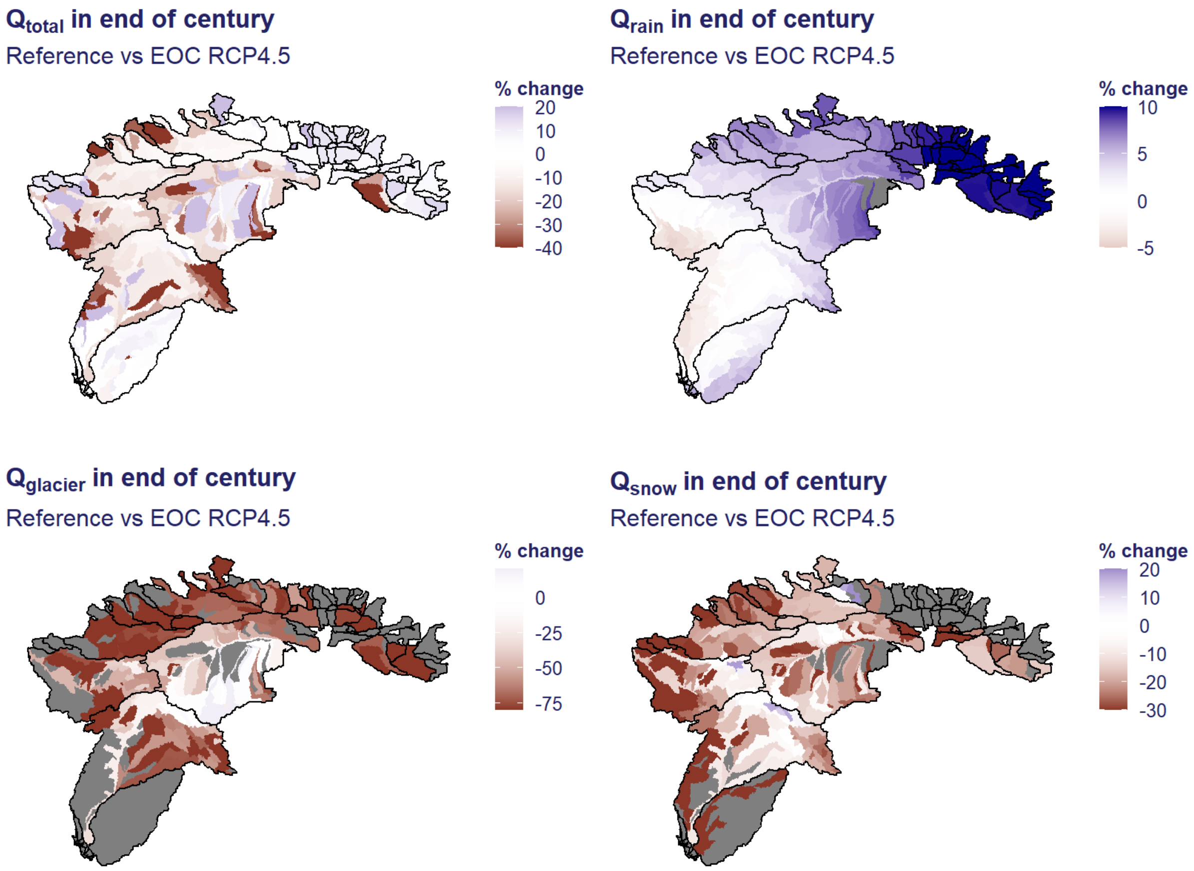

Figure 38: Example projections of future changes in discharge contributions under RCP4.5 for AWT subbasins associated to the BRI. These estimations are based on projections made in the QWATOW project (Section 4; Section 4.2; Section 7).

8.2 Impacts of physical changes on Asia's cryospheric economies

Many countries that intersect or surround the AWT are strongly dependent on meltwater from the cryosphere and their economies rely on the availability of this water. Climate change induced changes to the system, such as more frequent droughts, overall warming and shifts in precipitation patterns can affect the cryosphere and its water supply, thereby threatening future socioeconomic development. The BRI intends to connect landlocked economies in Northwest China and nations in the AWT regions to the global economy. Under the initiative, coordinated approaches are developed that address the interconnected natural and socioeconomic mountain systems as well as potential cascading effects of changes in the natural (cryospheric) system to downstream regions. For optimal effect of the BRI, it is crucial to explore the full potential of sustainable use of cryospheric water resources.

To inform the scientific community and the public on the state, processes, and possible feedbacks between the cryosphere of the AWT and the economies of nations downstream, and to spark discussion on this topic among scientists, the Utrecht University team has collaborated with Prof. Xiaoming Wang on a perspective article for a high-impact scientific journal. The perspective follows from discussions and brainstorm sessions that were held at the International Workshop on AWT in Beijing in July 2019 (section 9.3).

The key point brought forward in the perspective is the importance of cascading effects of the cryosphere on socioeconomic systems with feedbacks through cascading series of effects of anthropogenic activities on natural systems. Effects of cryosphere contributions are mostly related to (changes in) meltwater affecting natural and socioeconomic systems either directly or by cascading into the system indirectly along a series of socioeconomic relational chains. Effects of anthropogenic activities (potentially influenced by cryospheric changes) can impact natural systems directly or indirectly, and may also affect the AWT cryosphere.

Prof. Wang has, with input from Prof. Walter Immerzeel and Dr. Philip Kraaijenbrink, drafted the perspective piece and we have inquired at several journals for their interest. The novel high-impact journal One Earth showed interest, but its perspective articles are intended to "*identify a specific problem or knowledge gap with broader relevance, and propose an approach, framework, model, or case study with demonstrable potential to address this problem or gap in future research*". We were therefore asked by the editor to extend our perspective with a demonstrable potential. To this end, we now intend combine this perspective with (part of) our analysis and developed concepts (Section 8.1), model output of the AWTM (Section 7.1 and Section 7.2), and with additional economic system modelling that is currently being performed by Prof. Xiaoming Wang and the socioeconomic modelers from his group. We expect continued output and collaboration on this front over the coming years.

9. Workshops and meetings

9.1 Lhasa kick-off meeting

From 5 to 8 September, Walter Immerzeel and Arthur Lutz have attended the forum on Pan-TPE program and The Second Tibetan Plateau Scientific Expedition, which was held in Lhasa, China. At the forum, Walter Immerzeel presented an overview talk that touched upon past and recent scientific advances in studying the Asian Water Tower, and subsequently presented his plans and insights for the Pan-TPE project *Quantifying Changes in the Pan-Third Pole Water Tower and Impacts for a Green Silk Road*. Arthur Lutz has presented his views on ways to go towards sustainable future water strategies for the Third Pole region. They both spoke with high-profile scientists and politicians about the planned work as well as other related topics.

9.2 AGU Fall Meeting 2018

In December 2018, Walter Immerzeel and Philip Kraaijenbrink attended the Fall Meeting of the American Geophysical Union in Washington, DC. Walter Immerzeel presented our advances in studying snow in the Pan-TPE region in the session *The Third Pole Environment (TPE) Under Global Changes* chaired by Prof. Tandong Yao. Philip Kraaijenbrink presented his work on UAV monitoring of debris-covered glaciers in Nepal (Section 4.4), and provided a lightning talk on the results of his PhD thesis.

At the AGU Fall Meeting Walter Immerzeel was awarded the prestigious James B. Macelwane medal for his significant contributions to geophysical sciences as early career scientist. In light of this medal, he was also invited to talk about his views on the multi-scale exploration of Asia's Water Tower.

9.3 International Workshop on the Asian Water Tower

On July 11–12, 2019, Walter Immerzeel and Philip Kraaijenbrink took part in the International Workshop on the Asian Water Tower. At this event held in Beijing with about 40 participants, among which were both international and Chinese scholars and students, both Walter and Philip presented the progress within the Pan-TPE project in two separate presentation. That is, climate indicators and hydrological modelling, and large-scale analysis of snow, respectively.

The second day breakout sessions provided ample possibilities to discuss the status quo in different research topics, and pinpoint research gaps and future goals within the different research fields with respect to Third Pole research. There were hotspot regions identified as super sites where research should be intensified in the (near) future.

Furthermore, during the breakout sessions, a clever new modelling concept has been pitched by Dr. Xiaoming Wang (Lanzhou University), which provides a way to look at the intersection between natural systems and socio-economic systems and the cascading impacts and/or effects that may occur beyond the interface of the two systems. In a collaboration between Xiaoming Wang, Walter Immerzeel and Philip Kraaijenbrink, a perspective piece aimed at a high-impact journal was written that introduces this novel concept together with a first implementation (Section 8.2).

9.4 AGU Fall Meeting 2019

Walter Immerzeel and Philip Kraaijenbrink attended the AGU Fall Meeting in San Francisco in December 2019. During the conference, the water tower study was published in *Nature* and Walter Immerzeel gave several presentations, a press conference, and an interview. For more information on the outreach of this study see Section 10.1. Besides the water tower study, he presented the progress on our Tibetan lake study (Section 6) in the Third Pole Environment session at AGU (Figure 39; also see this post on TPE website). Philip Kraaijenbrink presented the advances regarding our study on the past, present and future changes in snow (Section 4).

Figure 39: Prof. Walter Immerzeel delivering invited keynote at AGU Third Pole Environment session in 2019.

9.5 Dutch Earth Sciences Conference

We intended to visit the Dutch Earth Sciences Conference (NAC), which was held in the city of Utrecht, close to Utrecht University. Philip Kraaijenbrink intended to present the advances regarding our study on the past, present and future changes in snow using a poster (Section 4). Unfortunately, the conference was cancelled last minute due to COVID-19-related government limitations on the amount of people allowed at a gathering.

9.6 EGU General Assembly 2020

Initially planned as an on-site event in Vienna, the COVID-19 pandemic forced the EGU General Assembly of 2020 to be held completely virtually, online. Philip Kraaijenbrink was invited by Prof. Fan Zhang to give a solicited oral presentation on the results of the snow study in the Pan-Third Pole environment session hosted at the conference. With great regret of not being able to present orally in the session, Philip has presented his work in the form of a digital poster during the online event.

9.7 EGU General Assembly, ICIMOD CryoForum & AGU Fall Meeting 2021

Dr. Léo Martin virtually attended three conference in 2021: the EGU General Assembly, the ICIMOD CryoForum and the AGU Fall Meeting of 2021. At all of these conferences he presented his work on recent ground thermo-hydrological changes in a Tibetan endorheic catchment and its implications for lake level changes (Section 6.4). Due to limitations imposed by COVID-19 restrictions across the world, other QWATOW team members have not attended any conferences in 2021.

10. Outreach

10.1 Press coverage of water tower paper

Our paper on the world's water towers (Section 2.1) (Immerzeel et al., 2020) has been published in *Nature*, and as such has received considerable scientific and societal attention. The study was published at the time of the AGU Fall Meeting of 2019 and a press conference was held there, because of the high impact of this study and close collaboration with the National Geographic Society. As a result, over 57 news outlets around the globe have picked up the story. Moreover, people have shared and commented on the paper on social media, on various blogs, leading to respectable altimetric score of 505 (Figure 40). A video recording of the press conference can be viewed at:

https://www.youtube.com/watch?v=wTktEfKXz-M

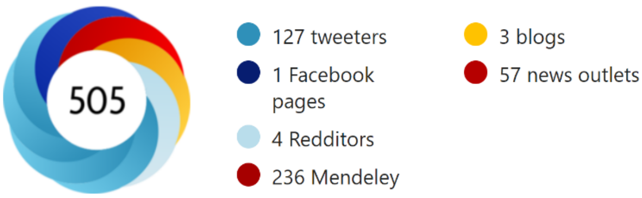

Figure 40: Our water tower article is in the 99th percentile (ranked 894th) of the 365,317 tracked articles of a similar age in all journals and the 88th percentile (ranked 95th) of the 811 tracked articles of a similar age in *Nature*.

Additional to the press conference and scientific presentation given at the AGU Fall Meeting by Prof. Dr. Walter Immerzeel, he was invited to give an "Ignite talk" (http://www.ignitetalks.io/) at the headquarters of famous Remote Sensing company *PlanetScope*. The talk was recorded and is expected to be published online in the future.

The close collaboration with National Geographic resulted in more outreach for this study trough their channels. On their *perpetual planet* website, built in collaboration with Rolex, National Geographic has hosted an interactive map of the main results of the paper. It can be found at:
https://nationalgeographic.org/water-tower-index/

Furthermore, the entire July 2020 issue of their magazine was devoted to mountain resources and research, and included a story and custom-made graphics and maps for our water tower story. Available at:
https://www.nationalgeographic.com/magazine/2020/07/asias-vital-rivers-perpetual-feature/

10.2 Press coverage of snow change paper

Our paper in *Nature Climate Change* on the climate change impacts on Asia's snow packs has been received well, yet press coverage was not as high as expected. Nevertheless, the paper achieved a respectivble altimetric score of 71 and was featured on several news outlets and blog posts. The UK-based influential website Carbon Brief interviewed Dr. Philip Kraaijenbrink about the study and this resulted in an interesting article on their website:
https://www.carbonbrief.org/climate-change-has-driven-16-drop-in-snow-meltwater-from-asias-high-mountains/

10.3 QWATOW video documentaries

During the project, we have worked with Dan Brinkhuis of *ScienceMedia* to produce two short documentaries on the work that the Utrecht University teams performs within the QWATOW project. We have worked together with Dan Brinkhuis on previous documentaries and we have found them to be well-received and of positive effect. For an example of the productions he has made for us prior, please refer to the "Monitoring Himalayan Glaciers" and "Water, from NL to HMA" videos that can be found at:
http://mountainhydrology.org/outreach/

Although the COVID-19 pandemic has resulted in significant delays with respect to documentary production, both 4-minute documentaries have now been published under the "Modelling the Future" series.

10.3.1 Climate change impacts on snow

The first documentary in the series was on our study on changes to the water resources across the entire Third Pole region and what that means for downstream water supply (Kraaijenbrink et al., 2021) (Section 4; 8). Documentary synopsis:

The high mountain regions of Asia provide an important source of water for the populated downstream areas. In the Pan-Third Pole Environment project Utrecht University works on understanding the large-scale impacts of climate change on the region's water supply, and on the impacts of socioeconomic development on water demand. In this video researcher Philip Kraaijenbrink explains how large-scale remote sensing and modelling tools are used to do this.

The documentary can be viewed at: https://youtu.be/f04wy8Y9lNY

Figure 41: Screenshots of the documentary about the impacts of climate change on snow packs in the AWT region.

10.3.2 Causes of changes in Tibetan lakes

The final documentary of the series focuses on the large scale and catchment scale work performed in the QWATOW project related to Tibetan lake level changes (Brun et al., 2020; Martin et al., 2022) (Section 6). Documentary synopsis:

The Tibetan Lakes keep on growing. Most of these lakes are not connected to river systems, which makes scientists wonder why they have been growing. At Utrecht University, a team of scientists explain how they use data analysis to explain the growing lakes. In this video researchers Fanny Brun and Leo Martin explain how they try to answer this question.

The documentary can be viewed at: `https://youtu.be/PgyIqmqoI-0`

Figure 42: Screenshots of the documentary about the changes in Tibetan Lakes.

10.4 Mountain Hydrology website

Philip Kraaijenbrink has renewed the website of Utrecht University's Mountain Hydrology group, which is led by Walter Immerzeel. This website is intended as our team's business card and provides an account of the research that we perform in the group and events that we attend. We also post our progress on the QWATOW project here. Content on the website varies from research summaries, interactive plots and maps, background stories and more. The website can be found at:

`http://mountainhydrology.org/`

11. Trainings

Throughout the project we intend to have close collaboration with Chinese counterparts. Therefore, we will give two comprehensive trainings (WP6) to interested participants from the Institute of Tibetan Plateau Research or other affiliates of the Chinese Academy of Sciences). The first training has been planned for October 2019, and we will provide another training in 2020, for which we have already did most preparations. Details about both trainings can be found below.

11.1 SPHY training October 2019

11.1.1 Description and schedule

The Third Pole is highly dynamic as there are many socio-economic and environmental drivers at play, including climate change. The impacts of these changes challenge the resilience of natural and human capacities and environments in the region. Recent studies have shown that the upstream and the downstream areas that depend on its water supply and ecosystem services are particularly vulnerable to climate change. To study the contributing roles of snow, glaciers, precipitation and groundwater to the total water resources, and how these roles might change in the future, a hydrological model is required that includes cryosphere and mountain hydrology.

To learn how to operate a hydrological model and understand its internals, we will provide a training coming October on the Spatial Processes in Hydrology (SPHY) model, which was developed by FutureWater in recent years and is available in the public domain. The overall objective of the training is to learn how to apply the SPHY model to specific use cases. To ensure that SPHY can be applied by a wide range of users, also those with only basic hydrological and computer skills, a user interface and data preprocessing tool were developed and will be presented at the training.

The interface now allows changing model input parameters and maps, selecting model output to be reported, running the model, and analyzing the model output. The newly developed preprocessing tool allows users to setup their own models easily by selecting a rectangular model extent and spatial resolution after which the software preprocesses input data from a predefined database and the SPHY model is ready to run. The new interfaces come with manuals of the underlying theory and hands-on training case studies.

The training was attended by 19 water and climate professionals and researchers (3 female and 16 male) from the Institute of Tibetan Plateau Research in Beijing on 14–18 October 2019. The training was provided by Sonu Khanal MSc (Hydrologist at FutureWater) and Dr. Arthur Lutz (Senior Hydrologist and Climate Change Expert at FutureWater).

Table 6: Schedule for the Spatial Processes in Hydrology (SPHY) model training in October 2019, Beijing.

Monday 14 October 2019		
Model concepts		
9:00–9:15	Arrival and registration	
9:15–9:25	Opening remarks	ITP-CAS representative
9:25–9:35	Opening remarks	Arthur Lutz
9:35–9:45	Round of introductions	Trainers and participants
9:45–10:00	Group picture	
10:00–10:30	Model concepts part I • Introducing models and data • Basic concepts of hydrological modelling systems	
10:30–11:00	***Tea/Coffee break***	
11:00–11:30	Model concepts part I - continued	Lecture
11:30–12:30	Model concepts part II • SPHY Theory • Forcing, parameterization, calibration and validation • SPHY data requirements and formats • QGIS, Python and PC-Raster • SPHY plugins for QGIS	Lecture
12:30–13:30	***Lunch break***	
Installing SPHY and GIS software		
13:30–15:00	Installing software on computers • SPHY-model • Numpy • PCRaster • QGIS • Preprocessor plugin • SPHY interface plugin	Hands-on
15:00–15:30	***Tea/Coffee break***	
15:00–17:00	• Continue installation	Hands-on
Tuesday 15 October 2019		
Case study using SPHY interface - Trishuli river		
09:00–10:30	Case study: Trishuli river • Exploration of datasets using QGIS	Hands-on
10:30–11:00	***Tea/Coffee break***	
11:00–12:30	Case study: Trishuli river • Create a new project • General settings • Groundwater • Land use	Hands-on
12:30–13:30	***Lunch break***	
13:30–15:00	Case study: Trishuli river • Glaciers • Snow	Hands-on
15:00–15:30	***Tea/Coffee break***	

15:30–17:00	Case study: Trishuli river • Run the model • Visualize results	Hands-on
Wednesday 16 October 2019		
Using the SPHY preprocessing tool		
09:00–09:30	• Using the SPHY data preprocessing tool	Lecture
Build your own SPHY model		
09:30–11:00	Setup own model • Model setup with forcing data from database	Hands-on
11:00–11:15	***Tea/Coffee break***	
11:15–12:30	Setup own model	
12:30–13:30	***Lunch break***	
13:30–15:00	Setup own model	Hands-on
15:00–15:30	***Tea/Coffee break***	
15:30–17:00	Setup own model • Model setup with own station data	Hands-on
Thursday 17 October 2019		
09:00–09:30	• Water balance calculation	Lecture
09:30–11:00	• Sensitivity analysis	Hands-on
11:00–11:15	***Tea/Coffee break***	
11:15–12:30	• Sensitivity analysis	
12:30–13:30	***Lunch break***	
13:30–15:00	• Model calibration	Hands-on
15:00–15:30	***Tea/Coffee break***	
15:30–17:00	• Model calibration	Hands-on
Friday 18 October 2019		
Build your own SPHY model		
09:00–10:30	• Model calibration	Hands-on
10:30–11:00	***Tea/Coffee break***	
11:00–12:30	• Model calibration/validation	Hands-on
12:30–13:30	***Lunch break***	
13:30–15:00	• Presentations by participants and discussion	Hands-on
15:00–15:30	***Tea/Coffee break***	
Closing session		
15:30–16:15	Training evaluation	Discussion
16:15–17:00	Closing Remarks & Certificate Distribution (SPHY)	Closing

11.1.2 Account of day-by-day events

Day one. The first days of the training were mainly dedicated to understanding of the basics of hydrological modelling using SPHY. Day one started with a brief introduction of the trainers and trainees including their research interest and expectations from training. During the first half of the day, the trainers Sonu Khanal and Arthur Lutz gave a brief introduction on the datasets available in the public domain and discussed general hydrological modeling concepts. The second half of the day was dedicated to SPHY modeling concepts and the data requirements for the model. During this session trainers demonstrated the user interface of the SPHY tool (Figure 43). By the end of the day the SPHY model and all required other software was installed on all the participant computers.

Day two. The second day of the training started with a case study of the Trishuli river basin in Nepal for which the model and required input data was prepared by the trainers. The participants started their hands-on exercise in conjunction with few exercises regarding the general model parameters, processes, and water balance concepts. The participants also learned the basics of QGIS to visualize model inputs and outputs. By the end of the day participants were able to calibrate the model with different parameter combinations to get their results close to observed states.

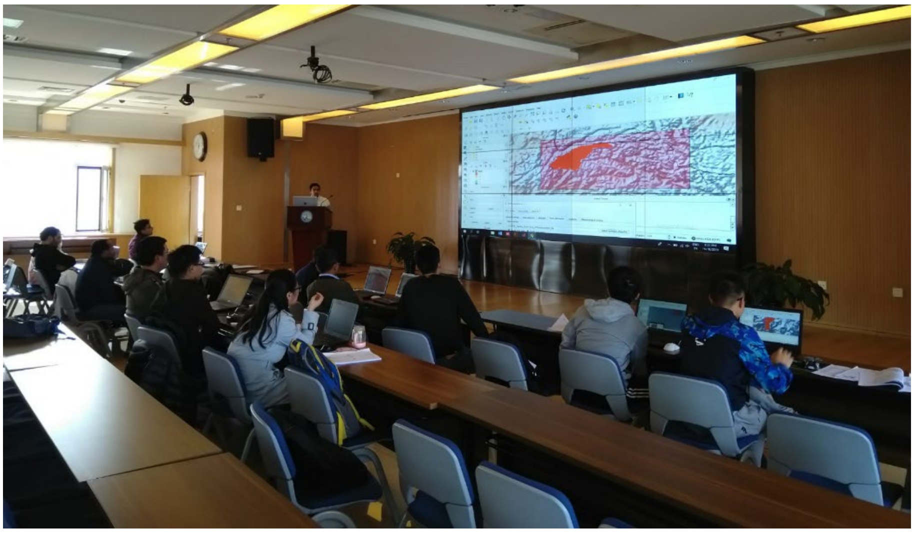

Figure 43: Trainers demonstrate the SPHY model user interface.

Day three. The third day started with lecture on the preprocessor tool, which enables the user to preprocess all the data based on their custom area of selection. The trainers demonstrated the different type of data, extent and sources already embedded in the database. After the lecture's, trainees started building their model of interest. Some trainees used the data from the database while others used their own custom meteorological and land use data. Most of the day was dedicated to model setup and data preprocessing for different regions of the trainees.

Day four. The fourth day was mainly dedicated to calibration of the SPHY model. Trainees evaluated the water balance output from the model and calibrated the processes accordingly. By the end of the day participants were able to calibrate and validate the model. The trainers also help the participants to adapt the model to their research requirements. The day ended up with discussion and presentation session by the participants (Figure 45).

Figure 44: Trainer and participant interaction during the training.

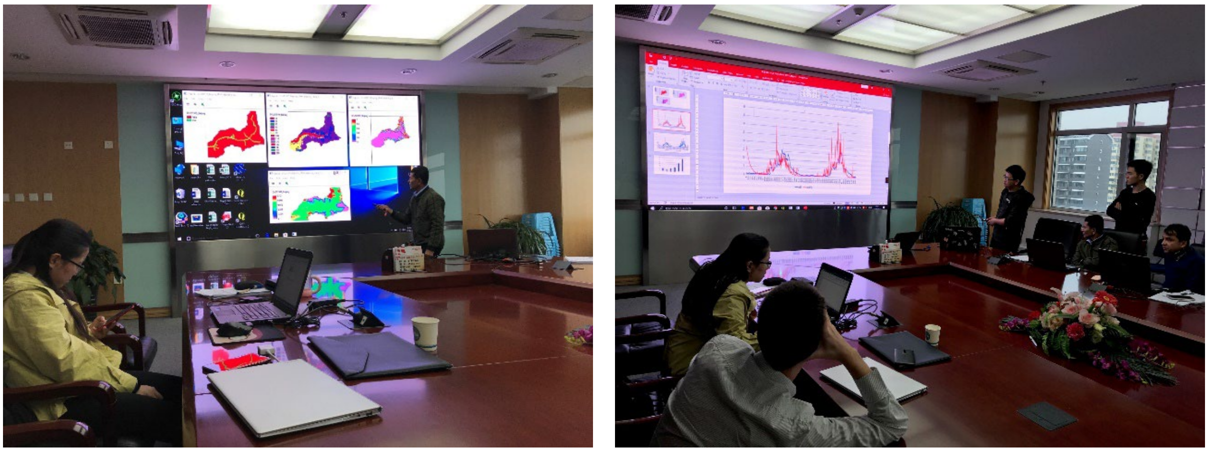

Figure 45: Participants presenting SPHY model the results for their region of interest.

Day five. The final day of the training was mainly dedicated to AWTM model demonstration and calibration. The trainers presented the AWTM they created for the QWATOW project. The model and the data were distributed to the trainees to help them to understand recent state-of-the-art developments in the project. The participants calibrated different regions of the AWTM model and provided useful insights on the further improvement of the calibration in the model. During the brief discussion session, participants shared their views on the improvement and further development of the several processes. The training ended with an evaluation and certificate ceremony (Figure 46). Overall, the training fulfilled all the needs of the project, and was positively evaluated by the participants. This training program has encouraged the researchers from ITP to use SPHY in their future research and led to further enhancement of the collaboration between Chinese and Dutch researchers.

Figure 46: Certificate distribution ceremony for completing the training.

Figure 47: Group picture of the training participants and the trainers.

11.2 Climate change and mountain hydrology *R* training

11.2.1 Description

For the second training that is proposed in the project proposal, we have developed a coherent set of exercises that cover a variety of topics. To help the participants to understand the concepts that are conveyed during the training more easily, all exercises use the same or similar source data and are all focused on the same study area. This allows the trainee to better understand and link different datasets, processes and concepts. The topics and concepts of the training, however, universally applicable to other (high-altitude) regions.

For ease of use, usability and reproducibility, the training has been set-up to use R and RStudio exclusively using completely self-developed packages and it uses an intuitive and interactive online web-based training manual in GitBook format (Figure 48). This freely available software is relatively plug and play and allows for an interactive and dynamic learning experience.

The following three topics are now covered within the training, with the title "*Climate change impacts on mountain hydrology–a multi-facetted analysis approach in R*":

1. **Climate data, scale differences, biases and downscaling**
   Objectives: (1) To gain insight in variation between climate models, reanalysis data and station data; (2) To understand the importance of bias correction and downscaling of climate model data and its uses for impact studies; (3) To implement the quantile mapping method for statistical downscaling.
2. **Snow trends, snow dynamics, and temperature index modelling**
   Objectives: To understand temperature index snow models, their advantages and limitations, and to investigate past and future changes on snow (hydrology) in a mountainous catchment.
3. **(Debris-covered) glaciers, glacier modelling and their response to climate change**
   Objectives: To understand the effects of debris cover and climate conditions on glaciers, and to investigate climate change impacts on glaciers.

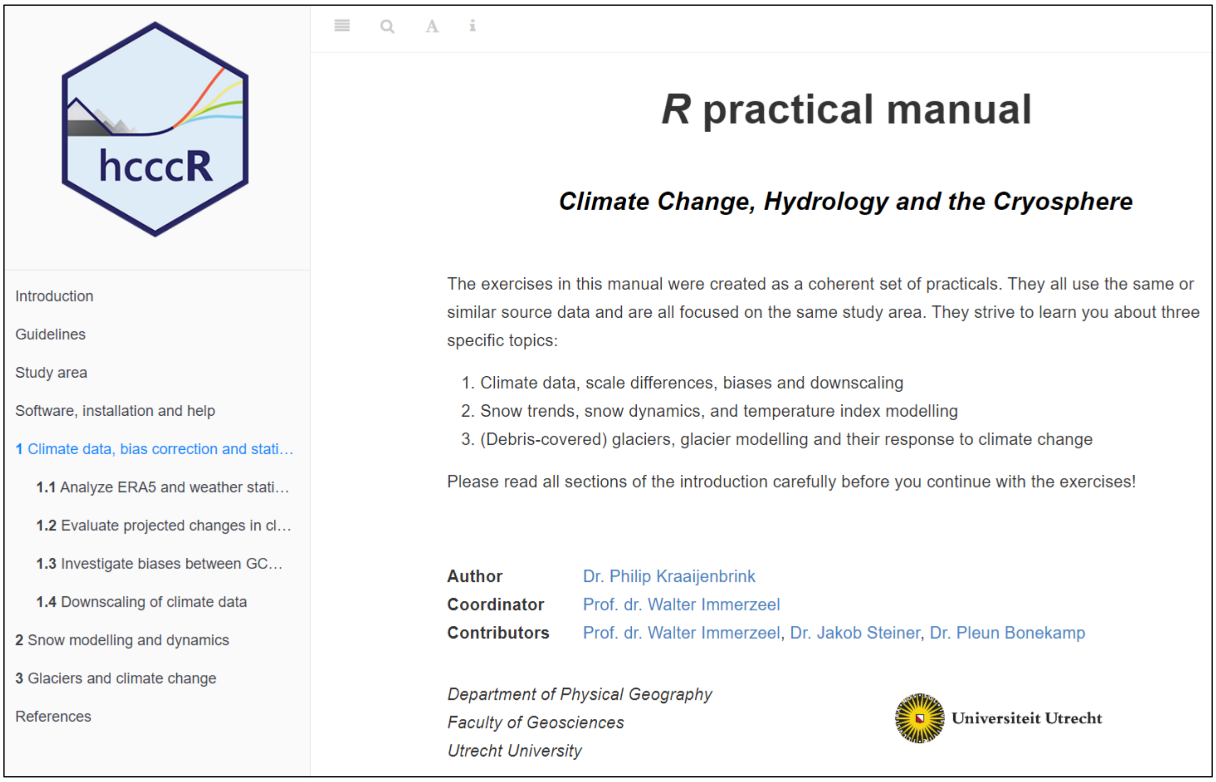

Figure 48: Interactive web-based manual for the planned climate change and mountain hydrology training.

11.2.2 Planning

Originally, the second training was set to take place in the Fall of 2020. We intended to hold the training in a location in China where it could have been combined with one or more interesting field trips, to spark trainees with an interesting mix of computer training and field knowledge. However, because of the global impacts of the COVID-19 pandemic and the related travel complications (and restrictions), the training had to be postponed. Unfortunately, due to continued travel restrictions enforced by both the Chinese and Dutch government, there has not been a possibility to give the training within the project period.

12. Scientific publications

Over project period there have been fourteen scientific publications related to the QWATOW project, which are listed below. Additionally, there are several publications still in preparation, in revision, or under review. For detailed descriptions of all entries, please refer to the respective section of this report.

Brun, F., Treichler, D., Shean, D., Immerzeel, W.W., 2020. Limited Contribution of Glacier Mass Loss to the Recent Increase in Tibetan Plateau Lake Volume. Front. Earth Sci. 8. https://doi.org/10.3389/feart.2020.582060

Farinotti, D., Immerzeel, W.W., Kok, R.J. de, Quincey, D.J., Dehecq, A., 2020. Manifestations and mechanisms of the Karakoram glacier Anomaly. Nat. Geosci. 13, 8–16. https://doi.org/10.1038/s41561-019-0513-5

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., Elmore, A.C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.S., Koppes, M., Kraaijenbrink, P.D.A., Kulkarni, A.V., Mayewski, P.A., Nepal, S., Pacheco, P., Painter, T.H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A.B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., Baillie, J.E.M., 2020. Importance and vulnerability of the world's water towers. Nature 577, 364–369. https://doi.org/10.1038/s41586-019-1822-y

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