A Scientific Assessment of the Third Pole Environment

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FOREWORD

Our planet has three main polar systems: the North and South Poles, and the Third Pole (TP). Like the North and South Poles, the Third Pole is among the most sensitive and vulnerable regions to climate change. Therefore, it is extremely urgent to address the complex crises of climate-induced disasters and impacts on lives, livelihoods, water, biodiversity. The TP is Earth's main mountain massif in Asia, which encompasses the Tibetan Plateau and surrounding areas including the Pamir-Hindu Kush mountain ranges in the west, the Hengduan mountains in the east, the Tienshan and Qilian mountains in the north and the Himalayas in the south. This Asian water tower provides freshwater resources to more than two billion people – 30 per cent of the global population. It regulates the climate, protects biodiversity and is socioeconomically of great importance. However, due to modern climate change caused by humans, warming rates in the TP are nearly double the global average, while the region's water balance is under severe threat. Disruption to the water cycle and increased environmental vulnerability are exacerbated by underlying issues of poverty, inequality, conflict and many other stress factors.

The TP is home to many charismatic alpine and mountain species of plants and animals which require concerted action to ensure their long-term survival. The iconic giant panda and charismatic snow leopard are both native to the region. For these flagship species and the nearly 170 other known threatened animal species which call the Third Pole their home, it's time humankind acts before it's too late to protect their habitat. The biodiversity loss is strongly interlinked with other environmental emergencies including climate change, environmental pollution, unsustainable use of chemicals and waste dumping. These crises must be addressed in a holistic and integrated manner, through the development and implementation of interlinked strategies that seek opportunities while avoiding further damage to the region's biodiversity.

Unfortunately, humans are reacting too slowly to the Earth's warning signs. We must wake up and work together to conserve and restore globally unique habitats in areas such as the TP. Governments should re-align their priorities to address environmental challenges of increasing intensity, severity and frequency. International organizations should convene experts, fund applied research and ensure the development of policies based on scientific evidence. Academic institutions should continue to educate and stimulate research to fill knowledge gaps and strengthen the science-policy interface. And civil society should push for global attention to the ongoing environmental crises and request appropriate action from decision-makers. An increasing body of scientific evidence points to cascading crises that need addressing immediately. Now is the time to define humanity's response to the mounting evidence of our deteriorating natural world.

Jian Liu
Director, Science Division
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This scientific assessment of the TP environment presents the latest knowledge on climate, freshwater bodies, ecosystems and their biodiversity, land surface changes and human impact. It considers the changes that have taken place in TP's regional environment over the past 2,000 years and are taking place today. It looks to the future and provides the most comprehensive and scientifically sound evaluation of a region with the largest complex of alpine ecosystems and freshwater systems in the world. The assessment underlines the importance of interdisciplinary research in tackling the complex threats that are leading to undesirable environmental changes as a result of human activity.

This assessment was produced by the United Nations Environment Programme (UNEP) in collaboration with the UNEP-International Ecosystem Management Partnership, the Third Pole Environment, and the Pan-Third Pole Environment and supported by the Second Tibetan Plateau Scientific Expedition and Research project, the International Centre for Integrated Mountain Development, and the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences. UNEP and the assessment's authors are grateful to all involved and hope that in the near future more global collaboration takes place to address issues affecting the TP environment.

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Glossary

The entries in this glossary are primarily taken or modified from definitions provided by classical text books, and/or scientific literature.

Third Pole (TP)

The unique high-elevation area around the Tibetan Plateau. It stretches west to the Pamir-Hindu Kush region, east to the Hengduan Mountains, north to the Tienshan and Qilian mountain ranges, and south to the Himalayas, encompassing over 5 million square kilometres with an average altitude of over 4,000 metres above sea level. It hosts the largest ice mass outside the Polar Regions, hence is also internationally acknowledged as the Third Pole on earth (Yao *et al.* 2012[1]).

Asian Water Tower

The huge glaciated mountain system in the TP, as mountains are the water towers of the worlds, including for Asia, whose rivers all are fed from the Tibetan plateau and adjacent mountain ranges (Immerzeel, van Beek and Bierkens, 2010[2]).

Climate proxies

Imprints created during past climate and used by scientists to interpret paleoclimate. They range from organisms, such as diatoms, forams, and coral, to ice cores, tree rings and sediment cores (which include diatoms, foraminifera, microbiota, pollen, and charcoal within the sediment and the sediment itself) (Bradley 1999[3]).

The westerlies

The zone of winds poleward from the subtropical high-pressure belt, present in both the Northern Hemisphere and Southern Hemisphere, that is characterized by migratory cyclones and anticyclones traveling generally west to east. Usually located poleward from approximately 35°N and S latitude, the westerlies extend much of the remainder of the distance to the poles and are developed to levels exceeding the height of the tropopause (Washington and Parkinson 2005[4]).

Monsoons

Large-scale quasi-steady wind regimes, often resulting from specific geographic and topographic features of the regions where they occur, and characterized by a seasonal reversal of wind direction. In response to the differential heating by the surface, they blow from land to sea in winter and from sea to land in summer, producing a wet-dry season cycle (Washington and Parkinson 2005[4]).

Elevation-dependent warming (EDW)

A phenomenon that the rate of warming is amplified with elevation, such as in mountain environments. It is similar to the amplification of the rate of temperature change with increased levels of greenhouse gases in the atmosphere at high latitudes (Pepin *et al.* 2015[5]).

Ecological buffers

Protected zones established around sensitive or critical areas — such as wildlife breeding or hibernation habitats, streams, and wetlands — to lessen the impacts of human activity and land disturbance. The TP as an ecological buffer is preserved to reduce or minimize the risks of land use disturbance and proximity of infrastructure specifically associated with shale energy development, and maintains biodiversity (The Nature Conservancy 2015[6]).

Permafrost

Perennially frozen ground as a naturally occurring material with a temperature colder than 0°C (32°F) continuously for two or more years. (Britannica Academic[7]).

1. https://doi.org/10.1016/j.envdev.2012.04.002.
2. https://doi.org/10.1126/science.1183188.
3. Bradley, R.S. (1999). Paleoclimatology: reconstructing climates for the Quaternary (3rd Edition). Elsevier, Academic Press.
4. Washington, W.M., Parkinson, C.L. (2005). An introduction to Three-Dimensional Climate Modeling (2nd Edition). University Science Books, Sausalito, California.
5. https://doi.org/10.1038/nclimate2563.
6. https://www.nature.org/media/centralapps/recommended-shale-practices-ecological-buffers.pdf?vu=shale-practices
7. https://academic.eb.com/

Emissions scenario

An estimate of future emissions based on our understanding of natural sources of greenhouse gases and on assumptions about future socio-economic trends i.e. how much greenhouses gases will be released into the atmosphere by humans (IPCC 2014[8]).

Representative Concentration Pathways (RCPs)

[Climate change] Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes the fact that not only the long-term concentration levels but also the trajectory taken over time to reach that outcome (IPCC 2014[8]).

Coupled Model Intercomparison Phase 6 (CMIP6)

The sixth phase of Coupled Model Intercomparison Project (CMIP), which coordinates somewhat independent model intercomparison activities and their experiments that have adopted a common infrastructure for collecting, organizing, and distributing output from models performing common sets of experiments. The simulation data produced by models under previous phases of CMIP have been used in thousands of research papers (some of which are listed here), and the multi-model results provide some perspective on errors and uncertainty in model simulations. This information has proved invaluable in preparing high profile reports assessing our understanding of climate and climate change (e.g., the IPCC Assessment Reports[9]).

Persistent organic pollutants (POPs)

Persistent Organic Pollutants (POPs) are toxic substances composed of organic (carbon-based) chemical compounds and mixtures. They include industrial chemicals like PCBs and pesticides like DDT. They are primarily products and by-products from industrial processes, chemical manufacturing and resulting wastes (Stockholm Convention on Persistent Organic Pollutants[10]).

8. https://archive.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-AnnexII_FINAL.pdf
9. https://www.wcrp-climate.org/wgcm-cmip
10. http://chm.pops.int/TheConvention/ThePOPs/tabid/673/Default.aspx

Acronyms

BC:	Black carbon
BP:	before the present era
CMIP6:	Coupled Model Intercomparison Phase 6
DDT:	dichlorodiphenyltrichloroethane
EDW:	elevation-dependent warming
ELA:	equilibrium line altitudes
ERA5:	European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5
GLOFs:	glacial lake outburst floods
HCB:	hexachlorobenzene
HCH:	hexachlorocyclohexane
HKH:	Hind Kush Himalaya
HMA:	high mountain Asia
HR:	heterotrophic respiration
IPCC:	Intergovernmental Panel on Climate Change
IPBES:	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN:	International Union for the Conservation of Nature
LIA:	Little Ice Age
LRAT:	long-range atmospheric transport
NDVI:	normalized difference vegetation index
NEP:	net ecosystem productivity
NPP:	net primary productivity
COVID-19:	Coronavirus Disease 2019
PM2.5:	particulate matter with a with a diameter of 2.5 µm or less
RCP:	Representative Concentration Pathway
RegCM:	regional climate model
RGI:	Randolph Glacier Inventory
SSP:	Shared Socioeconomic Pathway
SWE:	snow water equivalent
TP:	Third Pole
WRF-Chem:	Weather Research and Forecasting (WRF) model coupled with Chemistry
SAT:	surface air temperature

Key Messages

The Third Pole has experienced a general warming and wetting climate during the past two millennia.

- Using multiple sources of data and information resulting from the analysis of ice cores, tree rings, and sediment cores, the report highlights that the Third Pole's climate has experienced several warm and cold phases, with an overall warming and wetting trend over the past 2,000 years before present (BP).
- The Third Pole has especially experienced an increasing warming and wetting period during the past 60 years, with a warming rate of over 0.3°C per decade, far surpassing the global average in combination with more significant warming in winter compared to the other seasons.
- Meanwhile, precipitation in the last 60 years has increased by 0.76 per cent per decade compared to the recorded times before. However, precipitation trends show clear regional contrasts, with increases in the northern part of the Third Pole and decreases in the southern part.

Third Pole water bodies have shown increasing variations in the past 30 years.

- Variations of water bodies shows that the water cycle in the Third Pole is intensifying. Glacier melt has been intensifying since the 1980s, with more intensive melt along the Himalayas and in the southeastern sector of the Third Pole and less intensive melt in the more continental interior part .
- The number and surface area of the lakes in the Third Pole region were stable prior to the 1990s, but began to increase thereafter, with lake water increasing at a rate of 8 gigatons per year, corresponding to an increase in lake levels at a rate of 0.14 m per year. There is also a noticeable north-south contrast in lake level variations, with significant rises in the north and falls in the south.
- River run-off showed an overall decrease prior to the 21st century and started to increase thereafter.
- Glacial disasters such as ice collapse and glacial lake outburst floods (GLOFs) have become more frequent and dangerous in the past years.

Ecosystems in the Third Pole have been turning green since the 1980s.

- Ecosystems in the Third Pole have been changing, with earlier greening of the vegetation, later withering and a longer growth season, as well as an expansion in vegetation coverage and an increase in ecosystem productivity.
- As the productivity of alpine grass increases, it alters agricultural plantation systems, expands the potential areas suitable for two harvest seasons, and increases cropping cycles, thus contributing to optimization of the agricultural and farming system.
- Conservation interventions are causing some plant and animal species to increase in population size, but they still face major challenges such as climate change, the lack of transboundary conservation approaches, major infrastructure projects and the arrival and spread of alien species.

Human activities outside the Third Pole are negatively impacting the Third Pole environment.

- The atmospheric pollutants from extra-regional anthropogenic activities on the Third Pole, including black carbon and persistent organic pollutants (POPs), are negatively impacting the Third Pole environment.
- The Indian Summer Monsoon, Westerlies and local mountain valley winds are blowing such pollutants into the Third Pole from different source regions.
- Atmospheric pollutants brought to the Third Pole from distant and nearby countries not only have a negative impact on human health, but also contribute to increased glacial melt.
- Anthropogenic activities are characterized by inadequate coordination between regional development and environmental protection.

Projections show the potential of more risky consequences caused by a warmer and wetter climate in the future.

- Projected warming in the Third Pole is greater than the global average; it is expected that there will be widespread increases in annual precipitation over the coming period.
- Large spatial heterogeneities exist for both temperature and precipitation, with the Westerlies-dominated region experiencing greater increases by the end of the 21st century.
- Glacial melt and river run-off are both projected to increase. Net ecosystem productivity is projected to increase as well, and hence likely increases Third Pole's value as a carbon sink. However, current carbon sinks could become eroded due to amplified permafrost thawing leading to carbon losses. Other hazardous consequences such as ice collapse and GLOFs will also become more serious in the coming years and cause additional threats to the future of the Third Pole environment.

Executive summary

The Third Pole (TP), the Asian Water Tower and largest alpine ecosystems in the world, with an average elevation of 4,000 metres, encompasses the Tibetan Plateau and surrounding areas of the Pamir-Hindu Kush mountain ranges in the west, the Hengduan Mountains in the east, the Tienshan and Qilian Mountain in the north and the Himalayas in the south. With an area of more than five million square kilometres, the region is the largest storehouse of snow and ice outside the Arctic and Antarctica with about 100,000 square kilometres of glaciers in area. As the highest ecosystem in the world with 14 highest mountain peaks, the region provides freshwater to more than 12,000 lakes and more than 10 river systems. With vast coverage, varied and complex ecosystems, the TP is significant in terms of climate regulation, hydrological cycle, and environmental processes. Apart from being the most important Asian 'water tower', hosting globally important alpine ecosystems and biodiversity, the TP is equally significant as home to a diverse community.

The fragile highland ecosystem of TP is witnessing a higher rate of warming than the global average, resulting in faster glacier melt and increased frequency of ice collapse and glacial lake outburst floods. This environmental change is directly impacting the stability of the Asian water towers, thus threatening the ecosystem, biodiversity, and livelihood of people. Better understanding of the science behind the warming climate and its impact on ecosystem, biodiversity and livelihood is necessary for informed mitigation and adaptation policies for regional sustainability.

Considering the complex interactions of climatic and biophysical environment in the TP, an interdisciplinary approach is needed to address many challenges. Similar to the good examples set by the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the present report is the first comprehensive assessment of environmental changes over the TP that outlines the collective understanding from interdisciplinary research on four key areas: climate, water bodies, ecosystems and human impacts, covering respectively facts and impacts of: climate change, water availability, ecosystem change and human influences on the environment.

Ice core and tree ring data show that the climate of the TP has experienced several warm and cold phases, with a general warming and wetting trend over the past 2000 years. Current warming started in the late 19th century but accelerated in the 20th century, with this century becoming the warmest in the past 2000 years. Similar to the warming trend, the recent episodes of precipitation increase began in the 20th century and continues. Both the warming and wetting trends are confirmed by the observational data in the TP in the past decades, which highlight seasonal and regional differences, amplified warming in higher elevations, and increased amounts during extreme precipitation events.

The consequences of variations in temperature and precipitation are visible as glacier area and mass have decreased in past decades, with more loss along the Himalayas and less mass loss in the more continental interior TP. Such variations have also resulted in an increase of natural hazards largely associated with cryosphere in recent years and there are indications of an increase in risks that might be associated with the changing climate in the future.

Snow cover depth, area and duration have decreased in recent decades. River discharge has also shown an increasing trend in most of the TP Rivers over the past decades. The variations in discharge are closely linked to changes in precipitation and glacial melt runoff contributions.

The TP is characterized by diverse ecosystems largely dominated by grassland, shrubland and the steppes, followed by forests, farmland, and wetlands. Forest area, which covered 11.5 per cent in 2005, has seen a change from primary forests to secondary types. Farmland is mainly in the Lhasa and Nianchu River basins with one cropping season. Forests and wetlands harbor immense terrestrial and aquatic biodiversity and provide an array of ecosystem services. The ecosystems over the TP have been changing, with earlier starts to the growing season, the expansion of vegetation coverage and an increase in ecosystem productivity. The increase in the vegetation coverage is strengthening the water-holding capacity of soil, which used to experience active layer thickening and permafrost warming throughout the TP, while also expanding desertification in the head water regions. The overall worsening trend of soil quality and water loss improved slightly after the 2000s.

The human activities outside the TP, including air pollutant emissions such as those of black carbon, heavy metal, and persistent organic pollutants, are negatively affecting the TP environment. It has been observed that the Indian summer monsoon, westerlies and local circulation such as those of mountain valley winds are responsible for bringing such pollutants into the TP region from different source regions. While the current levels of atmospheric pollutants such as black carbon, heavy metals and persistent organic pollutants are low compared with urban environments, they are showing an increasing trend. The input of atmospheric pollutants from surrounding countries to the TP not only has a negative impact on human health, but also contributes to the glacier melt.

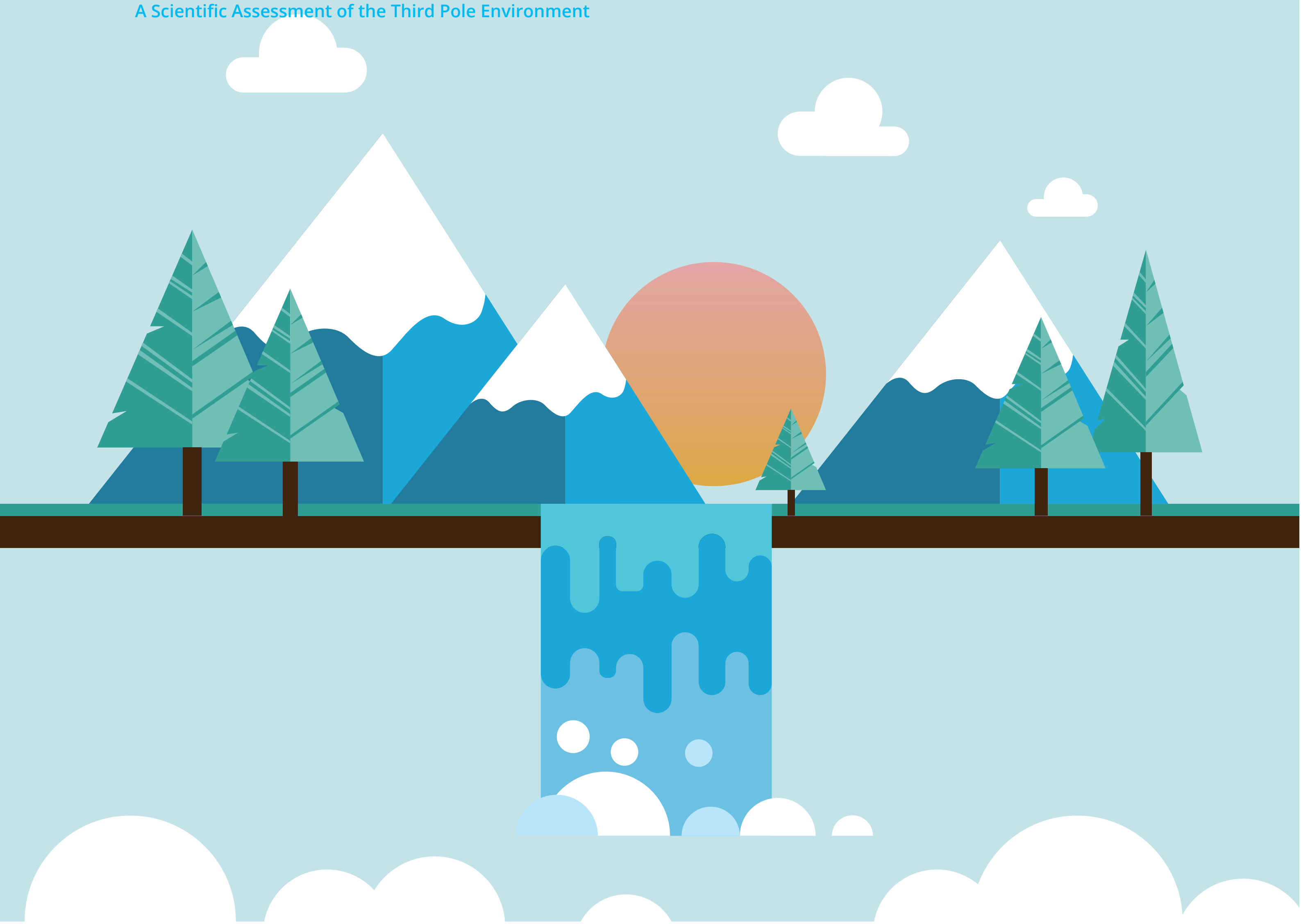
The TP is one of the most biologically diverse regions in the world and is well known for its rare and endangered flora and fauna. While biodiversity at the global level is being challenged with higher threats and even extinction rate by about 20 per cent , the rate in TP is about 9 per cent for vertebrates and 5 per cent for plants. There has been a positive trend in species with increasing populations such as Przewalski's gazelle and the Tibetan wild ass, largely with conservation efforts in the TP countries. There is a need to survey biodiversity and collect biodiversity baseline data, enlarge cross-border conservation efforts, increase general community protection awareness, further improve monitoring and management, strengthen law enforcement, advance the effectiveness and pertinence of protection actions, build an alarm system to alert against introduced species, and relieve ecological impacts of climate change.

Air temperature in the TP is projected to increase in the late 21st century by 1.4-5.6°C relative to the 1995–2014 reference period. The elevation dependent warming by 1.8 ± 0.4°C is projected to continue into the future with the global warming scenario of 1.5°C by the end of the century. Similarly, precipitation is expected to increase by 6-15 per cent by the end of the 21st century but with regional and seasonal variations. Greater precipitation increases are projected for the westerlies dominated areas during the winter and monsoon dominated areas in summer.

Projections show the potential for significant consequences caused by a warmer and wetter climate in the future. Glaciers are expected to rapidly decrease in mass in the coming century, with two thirds of the present mass gone by 2100 in the southeast TP. Similarly, substantial decreases in snow cover are expected in the coming century and significant changes in the seasonality of river discharge. Total runoff in the TP Rivers is projected to increase, with the magnitude of runoff larger in monsoon dominated river basins than in westerlies dominated basins. This difference is largely due to the changes in runoff from precipitation increase in monsoon region compared with melt-dominated westerly region. In glacier-fed river basins, the future runoff will typically rise until a maximum is reached, before steadily declining thereafter because warming-induced glacier shrinkage can no longer sufficiently support rising meltwater. The timing of this turning point depends upon regional variation, warming rates and glacier storage and can vary among river basins.

The cascading effect of such projected changes in temperature and precipitation are significantly impacting cryosphere and hydrosphere, which will further affect ecosystems and biodiversity. The increase in temperature and precipitation is increasing the photosynthesis and the Net Primary Productivity (NPP). However, the projected NPP will vary regionally, decreasing from east to west. The vegetation growth and dominant species transition-induced "greening" also have positive feedback due to albedo and radiation.

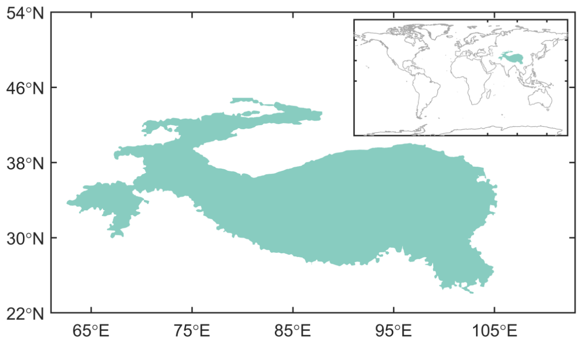
Vegetation distribution will move up to the higher elevation. Ecological models project that such trends would significantly increase the extinction risk of narrow range species and other species in climate sensitive areas such as toad-headed lizard (*Phrynocephalus*). Conservation efforts are therefore needed along with evidence-based management options.



1 Introduction

The Third Pole (TP) refers to the unique high-elevation area around the Tibetan Plateau (Qiu 2008; Chettri *et al.* 2012; Yao *et al.* 2012). It stretches west to the Pamir-Hindu Kush region, east to the Hengduan Mountains, north to the Tienshan and Qilian mountain ranges, and south to the Himalayas, encompassing over 5 million square kilometres (km^2) with an average altitude of over 4,000 metres above sea level (a.s.l.) **(Figure 1.1)** (Yao *et al.* 2012). The region stores more snow and ice than anywhere else in the world outside the Arctic and Antarctica, and hosts the world's 14 highest mountain peaks and about 100,000 km^2 of glaciers,Yao *et al.* 2012), and thus is widely acknowledged as the Asian water tower (Immerzeel, van Beek and Bierkens 2010). Meltwater feeds large lakes such as Qinghai Lake, Nam Co and Siling Co, as well as more than 10 major Asian rivers, including the Indus River, Brahmaputra River, Ganges, Yellow River and Yangtze River.

Δ Figure 1.1 Geographical location and outline of the Third Pole. The highlighted area shows the geographical range with elevations above 2000 metres a.s.l.



Δ Source: The Shuttle Radar Topography Mission (SRTM) data at 90 meter (3 arc-second) resolution.

1.1 Urgency for a regional environmental assessment in the Third Pole

The high elevation and large horizontal expanse of the TP underlines its significance in Earth's climate system, and implies complex interactions between and among atmospheric, cryospheric, hydrological, geological and environmental processes (Chettri *et al.* 2012; Wester *et al.* 2019). The TP is also recognized as an ecological buffer that bears great impacts on the Earth's biodiversity, climate and water cycle (Zhou *et al.* 2017; Dhyani *et al.* 2018).

The TP spreads across 12 countries (Afghanistan, Bangladesh, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Myanmar, Nepal, Pakistan, Tajikistan and Uzbekistan). More than 2 billion people depend on its resources within and around the TP regions and many of whom still live in poverty. With a warming rate higher than the global average, the region is identified as one of the most vulnerable regions on Earth to environmental and climate changes. Previous studies have demonstrated that thermal and dynamical effects of the TP on the circulation system of the westerlies and Asian monsoon, as well as global atmospheric circulation and climate (Yanai, Li and Song 1992; Zhang, R. H. *et al.* 2012). Its vulnerability can be exacerbated by other stresses, such as current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalization, conflict and incidence of diseases such as COVID-19 (United Nations Environment Programme [UNEP] 2021).

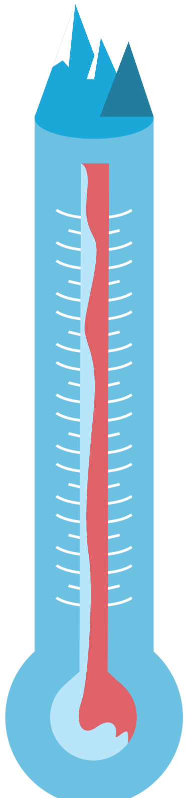
Recent studies report that environmental conditions in the TP have changed significantly in the last century (Kang *et al.* 2010; Wester *et al.* 2019). Meteorological records reveal that the warming rate in the TP is double that observed globally over the past five decades (Chen, D. *et al.* 2015). Global warming-induced glacier retreat, ice collapse, glacial lake expansion and frequent glacial lake outburst floods (GLOFs) are degrading the stability of the Asian water towers, threatening lives in the region (Veh, Korup and Walz 2020; Ahmed *et al.* 2021). Warming-induced changes in the TP's ecology and biodiversity may even drive climate and environmental changes at the local, regional and global levels (Dhyani *et al.* 2018; Foggin 2018; Pei *et al.* 2019). The cryosphere change in the TP has a global influence as the thawing of permafrost and melting of glaciers not only decrease the stability of high mountain slopes (Intergovernmental Panel on Climate Change [IPCC] 2019), threatening regional security, but also affects long-term water supplies in the region for hydropower, irrigation, and drinking (Hock *et al.* 2019), thus affecting regional sustainability and harmony.

There are also growing evidences of the impact of anthropogenic activities on the TP's environment (IPCC 2021), which along with anticipated changes in the future, may potentially threaten livelihoods that depend on TP resources and its environment (Gioli *et al.* 2019; Yang *et al.* 2021). It is therefore increasingly crucial that environmental changes in the TP are assessed so that scientific knowledge of the region's climate, water, ecosystems, biodiversity, human activities and hazards is as up to date as possible, and can therefore be used to inform mitigation and adaptation policies for regional sustainability. This is particularly important for developing regions to counteract the limitations inherent in implementing adaptation actions with insufficient financial resources (UNEP 2021).

1.2 Overarching design of the report

This report has been developed to consider the complexities of environmental changes and their impacts. It has been built on the principals of the IPCC and IPBES. This assessment report has used climate, water body, ecosystem and human impacts to quantify the environmental changes in the TP. Chapter II of this report discusses the basic facts about past and present environmental changes in the TP, with special focus on the impact of environment changes and human activities. Chapter III focuses on the impacts of human activities on the environment, highlighting the external and internal impacts on biodiversity and human sustainability in the region. Chapter IV explores, where feasible, projections of future changes for both near-term (present–2050) and long-term (2051–2100) environmental scenarios.

This report is the first comprehensive scientific assessment of environmental changes over the TP. The core of this assessment revolves around significant impacts resulting from environmental changes and human activities over the TP, and future scenarios.



2 Environmental changes in the Third Pole

As the majority of TP inhabitants rely on agriculture for a living, which is closely related to precipitation and temperature. This chapter assesses Third Pole environmental changes over the past 2000 years using both proxy and observational data. In the evaluation of paleoclimate, only some unsystematic records were obtained from ice cores, tree-rings, lake sediment cores and glacial fluctuation signs to assess the climate and water bodies' changes. The current climate changes, specifically, temperature and precipitation, is evaluated based on 95 meteorological stations across the TP, with water bodies' changes evaluated using in situ observation and remote sensing data, and ecosystem mainly assessed for its structure, functionality and spatial distinctions. Due to the data scarcity, assessment of the permafrost is mainly confined to the active layer thickness.

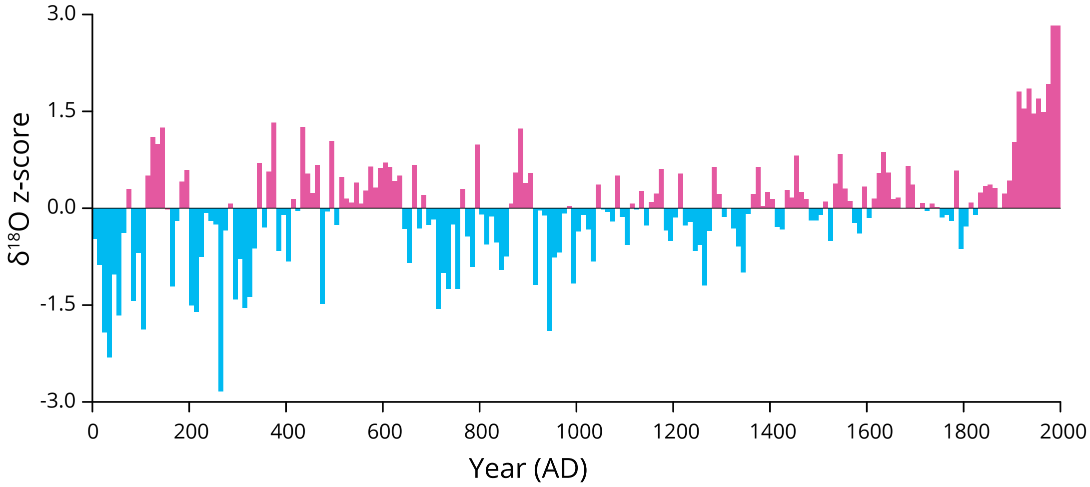
2.1 Climate of the Third Pole has been warming and wetting in the past 2000 years

2.1.1. Temperature

The TP's paleoclimate records over the past 2000 years are of the highest resolution of all environmental series (Ding 2010). The extremely high elevation of the TP facilitates extensive coverage of alpine glaciers that together comprise the largest ice mass outside the Arctic and Antarctica (Shi, Liu and Kang 2009; Farinotti *et al.* 2019). Multiple paleoclimate records can be produced from this rich glacial resource using ice cores, which along with tree rings retrieved from the TP in the past decades, shed light on historical climate changes. This significantly contributes to the unravelling of the climate change history throughout the region (Yao *et al.* 2019).

Both ice core and tree ring records revealed generally consistent temperature variations throughout the TP over the past two millennia, with noticeable fluctuations **(Table 2.1)**. In general, the cooling and warming episodes occurred almost equally frequent prior to A.D. 1000, while thereafter, warming predominated the fluctuations. Particularly, warming since the 1900s reached an unprecedented level in the last 2000 years **(Figure 2.1).**

Δ Figure 2.1 Temperature variations composited from four Tibetan Plateau ice cores for the past 2000 years.



Δ Source: adapted from Figure 1b in Yao *et al.* (2019)

2.1.2 Precipitation

The Guliya ice cap provides a history of net accumulation over the past 2000 years (Yao *et al.* 1996a; Thompson *et al.* 2018), revealing four dry and five wet periods **(Figure 2.2a)**. In the period between 300 and 560, there were alternating wet and dry periods, after which the climate settled into a dry period between 560 and 1270, with the exception of 560–720 and 980–1080. Net accumulation shows an overall increasing trend from 1270 to 1900, which was interrupted by increased arid periods between 1600 and 1640 and 1810 to 1930.

There is a positive correlation between net accumulation and temperature in the Guliya ice core record, implying that warm periods correspond to high precipitation, and cold periods to low precipitation, although the correspondence between temperature and humidity are not exactly in phase. Precipitation varies less often than temperature, and the transition from wet/dry state often lags behind warm/cold temperature shifts/phases by 50–100 years.

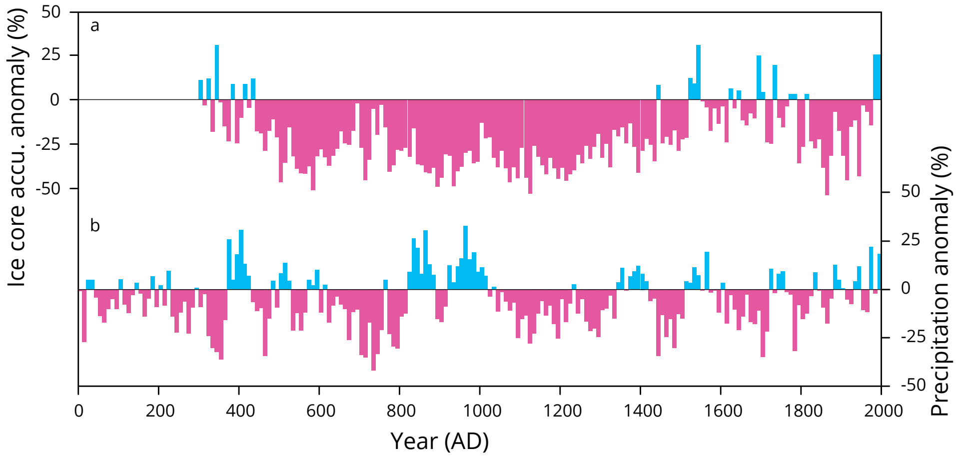
Multiple tree ring samples collected from north to east across TP provide annual precipitation information for the past millennium (Zhang *et al.* 2003; Gou *et al.* 2010; Shao *et al.* 2010), revealing coherent variability regardless of the locations (Li *et al.* 2008; Yang, B. *et al.* 2010). The spring precipitation record reconstructed from tree rings acquired from the lower forest of Dulan over the past 2000 years, **(Figure 2.2b)**, shows arid conditions with little variability between the 1st and 3rd centuries, followed by a sharp transition to wet conditions in the mid-4th century, with alternations between wet and dry conditions until the mid-7th century. A dry period then occurred until the early 9th century before turning humid in the 11th century, which peaked from 930 to 1030. The period is characterized by alternating wet and dry climates until the mid-19th century, followed by an apparent wetting trend to 2000 (Zhang *et al.* 2003).

Some tree rings in the southeastern part of the TP also recorded precipitation changes (Liu *et al.* 2009; Fang *et al.* 2010; Yang, B. *et al.* 2010; Griessinger *et al.* 2011; He *et al.* 2013), although the time series seldom exceed 1000 years. Precipitation changes reconstructed from tree rings

Δ Table 2.1 Temperature variations from TP paleoproxies

Proxy	Location	Parameter	Indications
Ice core	Guliya, north-central TP	$\delta^{18}O$	Overall warming interspersed by seven cold periods and eight warm periods. Warming intensified over time before culminating in the 21st century, while cooling weakened. LIA encompassed three cold periods (16th, 17th and 19th centuries) is not the coldest period of the past 2000 years (Yao *et al.* 1996b).
Ice core	Dunde, north-eastern TP	$\delta^{18}O$	No clear warming trend. LIA encompassed three cold periods (15th, 17th and 19th centuries). Cooling and warming generally evolve in alternation (Yao and Thompson 1991).
Ice core	Puruogangri, central TP	$\delta^{18}O$	Medieval Warm Period (MWP) and LIA are not outstanding. Warming from the 13th to 20th centuries, with cooling in the 19th century. 20th century warming is strong (Thompson *et al.* 2006).
Ice core	Dasuopu, southern TP	$\delta^{18}O$	Indistinguishable MWP and LIA. Obvious 20th century warming. Warming and cooling evolve in alternation, though do not have the same duration (Yao *et al.* 2002).
Tree ring	Dulan and Wulan, north-eastern TP	Tree ring width	LIA is obvious and has numerous cooling periods. Warming in the late 20th century is particularly obvious (Liu *et al.* 2009).
Tree ring	Qamdo, south-eastern TP	Tree ring width	Two cold periods and one warm period during 1000–1220. LIA is obvious (seventeenth, eighteenth, nineteenth centuries) Accelerated warming since the 1960s, with the most recent 30 years as the warmest period in the past millennium (Wang, J.L. *et al.* 2014).
Ice core	Composite across the TP	$\delta^{18}O$	Warming over the past two millennia, with larger variation amplitude before 1000.

Δ Figure 2.2 Reconstructed precipitation variations in the TP over the past 2000 years through (a) Guliya ice core net accumulation, and (b) Dulan tree ring



Δ Note: The red and blue areas represent dry and wet climates, respectively, with 1961–1990 serving as the base period.

Δ Sources: Yao *et al.* 2019

acquired at Linzhou, Sangri and Lang counties in south-eastern Tibet share several common features, including low precipitation periods in 1570–1620, 1800–1850 and 1960–1980, and high precipitation in 1350–1390, 1510–1550, 1700–1750, 1850–1870 and 1890–1910.

Unlike temperature, which shows relative coherence across the entire TP, precipitation shows significant spatial heterogeneity in different studies **(Table 2.2).** The regional differences in precipitation patterns between the northern and southern parts of the TP that have occurred in the last 500 years, or on even longer time scales, are the result of dominating monsoons and westerlies (Chen, Chen and Huang 2009; Chen *et al.* 2010). The westerlies anomaly associated with the North Atlantic Oscillation may be primarily responsible for this north-south precipitation difference (Liu and Yin 2001; Wang, W. *et al.* 2013).

Beyond the Tibetan Plateau, lake sediment records from Tso Kar and Tso Moriri, North and South Pulu and Yaya Tso (Ladakh Range) (Phartiyal *et al.* 2020), and the eastern side of Pensi-la (Zanskar Himalaya) (Ali *et al.* 2020) showed an overall similarity in climate variability for the past two millennia and highlighted a trend of increased aridity from west to east in the Trans-Himalaya and Zanskar. This is likely due to the effect of westerlies, which dominate the precipitation regime and decrease from west to east in the semi-arid Ladakh sector.

A detailed study of the lake sediment records revealed three broad climate zones **(Figure 2.3),** with zone 1 covering 3.3 to ~1.5 kiloyear (ka) before the present era (BP) and featuring cool and moderately wet climatic conditions, zone 2 covering 1.5 to ~0.9 ka BP and dominated by moderately warm and wet conditions, and zone 3 covering 0.9 ka BP to present and featuring a return to arid conditions with an intensified westerly circulation.

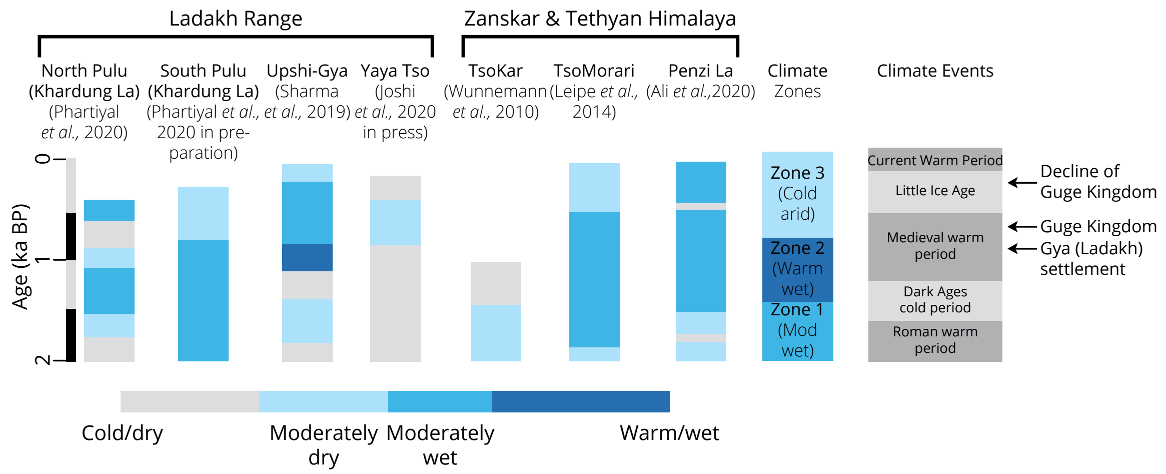
Human societal development is also suggested to be linked to these climate conditions: the Upshi record, for example, shows the warmest and wettest phase at ~1 ka, with minimum levels of westerlies (Herzschuh 2006), which coincides with the ancient Gya settlement at Upshi, Ladakh (Leipe *et al.* 2014) and the Guge Kingdom in the western Tibet, whose decline corresponds to an increase in aridity and westerlies demonstrated in zone 3.

Δ Table 2.2 Heterogeneous variation of precipitation revealed by the Palmer Drought Severity Index from reconstructing TP paleoproxies

	1450–1499	1500–1549	1550–1599	1600–1649	1650–1699	1700–1749	1750–1799	1800–1849	1850–1899	1900–1949	1950–2000
North TP	wetting		drying			wetting	wetting				drying
South TP	drying		wetting			drying	drying				wetting

drying   wetting

Δ Figure 2.3 Spatio-temporal variation in climatic data of the Trans-Himalaya and Zanskar regions



Δ Note: Data of sediment records of the last 2000 years of an area covering 206,505 km^2 of the Trans-Himalaya and Zanskar regions, with three distinct climatic zones of varying intensities in different regions.

Δ Sources: Wuennemann *et al.* 2010; Leipe *et al.* 2014; Ali *et al.* 2020; Phartiyal 2020

2.2 Climate, water bodies and ecosystems have shown significant changes characterizing a greening Third Pole

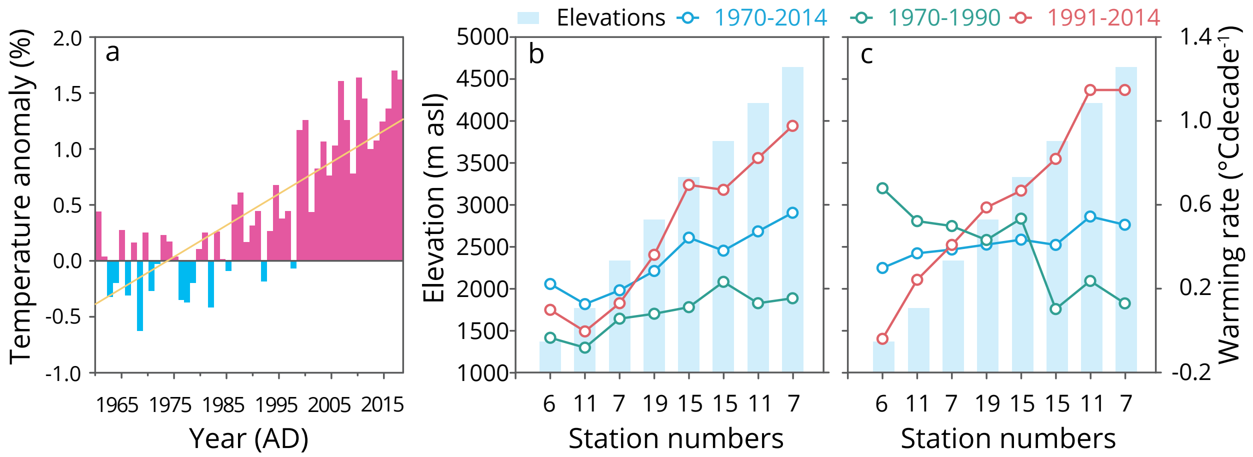
2.2.1. Climate

Temperature increase throughout the TP accelerated by 0.3°C per decade during 1960–2018 **(Figure 2.4a)**, almost doubling the global average (IPCC 2021). The warming rate is higher during winter (Liu and Chen 2000), reaching as high as 0.44°C per decade during 1961–2015 (Xu *et al.* 2017). The TP is therefore recognized as a site of amplified global warming and a harbinger of global climate temperatures (Pan and Li 1996; Pepin *et al.* 2019; Li, Q.Q. *et al.* 2021), though most meteorological studies are based on low-elevation observations in the region and show heterogeneously rising temperatures over the past five decades (Nepal 2016; Azam *et al.* 2021). The warming of the TP varies across regions by 0.09–0.74°C per decade, with more intense warming occurring in the north than in the south. There is growing evidence of elevation-dependent warming (EDW) **(Figure 2.4b)** (Li, X. *et al.* 2017; Yao *et al.* 2019) over the TP since the 1990s, which is particularly noticeable below 5,000 metres (Qin *et al.* 2009) and during winter season (Hock *et al.* 2019) **(Figure 2.4c)**.

Temperature change throughout the TP is asymmetric, as the daily minimum temperature variation is much greater (0.41°C per decade) than the maximum temperature (0.18°C per decade) (Liu *et al.* 2006), with the number of extremely cold days decreasing and the number of hot days increasing.

Observational data for the past century and the last half-century based on global land surface air temperature (Ren and Zhou 2014; Xu**,** Li and Yang 2014; Sun**,**Ren and Xu 2017) data and ECMWF Reanalysis v5 (ERA5) (Krishnan *et al.* 2019; Azam *et al.* 2021) show a significant and universal increase across the whole TP. The annual mean surface air temperature for the period 1901–2014 shows significant upward trends ($p < 0.05$), and the increase rates of mean, maximum, and minimum are 0.10°C per decade, 0.08°C per decade, and 0.18°C per decade, respectively. The diurnal temperature range shows a significant negative trend of −0.10°C per decade, due to the much larger rise in minimum temperature than in maximum temperature in the region (Ren *et al.* 2017). Locally, deviations from the general pattern described above have been found in the Karakoram region, where decreasing temperatures (most notably in summer) have been measured or reported. The Karakorum vortex has been identified using a regional circulation metric that quantifies the relative position and intensity of the westerly jet, and its interannual variability is introduced to explain such an anomaly and the variability in energy-constrained ablation (Forsythe *et al.* 2017).

Δ Figure 2.4 Anomaly of annual average air temperature in (a) 95 TP meteorological stations and the elevation depending warming for (b) annual mean air temperature, and (c) winter mean air temperature



Δ Note: (a) Uses a variation rate of 0.3°C per decade (R=0.83, p<0.0001) with 1961–1990 as the base period.

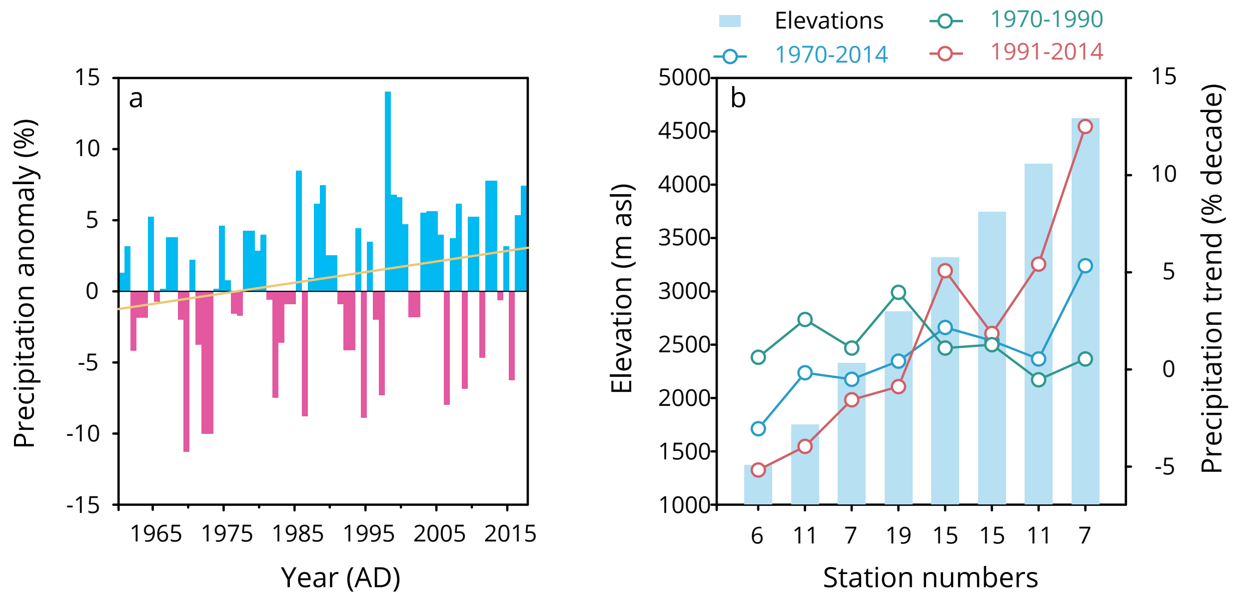
Δ Sources: China Meteorological Data Service Center 2019; Li, X. *et al.* 2017; Yao *et al.* 2019

Precipitation increased by 0.76 per cent per decade in the TP during 1960–2018 **(Figure 2.5a)**, while over the Hindu Kush Himalaya (HKH) region annual precipitation over the last century did not show a clear trend (Krishnan *et al.* 2019). Instead, precipitation trends show a clear regional heterogeneity, increasing in the north and decreasing in the south, with more detailed studies finding positive anomalies over most of the central and eastern Himalaya and negative anomalies over the Karakoram, western Himalaya, and far eastern Himalaya (Krishnan *et al.* 2019). This heterogeneity is attributed to the dominance of the Indian monsoon over the south and the monsoon weakening, compared with the predominance of westerlies over the north and the Karakorum anomaly (e.g. Forsythe *et al.* 2017). The westerly-monsoon interactions result in precipitation variations at different altitudes throughout the TP, with mean annual precipitation generally decreasing by 17–128 millimeters (mm) per 100 metres between 2,500 and 5,500 metres in the monsoon region, and increasing with altitudes by 5–64 mm per 100 metres in the westerlies region (Sun *et al.* 2020).

Precipitation mainly occurs in summer (June–September) throughout the TP, accounting for 60–90 per cent of total annual precipitation, and increases faster in higher elevation areas **(Figure 2.5b)**. Similar to the EDW, summer precipitation from 1970 to 2014 increased with altitudes by 0.83 per cent per decade per kilometer, with more increase during 1991 to 2014 (2.23 per cent per decade per kilometer) (Li, X. *et al.* 2017).

Extremes in precipitation increased over the TP in the past century. Annual mean daily precipitation increased significantly and positive correlated with elevation (Krishnan *et al.* 2019). Studies have shown that variability in western disturbances has increased in the recent years (Dimri *et al.* 2015; Madhura,Krishnan and Revadekar 2015; Chen, F. *et al.* 2019), leading to higher propensity of winter precipitation in the Western Himalaya and Karakorum.

Δ Figure 2.5 (a) Anomaly of annual mean precipitation in 95 TP meteorological stations, (b) elevation dependence of trends (per decade) in summer precipitation throughout the TP.



Δ Notes: (a) Using a variation rate of 0.76 per cent per decade (R=0.23, p<0.100) with 1961–1990 as the base period. (b) For three time periods (1970–1990, 1991–2014 and 1970–2014).

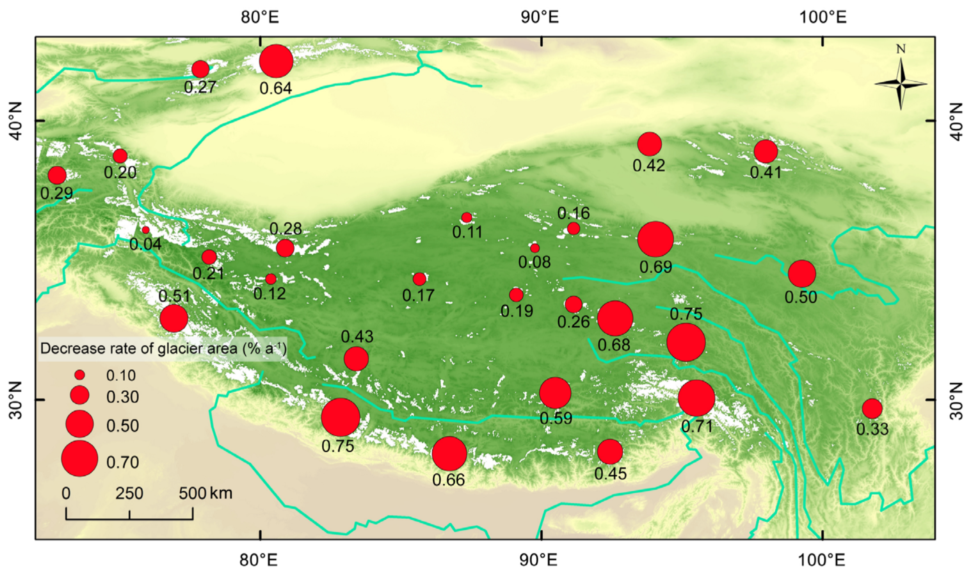
Δ Sources: China Meteorological Data Service Center 2019; Li *et al.* 2017

2.2.2. Water bodies

Glaciers

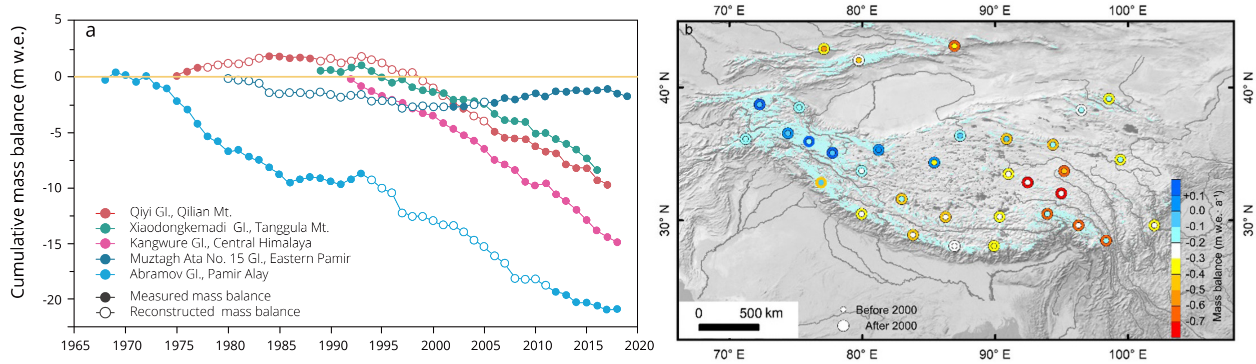
There are about 100,000 glaciers throughout the TP, with a total coverage of approximately 100,000 km^2 and volume of (7.0 ± 1.8)×10^3 cubic kilometres (km^3) (Yao et al, 2012; Randolph Glacier Inventory [RGI] 2017; Farinotti *et al.* 2019; Zemp *et al.* 2019). However, due to geographical constraints, only a limited number of glaciers in selected regions of the TP are subject to continuous glacier mass balance monitoring (Bolch *et al.* 2012; Azam *et al.* 2018; Zemp *et al.* 2019). Over the past 50 years, these glaciers have shown retreating trends, with their equilibrium line altitudes (ELAs) gradually increasing. For example, the ELAs of Glacier No. 1 at the source of the Urumqi River in Tienshan, and the Qiyi Glacier in the Qilian Mountains have risen by roughly 110 m, and 250 m, respectively, since the 1960s (Wang, N.L. *et al.* 2010; Zhang, G. *et al.* 2014). Over the past decade there has also been intensified mass loss and an accelerated decrease in glacier area **(Figure 2.6)** and mass **(Figure 2.7)** across the TP. However, like the heterogeneous glacier mass loss pattern across Asia (Gardner *et al.* 2013), this shrinkage is not homogenous, generally decreasing from the south-eastern part of the TP and the Himalayas to the continental interior. The Karakoram and eastern Pamir Mountains have experienced the lowest decrease in glacier volumes (Brun *et al.* 2017; Bolch *et al.* 2019; Wang 2019; Shean *et al.* 2020; Bhattacharya *et al.* 2021).

∆ Figure 2.6 Spatial distribution of glacier area change throughout the TP over the last 40 years during 1971-2010.



∆ Source: Wang 2019

∆ Figure 2.7 (a) Variation of observed cumulative mass balances of selected glaciers throughout the TP, (b) spatial and temporal changes of glacier mass balance over the TP.



∆ Source: Maurer *et al.* 2019; Yao *et al.* 2019

A comprehensive inventory of the glaciers in the Himalaya Karakoram suggests that one fifth of all glaciers present in 1985 had disappeared by the beginning of the current century (Cogley 2011). In the same region 18 glaciers have mass balance data, with an average loss between 1975 and 2015 of about 0.59 metres water equivalent (m w.e.) per year (Azam *et al.* 2018). The longest (2002–2019) in situ mass balance study from India found that the Chhota Shigri Glacier in Lahaul-Spiti in Western Himalaya lost an average of 0.5 m w.e. of ice each year. Apart from the warming-induced large-scale atmospheric circulation fluctuations, variation in precipitation seasonality, i.e. ratio of summer precipitation to winter precipitation, plays an important role in the fate of glaciers (Mandal *et al.* 2020; Soheb *et al.* 2020). The heterogeneous topography and surface properties of glaciers in the region has also been found to significantly influence glacier area change (Scherler, Bookhagen and Strecker 2011; Garg, Shukla and Jasrotia 2017).

Rapid glacier changes in the TP may lead to natural disasters such as glacier collapses, GLOFs and associated debris flows and may influence surging behaviour of glaciers (Kääb *et al.* 2018; Allen *et al.* 2019; Kääb *et al.* 2021). These glacial disasters each have different spatio-temporal distribution characteristics, dynamic processes and mechanisms.

Glacier surging actively occurs in the Karakoram, Pamir and Kunlun Mountains (Sevestre and Benn 2015; Bhambri *et al.* 2017; Chudley *et al.* 2019). On individual glaciers in the Karakoram, surface flow rates of ~20 metres per day have been observed in recent years, making them among the fastest rates ever experienced on mountain glaciers in the world (Steiner *et al.* 2018; Bhambri *et al.* 2020). As many as 221 glaciers in the region have recently been identified as surging (Bhambri *et al.* 2017). The surges sometimes lead to formation of lakes that have resulted in multiple GLOFs in the Karakoram in recent years (Round *et al.* 2017; Steiner *et al.* 2018; Bhambri *et al.* 2020).

New types of glacier-related disasters are also occurring throughout the TP. In 2016, two massive glacier collapses occurred in the Aru Range, Ngari, in the western region of the TP on 17 July and 21 September (Kääb *et al.* 2018). The Aru Glacier collapses caused the death of nine shepherds and the loss of hundreds of livestock. On 17 and 29 October 2018, a glacier collapse caused ice and moraine flow and blocked the Yarlung Tsangpo at Sedongpu Valley in the south-eastern Tibetan Plateau (Chen *et al.* 2020). The fact that both the continental (Aru) and maritime (Sedongpu) type glaciers have experienced collapses seems to suggest that glaciers across the TP might be in an unstable state. Other disasters such as multiple destructive debris flows in the Pamir (Leinss *et al.* 2020) as well as the Indian Himalaya (Shugar *et al.* 2021) have also been linked to unstable ice.

Snow cover

Snow is a temporary form of seasonal liquid water storage. Its accumulation and melt impinge largely on regional water resources and climate, both across and beyond the TP. With its snow cover mainly present from October to May, the TP is considered a stable snow cover area in Earth's low and middle latitude zones. However, research on both snow fall as well as snow cover have been relatively limited (Viste and Sorteberg 2015). From what is available, there is large spatial heterogeneity in snow cover and residence time throughout the TP (Tang *et al.* 2013; Hammond, Saavedra and Kampf 2018), with three high value centres noted for snow cover on the northern Himalayas, eastern Tanglha and Nyenchen Tanglha, and the eastern part of the TP centred around the Anemaqen Mountain and the Bayan Har Mountains (Wei *et al.* 2002).

Large inter-annual variations in snow cover with an overall negative trend have been observed on the TP since the 1960s (Barry and Hall-McKim 2018). The total snow-covered area has decreased by approximately 1 per cent per year and the snow-covered period by on average 23 days between 1966 and 2001 (Rikiishi and Nakasato 2006). There are considerable variabilities in snow cover features over TP (Huang *et al.* 2017), with generally more confidence in remotely sensed snow extent data on the Tibetan Plateau than the higher relief HKH, Tien Shan and Pamir mountain ranges along the fringes of the plateau. In the Karakoram and Kunlun Shan, there are even some indications of a recent increase in snow fall (de Kok *et al.* 2018).

On the Tibetan Plateau, maximum snow cover extent was approximately 2.5×10^6 km^2 in the winter of 1994–1995. Similarly, snow depth decreased from 1980 to 2018, with large inter-annual fluctuation before 2000 and less variation after 2000 **(Figure 2.8).** There is spatial inconsistency in snow depth change across the Tibetan Plateau, with a clear decrease of 0.1–0.2 c entimetres per year observed in the Nyenchen Tanglha, and a slight increase (less than 0.1 cm per year) observed in the Qilian Mountains, Hoh Xil mountain range and the north slope of the Himalayas (Che *et al.* 2019).

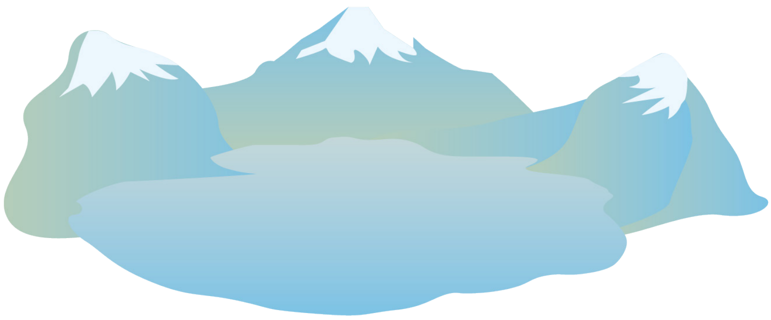
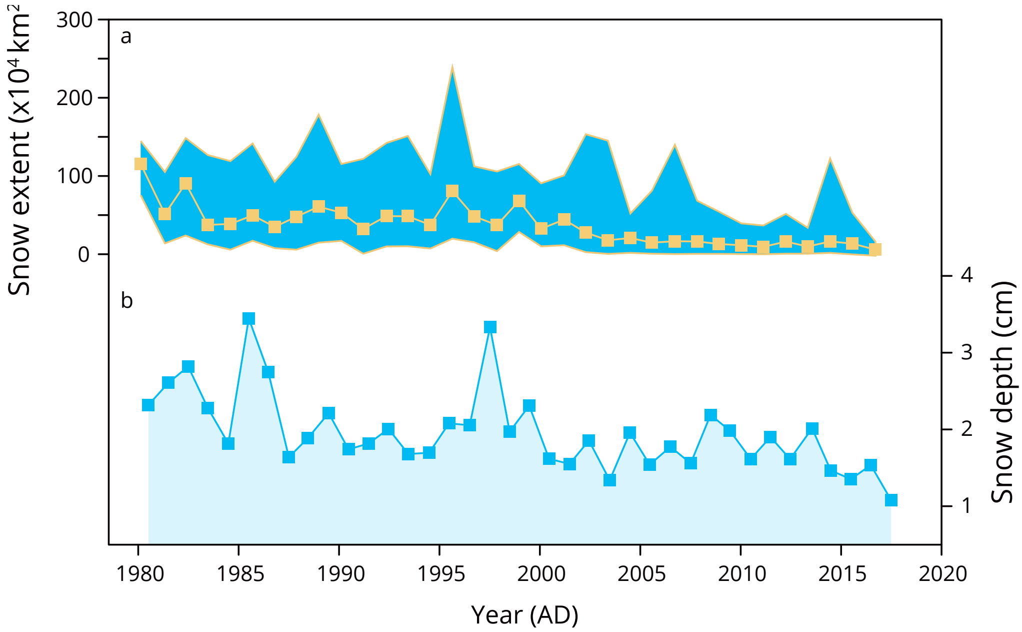


Figure 2.8 (a) Variation of snow cover extent and (b) snow depth during 1980–2018 on the Tibetan Plateau.



Note: The upper and lower limit of the blue shaded area represents the maximum and minimum value of snow cover extent, with the pink squares representing the mean value.

Source: Che *et al.* 2019

Climate change significantly affects snow cover and its associated hydrological processes across the TP. Several recent studies found an increase in river flows, along with an earlier peak of snowmelt runoff (Wang and Li 2006; Immerzeel, van Beek and Bierkens 2010; Kraaijenbrink *et al.* 2021). However, changes in the snow water equivalent (SWE) remain highly heterogeneous in space and time (Smith and Bookhagen 2018).

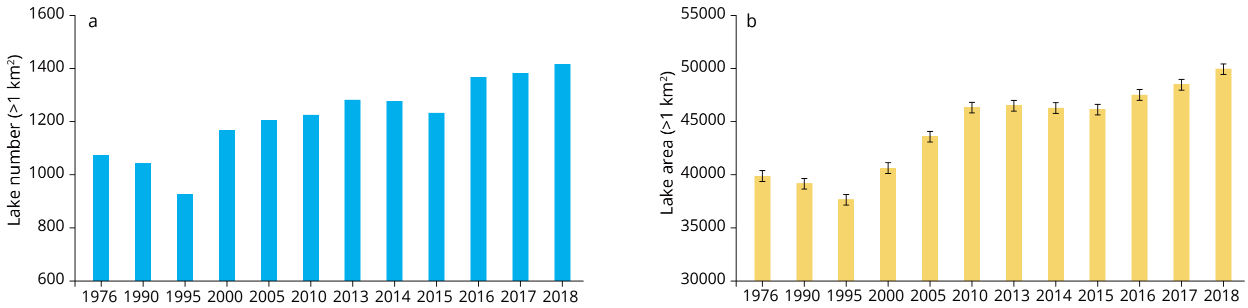
Lakes

The TP has over 1,000 large lakes with areas greater than 1 km^2 (Ma *et al.* 2011; Zhang, G.Q. *et al.* 2014). The total lake area is around 45,000 km^2 (Zhang *et al.* 2019), with total water storage reaching 608 gigatons (Gt: 1 Gt = 10^{12} kg), including 210 Gt of fresh water. Most lakes in the TP are endorheic, comprising 90 per cent of the TP's total lake cover and are located between 4,000 and 5,000 metres a.s.l. (Zhang *et al.* 2020).

Recent studies (Zhang *et al.* 2019; Zhang *et al.* 2020) of lake areas in the TP, utilizing Landsat remote sensing data, has advanced the understanding of TP lake areas and numbers, indicating that lake numbers (and areas) were 1,081 (40,000 km^2), 1,070 (39,700 km^2), 1,204 (41,300 km^2) and 1,424 (50,400 km^2) in the 1970s, 1990, 2000 and 2018, respectively **(Figure 2.9)**, and that over 80 per cent of the lakes are expanding. More specifically, number of lakes larger than 1 km^2 in particular increased from 1,070 to 1,424 from 1990 to 2018, corresponding to a total area increase from 39,700 km^2 to 50,400 km^2. During 2003–2009, lake levels rose by 0.14 metres per year, which is equivalent to an increase in lake volume of 8 billion tons. Meanwhile, there is an obvious contrast in lake changes across the TP, with a dramatic increase in lake levels in the north and decreases in the south **(Figure 2.10)**. Nevertheless, overall lake numbers and extent are increasing across the TP.

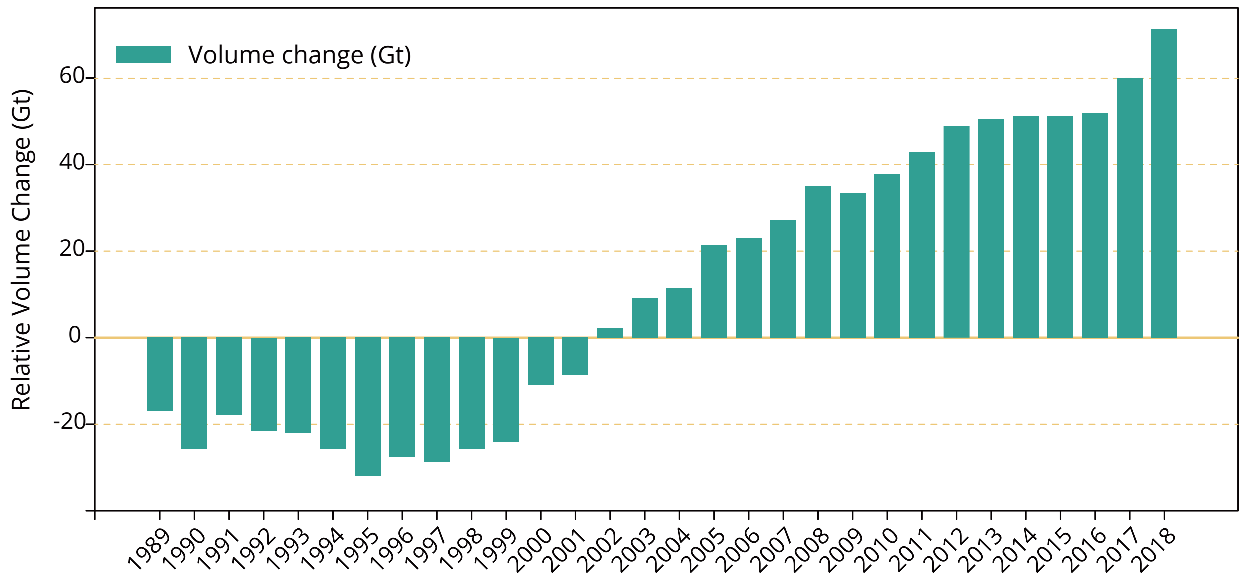
The Ice, Cloud, and Land Elevation Satellite (ICESat) data cover about 200 lakes in the TP for the 2000–2009 period (Zhang, G.Q. *et al.* 2013). Analysis of the data shows an annual variation of 0.14 metres in lake level fluctuations, based on the increasing levels of 152 lakes (76 per cent of the total) by 0.21 metres per year, and the decreasing levels of 48 lakes (24 per cent of the total) by 0.08 metres per year. The lake level of the Siling Co in particular was found to have dramatically increased by 0.67 metres per year, surpassing that of the Nam Co (2,026 km^2) in 2017 (Zhu, L.P. *et al.* 2019). Endorheic lakes generally tend to have more rise than flow-through lakes, as is observed in the Yarlung Tsangpo catchment, where lake levels mostly decrease. The volume of the lakes has been estimated using information of lake level and area changes, revealing an increase in the extent of lakes greater than 50 km^2 by 102.64 Gt from 1976 to 2013, with the largest increase during 2000–2005 (Yang *et al.* 2017). The total lake volume is estimated to increase by 8.0 Gt per year for the entire Tibetan Plateau (Zhang, G. *et al.* 2013).

Δ Figure 2.9 (a) Variation of numbers and (b) areas of lakes above 1 km² in area in the Third Pole.



Δ Source: Zhang *et al.* 2020

Δ Figure 2.10 Relative lake volume changes in the Third Pole, 1989–2018



Δ Sources: Zhang *et al.* 2020

The expansion and volume increase of lakes across the TP is mainly attributed to the increase in precipitation and glacial melt and decrease in evaporation. Overall, precipitation increases are the major driver behind lake expansion (Lei *et al.* 2014; Yang *et al.* 2017), with evaporation weakening adding to this (Lei *et al.* 2013; Zhou *et al.* 2015). Glacial melt is the main cause of lake expansion and volume increase in the north-western part of the TP (Qiao *et al.* 2017), though it also has a noticeable impact on lakes in the south-eastern part of the Qangtang region (Song *et al.* 2016). According to one study (Zhu, Xie and Wu 2010), the contribution of glacial melt to lake expansion has been quantified as 52.9 per cent for the Nam Co.

Rivers

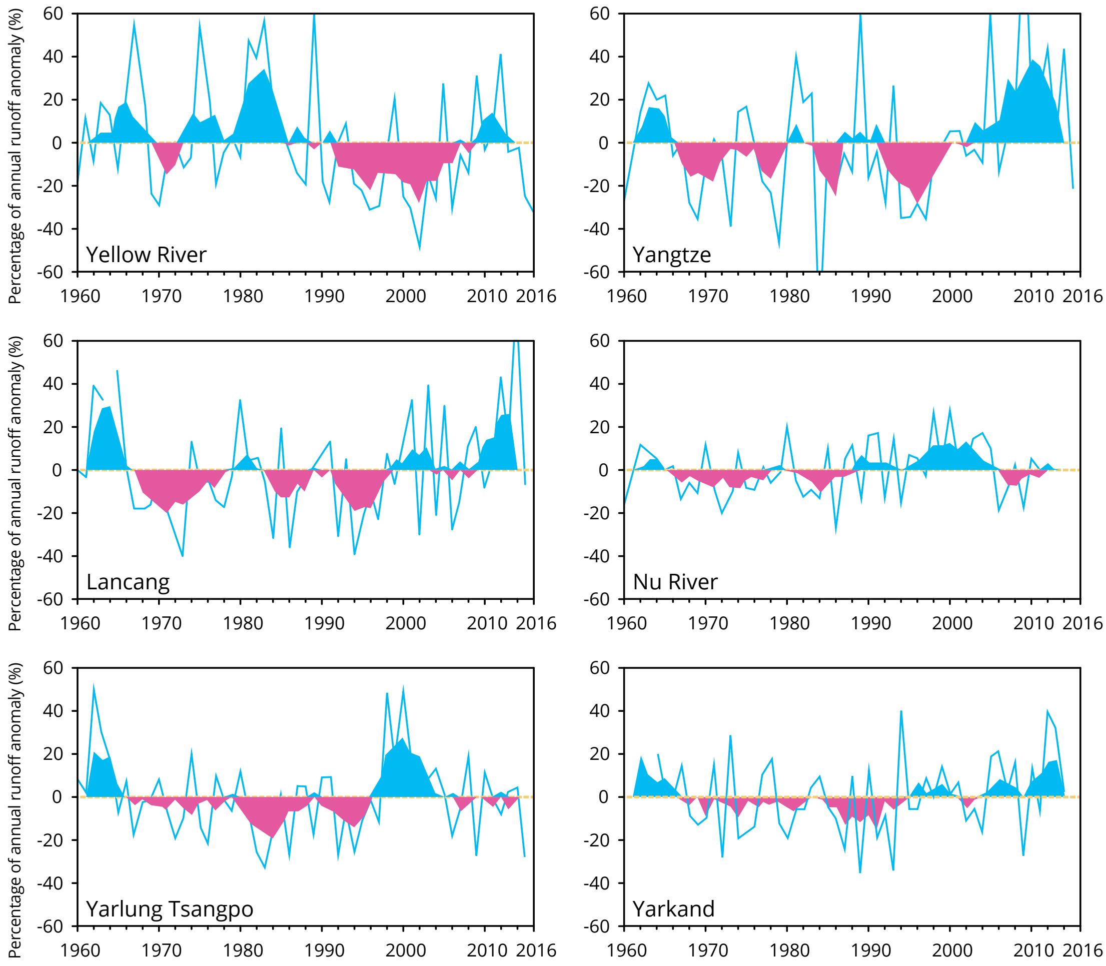
Throughout the TP, rivers flow into both endorheic and exorheic basins. There are five major endorheic basins in the TP based on each of their geographical locations and water supply networks: northern Tibet, Qaidam Basin, Qinghai Lake, Hexi Corridor and Tarim Basin. In these basins, the Yarkand River and Hetian River, which originate from the Karakoram and Western Kunlun Mountains and merge into the Qaidam Basin, are longer and produce more discharge than any other rivers in the endorheic basins, owing to the abundant alpine glacial melt supply. The Yangtze River, Yellow River and Lancang (Mekong) River in the exorheic basins belong to the Pacific Ocean system, while the Nu River, Ganges, Yarlung Tsangpo (Brahmaputra) and Indus River emerging from the Sengge Zangbo and Langqen Zangbo all belong to the Indian Ocean system. Most exorheic rivers are transboundary. The Indus River is the lifeline of Pakistan's agricultural-based economy, emerging from the Tibetan Plateau and separating the central Karakoram from the Himalayas. The upper part of the river is referred to as the Upper Indus Basin, with approximately 12 per cent of this area above 5,500 metres a.s.l. and almost entirely covered by glacier ice (Farhan *et al.* 2014). Similarly, the Ganges and Brahmaputra rivers drain through the Indo-Gangetic Plain which is considered as a food basket for South Asia (Aggarwal *et al.* 2004).

The Amu Darya and Indus rivers have snow and glacier melt runoff contribution of about 79 per cent and 45 per cent, while the Ganges and Brahmaputra in central Himalaya contributes about 13 per cent and 15 per cent (Khanal *et al.* 2021). The melt runoff from these rivers is crucial for agricultural production in downstream areas as in the case of Indus, Ganges and Brahmaputra. For example, during the pre-monsoon season, up to 60 per cent of the total irrigation withdrawal comes from mountain snow and glacier melt in the Indus basin as suggested by (Biemans *et al.* 2019).

In general, there has been little anthropogenic impact on river runoff variations in the TP over the past decades **(Figure 2.11)** (Tang *et al.* 2019). No significant trend has been observed for run-off from the TP's major rivers, except for the Yellow River (decrease), Yangtze River (weak increase) and the Upper Indus Basin (significant increase). Run-off variations are closely linked to changes in precipitation and glacial melt.

Sediment yield of major rivers in the TP shows an inverted parabolic relationship with precipitation and a positive correlation with glacier area ratio, indicating that sediment yield is a minimum at about 500-600 mm of precipitation, increasing sharply on both sides of this minimum in one case owing to decreased vegetation protection and in the other to enhanced erosive power and that erosion rate in the glacierized area is generally higher than non-glacierized area (Zhang *et al.* 2021). Among the eight major rivers, sediment yields of four (i.e., the Yarkand River, Shule River, Heihe River and Nu River source regions) show significant increasing trends while the others indicate non-significant changing trends during 1960-2017 (Zhang, Shi and Zeng 2019) **(Figure 2.12).** Three river basins (the Yarkand River, Shule River, and Nu River) with the largest glacier area ratios are of glacier dominancy, with sediment yield positively correlated with air temperature, and the increase of glacier melt leading to significant increase of sediment yield.

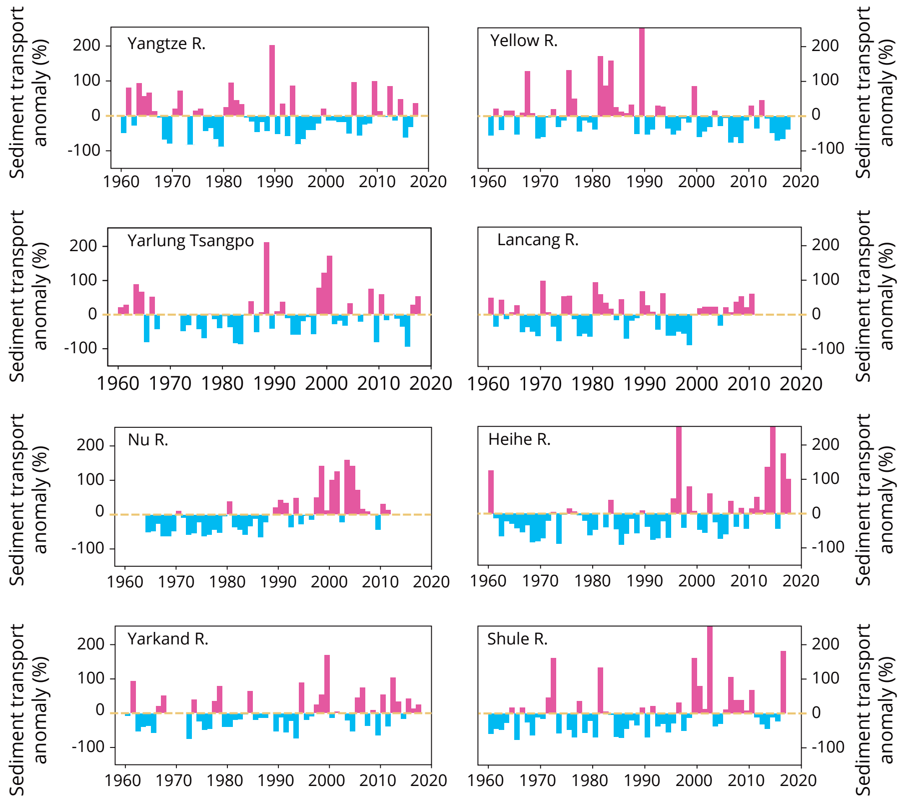
Δ Figure 2.11 Annual river run-off anomaly in major river source regions of the Third Pole, 1960–2016



Δ Note: The black curve is the annual average, and the shaded areas are the five-year running averages.

Δ Source: Wang *et al.* 2021

Δ Figure 2.12 Changes in annual sediment flux in major river source regions in the Third Pole, 1960–2017.

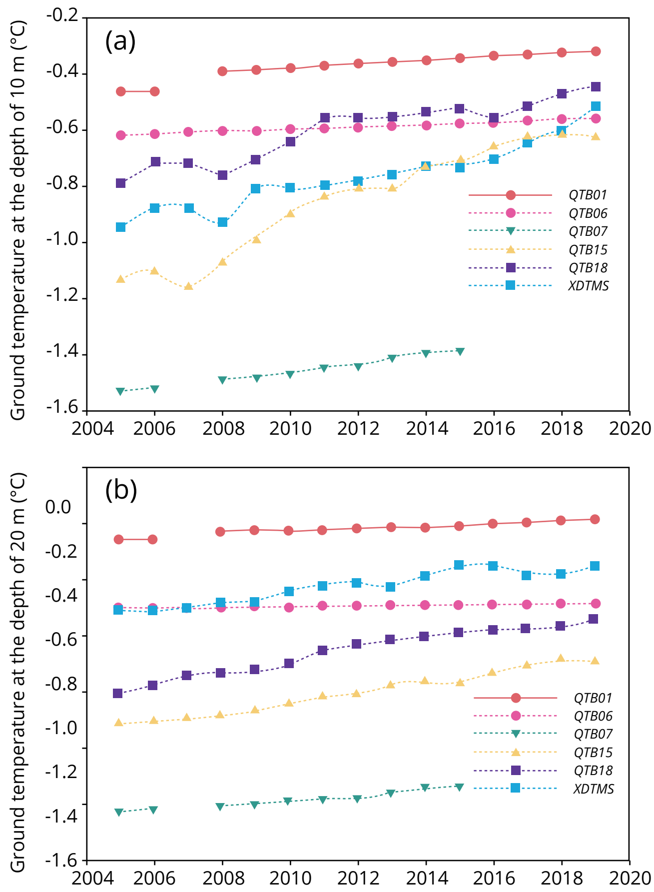


Δ Source: Zhang, Shi and Zeng 2019

2.2.3. Permafrost and its active layer thickness

Vast extent of continuous permafrost is located in Qiangtang Plateau between Tangulha and Kunlun-Karakorum mountains, which are surrounded by the alpine permafrost zone in Qilian, Animaqin and Himalaya mountains. The observed degradation of permafrost is mainly characterized by ground temperature and active layer thickness increases (Cheng *et al.* 2019). All permafrost temperature observation sites showed remarkable warming tendencies, but the increments and rates vary significantly across sites, featuring a maximum increase of ground temperature at 10 metres depth as high as 0.45°C per decade, whilst the minimum as small as 0.04°C per decade **(Figure 2.13a)**. The rates of change of ground temperature at 20 metres depth range from 0.02°C to 0.24°C per decade during the observation years (2005-2020) **(Figure 2.13b)**. Generally, the permafrost with higher temperature has relatively higher warming rates than lower-temperature permafrost (Zhao *et al.* 2021).

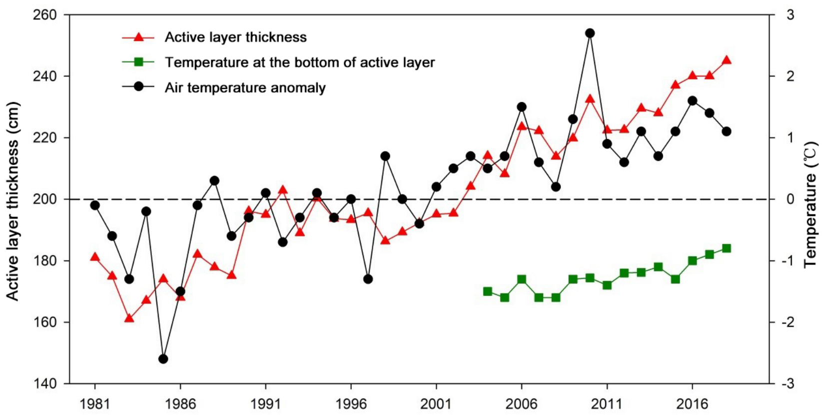
Δ Figure 2.13 Variation of ground temperature at the depth of 10 metres (a) and 20 metres (b) from 2005 to 2019



Δ Source: Zhao *et al.* 2021

Monitoring results of 10 active layer observation sites in permafrost regions along the Qinghai-Tibet highway (Kunlun Mountain pass to Liangdaohe) show that from 1981 to 2019, the active layer is still obviously thickened, with an average thickness increase by 19.5 centimetres every 10 years **(Figure 2.14)**. The active layer has shown the characteristics of thickening in recent years, with the thickening rate accelerating, and the permafrost obviously degraded (Cheng *et al.* 2019).

Δ Figure 2.14 Active layer thickness and bottom temperature in permafrost regions along the Qinghai-Tibet highway (i.e., from Mt Kunlun pass to Liang Dao He sector).



Δ Source: Zhao, L. *et al.* 2019

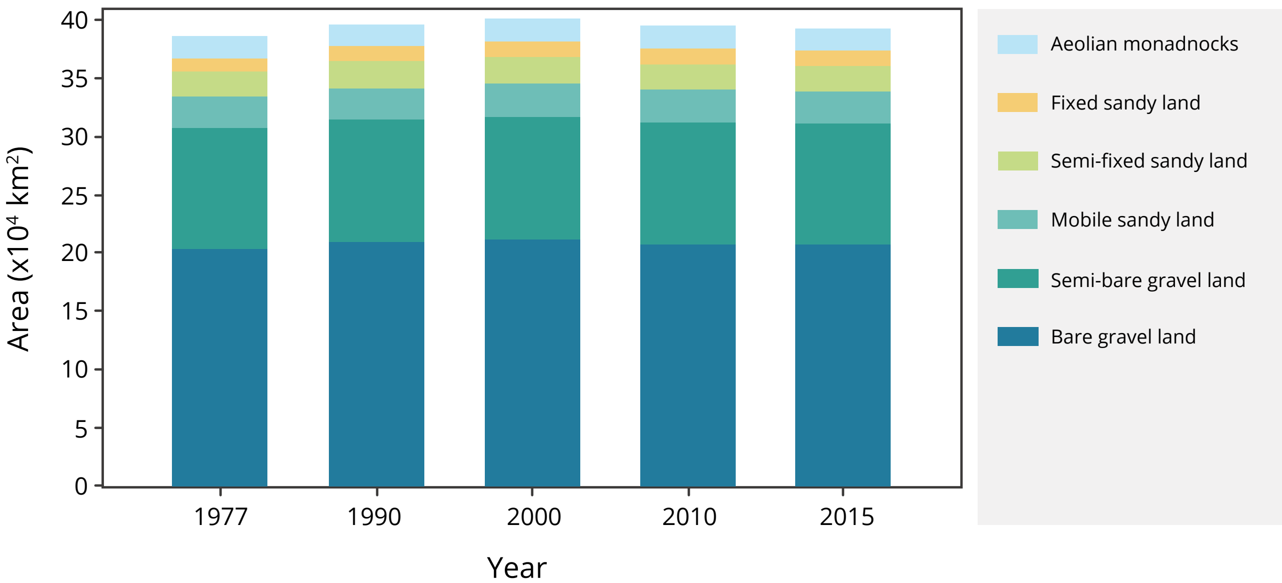
2.2.4. Ecosystem

Soil conditions

Soil in the TP is relatively young and is therefore typically shallow and infertile and dominated by alpine meadow soil (Fang *et al.* 2015). Permafrost thawing and desertification are two major drivers of soil degradation in TP under global warming (Yao *et al.* 2019).

Desert area was around 393,000 km² in the TP in 2015. Overall, desertification across the TP is slight, and the changes from rapid intensification prior to 2000 have decreased in the years thereafter. From 1977 to 2015, desertification increased by 6,255 km² in land area, i.e., 165 km² per year (Zhang, C.-L. *et al.* 2018). While it is not a continuous expansion process for the desertification of land, rather a two-phase process encompassing expansion followed by shrinkage. Particularly, desertification intensified continuously during 1977-2000 at an annual desertification rate of 650 km², while turned to significant reversal during 2000-2015, with the decrease in desertification land area by 580 km² per year **(Figure 2.15).**

Δ Figure 2.15 Area change from land desertification in the Third Pole, 1977–2015



Δ Source: Zhang, C.-L. *et al.* 2018.

Forests

Forests covered 11.3 per cent of the TP's total land area in 2005 (He 2008; Wang *et al.* 2020), mainly comprising firs and alpine pines. At low altitudes, the southern TP region also has evergreen broadleaf forests, a mixture of evergreen broadleaf and deciduous broadleaf forests, and needleleaf and broadleaf forests (Li 1985; Sichuan Forestry Editorial Committee 1990). Forests in the TP underwent three major phases during 1950–2010, including large-scale clearing (1950–1985), coexistence of clearing and forest restoration (1986–1998), and preservation and restoration (1998–2010) (Sichuan Forestry Editorial Committee 1990; Qinghai Forestry Editorial Committee 1993; Bao *et al.* 2002).

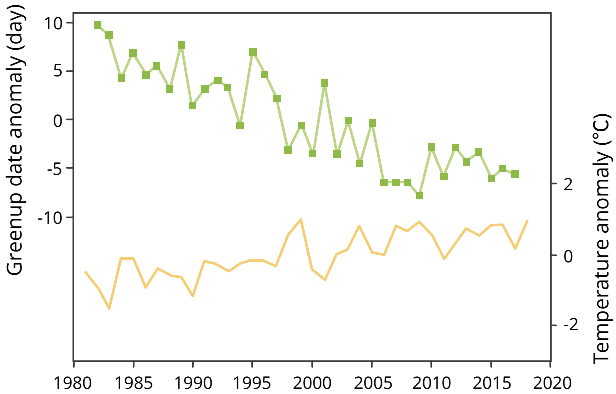
TP forests have exhibited changes, such as the rapid change of the forest age-class structure, i.e. the decrease in old forests and increase in young forests (Hao, Jiang and Wang 2009). The fast disappearance of primary needleleaf forests from the 1960s to 1980s has led to the natural recovery of secondary broadleaf forests and planted spruce forests, thus forming a mosaic of planted needleleaf forests, broadleaf forests and shrub forests (Yan *et al.* 2013). Both forest area and growing stock decreased before 1998, before continuously increasing in the years thereafter. It increased by around 1.3 per cent of the total TP area in 2018 (Wang, Z.P. *et al.* 2020).

Grasslands

Global warming is causing the TP's temperate zone to expand, with it now covering the eastern plateau and northern Qinghai, where the Arctic tundra is becoming grasslands (Zhao, Zhang and Wan 2002). The cold alpine meadow in the Sanjiangyuan (Source of Three Rivers) region has reduced by 8 per cent in area from 1986 to 2000, while the peatland ecological region has sharply reduced by 28 per cent in area. Meanwhile, the alpine-steppe vegetation increased significantly in area, particularly in low-coverage grasslands (< 30 per cent) which expanded by 10 per cent (Wang, Z.P. *et al.* 2020). It is therefore likely that warming will increase the elevation of alpine meadow distribution and its upper limit (Harsch *et al.* 2009; Myers-Smith *et al.* 2011; Li, N. *et al.* 2013; Wang, Z. *et al.* 2013; Myers-Smith *et al.* 2020). Increasing precipitation positively correlated with the vegetation expansion for the arid and semi-arid northwest Tibetan Plateau and warming contributed to the vegetation expanding in the semi-humid southeast Tibetan Plateau (Wang, Z.P. *et al.* 2020). The sharp decline in the croplands is attributed to the shifting from croplands to grasslands, which may be related to the grassland protection projects and urbanization in the past two decades (Luan and Li 2021).

Warming in the TP, particularly in spring and winter periods, has brought about noticeable changes in plant phenology and ecosystem productivity (Natali, Schuur and Rubin 2012; Wang, Z.P. *et al.* 2020). Since the 1980s, vegetation phenology in the TP has advanced in terms of greening, withering and the growing season (Piao *et al.* 2011; Ding *et al.* 2013; Che *et al.* 2014; Piao *et al.* 2017; Wang, Z.P. *et al.* 2020), with an average advancement of 15–18 days **(Figure 2.16).**

Δ Figure 2.16 Time series of greening date and spring temperature anomalies in 1982–2017

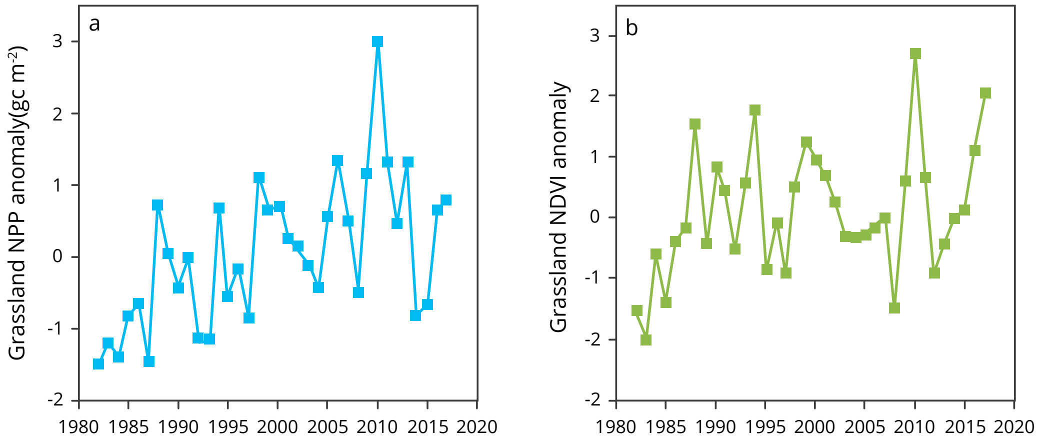


Δ Sources: Piao *et al.* 2017; Wang, Z.P *et al* 2020

Productivity of grasslands in the TP has increased by 5.4 per cent since the 1980s, with an increase of 16.8 per cent due to warming and wetting over the last two decades of the twentieth century (Piao *et al.* 2011; Chen *et al.* 2014; Wang, Z.P. *et al.* 2020), and a decrease in the growth rate to 1.8 per cent in the past two decades following the significant declining trend of the last decades **(Figure 2.17)**. Regional differences in productivity increase of grasslands are evident. The western part of the TP became warmer and drier (leading to decreased productivity) and the eastern part became warmer and wetter (resulting in increasing productivity) (Wang, Z.P. *et al.* 2020). In short, climate change and the implementation of China's Conversion of Cropland to Forest Programme in the TP have positively impacted the productivity of grasslands (Che *et al.* 2014).

Warming increases the net primary productivity as well as carbon uptake of tundra and alpine vegetation and elevates respiration, which may result in a significant change to the terrestrial carbon cycle and soil carbon storage (Davidson and Janssens 2006; Natali, Schuur and Rubin 2012; Sistla *et al.* 2013). The vegetation growth and dominant species transition-induced "greening" also has positive feedback for warming by reducing the land surface albedo and increasing the radiation absorption (Pearson *et al.* 2013).

∆ Figure 2.17 NPP (Figure a) and NDVI (Figure b) variations of Third Pole grasslands, 1982–2017



∆ Notes: NPP is calculated using the Carnegie Ames Stanford Approach (CASA) model.

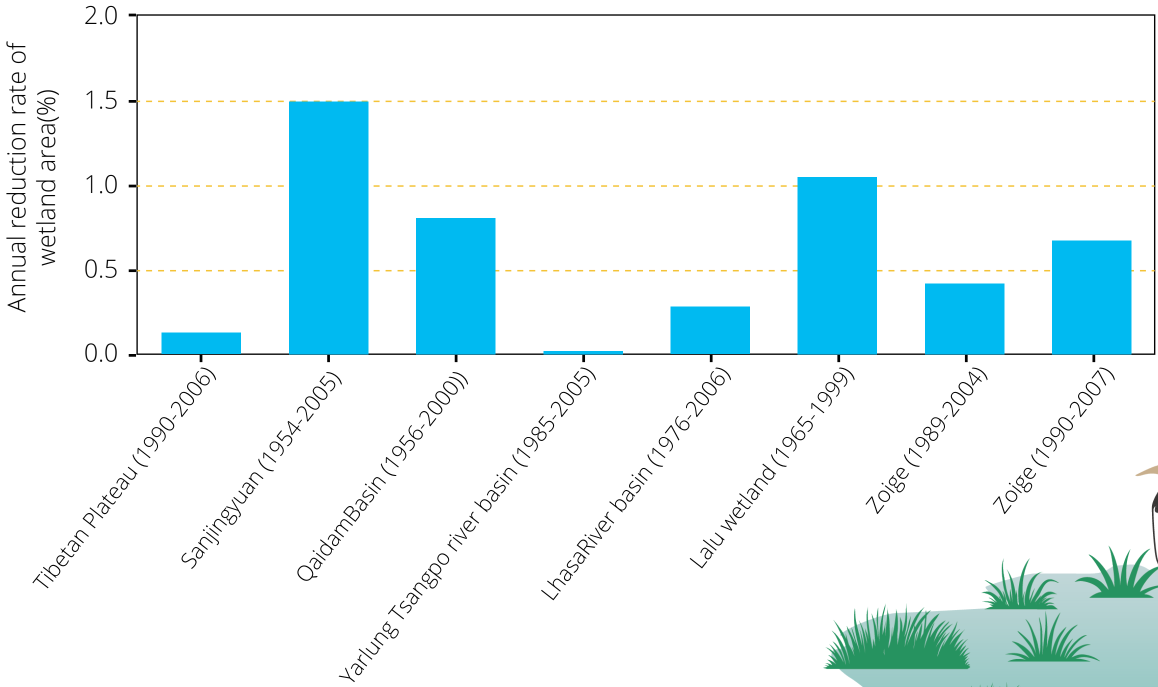
∆ Source: 1982-2011 data are from (Chen *et al.* 2014), 2012-2017 data are extended using the same method.

Wetlands

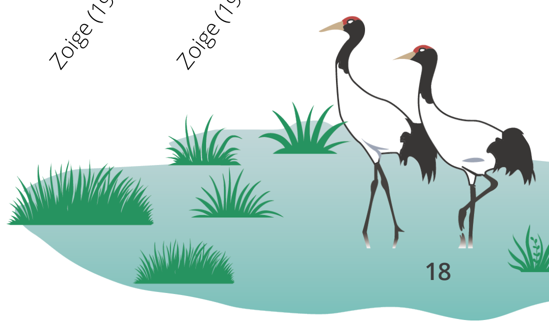
Having shrunk at an annual rate of 0.1 per cent during 1990–2006, the TP's wetlands experienced overall shrinkage and continuous deterioration prior to 2000, decreasing by 3,000 km^2 in total area (Qiu 2008).

The variation of wetland decline shows distinctive spatial and temporal variation patterns. Spatially, the area of wetlands in Sanjiangyuan and Zoige have decreased at an annual rate of 1.5 per cent and 0.7 per cent, respectively, while those on Qangtang Plateau have increased at an annual rate of 12.4 per cent **(Figure 2.18)** (Wang *et al.* 2007; Xing *et al.* 2009; Yao *et al.* 2011; Wang, Z.P. *et al.* 2020). Temporally, wetlands in Sanjiangyuan, Zoige and Qangtang Plateau deteriorated during 1985–2000 (the shrinkage of which accounts for more than 70 per cent of the total wetlands area), with rates slowing in Sanjiangyuan and Zoige after 2000, yet further intensifying in the Qangtang Plateau (Xing *et al.* 2009; Yao *et al.* 2011; Li, N. *et al.* 2013; Wang, Z.P. *et al.* 2020). In general, wetlands in the TP have suffered large-scale declines during the past several decades because of climate change (Qiu 2008) and increasing human population (by 61.9 per cent) with a huge influx of tourists from 35,000 to 6.0 million (Xue *et al.* 2014). The total area of wetlands is predicted to decline further by 35.7 per cent, and all wet meadow and saltmarsh areas in the Qiangtang basin will disappear under all scenarios. Vital functions of alpine wetlands such as carbon sequestration, water maintenance and habitats will be at severe risk (Xu *et al.* 2019).

∆ Figure 2.18 Annual average reduction rates of peatland areas in selected regions



∆ Sources: Wang *et al.*2007; Xing *et al.* 2009; Yao *et al.* 2011; Wang, Z.P. *et al.*2020



Farmlands

Farmlands in the TP are mainly located around the Lhasa and Nianchu river basins along the Yarlung Tsangpo ('one river, two streams area') and the Yellow River valley. Crop plantation in the TP is constrained by thermal conditions and thus has one harvest season and suitable elevation below 4,200 metres a.s.l. An increase in temperatures would contribute to the expansion of agricultural areas and uplift in the altitudinal limit of the regional plantation (Peng *et al*. 2012). The agricultural area used to grow winter wheat, i.e., the typical TP plantation, has significantly increased from the mid-1970s, following the elevation of its upper growth limit by 133 m in altitude from 1970 to 2000. The upper limit for spring barley plantations also increased, rising from 4,270 metres to 4,827 metres a.s.l (Zhang 2011).

Crop growth and productivity have also responded to climate changes. Temperature rise in the TP over the past 30 years has brought about considerable changes to agricultural thermal resources. Crop growth periods with daily temperatures above 0ºC have extended by 4–9 days per decade, while periods with daily temperatures above 10ºC have extended by 4 days per decade (Zhang *et al.* 2010; Fiwa *et al.* 2014; Zhao *et al.* 2015). Warming in the TP is particularly significant during the winter periods, resulting in a safe overwintering for crops. Overall, global warming has led to increased crop productivity in the TP (Zhao *et al*. 2015). However, rising temperatures have negatively influenced the nutritional quality particularly starch concentration in cereals (Zhao *et al*. 2015). The growth acceleration due to higher average temperature also results in less radiation interception, increases invasion and establishment of alien plant species, which extirpate native biodiversity and increase incidence of plant diseases and pest infestation (Aryal *et al.* 2020; Bhatta *et al.* 2019; Fang *et al.* 2020).

2.3. Summary

The region experienced both warm and cold periods, with a general warming and wetting trend over the past 2000 years. Temperature increase has accelerated in recent decades, with a warming rate that doubles the global average and shows seasonal and regional differences. Precipitation has also increased in the TP since 1960s. However, there is a significant regional heterogeneity in the precipitation trend, which has increase in the north and decreases in the south of TP.

The general warming since the twentieth century has triggered an overall glacial retreat. This loss of glacier mass is particularly noticeable in the Himalayas and south-eastern region of the TP. The number and areas of lakes in the TP were stable prior to the 1990s, but began to increase and expand thereafter. River run-off in the TP has generally shown no significant trend over the past decades, with the exception of the Yellow River (increasing), Yangtze River (decreasing) and Upper Indus (increasing). This result suggests there has been little human impact and that the effects are instead mostly the result of precipitation and glacier melt.

Overall, there has been a significant change in the ecosystem. Vegetation is generally improving in the TP, as demonstrated by earlier starts to the growing season, the expansion of vegetation coverage and the increase in ecosystem productivity. The increase in the vegetation coverage is strengthening the water-holding capacity of soil, which used to experience active layer thickening and permafrost warming throughout the TP, while also expanding desertification in the river source regions. The overall worsening trend of soil and water loss improved slightly after the 2000s.

3 Impact of human activities on the Third Pole environment

Despite the harsh living conditions associated with its high elevations, the TP is mostly inhabited by ethnic minorities and also surrounded by populous nations which feature different religions, lifestyles, and diverse development modes and concepts. The TP is also one of the most biologically diverse regions in the world, having high plant and animal endemism, and well known for its rare and endangered flora and fauna. At present, governments and scientific institutions are making great efforts to conserve this region with successful results. This chapter assesses the impact of human activities on the TP's environment and presents current status of biodiversity research, protection and challenges. The issues feature transboundary concerns, which comprise alien species invasion and air pollution including black carbon (BC), heavy metals and persistent organic pollutants (POPs). The assessment therefore focuses on the impact of activities within the TP area as well as pollution generated outside the TP that has been transported into the region. It also evaluates the impact of invasive species.

3.1 Air pollutants from the surrounding regions are negatively affecting the Third Pole environment

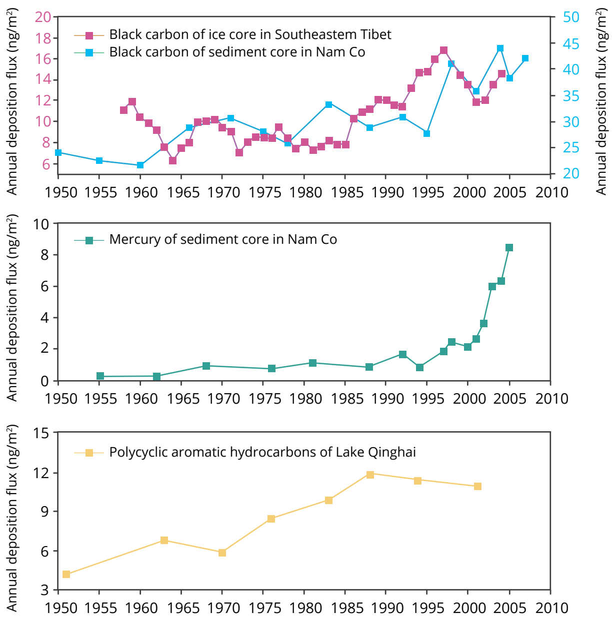
This section assesses the available information on the three major classes of air pollutants on the TP - BC, heavy metals and POPs. BC is important in climate change due to its strong solar absorption properties, and it is also considered as a proxy for anthropogenic emissions, such as biomass burning and coal combustion (Bond *et al.* 2013). POPs and mercury (Hg) are toxic chemicals that have adverse effect on human and ecosystem health, and can be transported long distances due to their persistent characteristics (Kang, S.C. *et al.* 2019).

Due to the relatively small population and hence limited sources of air pollution, TP receives less influence from local anthropogenic emissions. However, TP is located downwind of various anthropogenic air pollution hotspots, such as South Asia and Middle East/West Asia. Anthropogenic emissions (especially combustion related) from South Asian Countries and Middle East/West Asian Countries could be brought into TP under favourable atmospheric circulations (Cong *et al.* 2015), while arid dust from the surrounding deserts such as the Taklamakan is also carried to the TP (Huang *et al.* 2017). A comprehensive experiment integrated in situ measurements and remote sensing observations on the TP revealing that although the overall mass concentrations of atmospheric particulate matters are relatively low on the TP, obvious regional variations were identified (Liu *et al.* 2017). Specifically, based on the long-term observation in background sites, the daily averaged PM2.5 concentrations in west (i.e., Ngari, 18.2 ± 8.9 microgram per cubic metre [μg m^{-3}]) and south (i.e., Mt. Qomolangma 14.5 ± 7.4 μg m^{-3}) of the TP are higher than that in the inland of TP (i.e., Nam Co, 11.9 ± 4.9 μg m^{-3}). This implies that the atmospheric environment on the TP could be affected by dispersion of air pollutants from South Asia and Middle East/West Asia.

Meteorological factors play a significant role in the air pollutant transport. Given its high elevation, the TP region has enhanced thermal (heating and cooling) contrasts compared with the surrounding region and oceans. This phenomenon plays a major role in modulating the East Asian Summer Monsoon and the South Asian Summer Monsoon. Both these monsoon systems have their own atmospheric pathways and mechanisms for transporting air mass, moisture and pollutants (Azam *et al.* 2021). High winds (especially during pre-monsoon and summer seasons) lift the natural dust from the arid/desert region and, depending upon the wind magnitude can transport dust over long distances inside the TP region (Liu *et al.* 2008). Beside the monsoon circulation, the westerlies also could bring polluted air mass into the TP region (Dimri *et al.* 2015; Kang, S.C. *et al.* 2019). Further, field observations (Bonasoni *et al.* 2010; Cong *et al.* 2015) have confirmed the uplifting and delivering across the Himalayas of air pollutants (e.g., BC and ozone) at the South Asia lowland by the daytime up-valley breeze, the mechanism conducive to enhancing the transport of air pollutants to the Plateau (Kang, S.C. *et al.* 2019).

Examination of the ice core and lake sediment records allows the re-construction of atmospheric pollutant deposition over a longer time scale. **Figure 3.1** shows the evolution of BC, mercury and polycyclic aromatic hydrocarbon in the TP for the past half-century. Results show that the deposition flux of BC and mercury peaked early this century while polycyclic aromatic hydrocarbon shows a different albeit an increasing trend. The following sections provide further assessment on each of different types of pollutants.

Δ Figure 3.1 Deposition flux of black carbon, mercury and polycyclic aromatic hydrocarbons reconstructed from ice and lake sediment cores in the Third Pole.



Δ Note: Deposition flux is calculated by multiplying the concentration of a given pollutant with the accumulation rate of ice or sediment.

Δ Sources: Cong *et al.* 2013; Xu *et al.* 2009; Yang,H.D. *et al* 2010; Wang *et al.* 2010

3.1.1. Black carbon

Black carbon (BC) not only contributes to global warming with its radiative forcing affects, but also darkens glacier surface and reduces albedo, and consequently accelerates glacier melt by absorbing the heat. In recent years, there has been a wealth of research on BC and its impact on increased surface temperature, reduction of surface snow/ice albedo, and enhanced glacier melt in TP by using in-situ, satellite and modeling techniques (Kang, S.C. *et al.* 2019). In general, atmospheric BC concentrations decreased noticeably from the surrounding urban regions into the TP interior, consistent with its emission load and also affected by transport process and meteorological conditions (Chen, F. *et al.* 2019; Yang, J. *et al.* 2019; Pandey *et al.* 2020; Prabhu *et al.* 2020). In the surrounded urban areas, such as Kathmandu (Nepal), Karachi (Pakistan), and Dushanbe (Tajikistan), there exhibited extremely high BC concentrations (9.97±5.84, 8.52±4.79, and 5.13±2.24 μg m^{-3}, respectively), with low and high values occurring in the monsoon and non-monsoon seasons, respectively; however, results in remote regions in the TP interior (e.g., Nam Co and Ngari, with BC of 0.13±0.11 and 0.31±0.13 μg m^{-3}, respectively), southeastern margin (Lulang, with BC of 0.70 ± 0.33 μg m^{-3}) of the TP, or high-altitude sites over western TP (e.g., Muztagh Ata with BC of 0.055 μg m^{-3}) demonstrated much lower BC concentrations (Cao *et al.* 2009; Chen, F. *et al.* 2019; Kang, S. *et al.* 2019; Zhao, Z. *et al.* 2019; Dumka *et al.* 2020).

When deposited on glacier and snow surface, the average BC concentrations in snow pits were about 50 nanogram per gram (ng g^{-1}) over the TP, but ranged from a few ng g^{-1} to thousands of ng g^{-1} based on snow and ice condition (Ming *et al.* 2013; Kang *et al.* 2020; Gul *et al.* 2021). Relatively higher BC concentrations in snow were observed in the central to northern TP compared to southern TP. Ice core BC records revealed that the amplification of BC concentrations during contemporary period (since 1950s) was consistent, showing a two-to three-fold increase compared with that during 1850~1940s (Xu *et al.* 2009; Ge *et al.* 2017; Kang *et al.* 2020). However, despite the similar magnitudes of BC increases in the Tibetan ice cores, the timings of the increases and peaks in BC concentrations were not in concert. The ice cores in central and western TP showed a rapid increase in concentration of BC from 1850 to 2010s and from 1850s to 1980s, respectively (Kang *et al.* 2020). While in the Himalayas, ice core from Mt. Everest region indicated the timing of the increase in BC was consistent with BC emission inventory data from South Asia and the Middle East; however, since 1990, the ice core BC record did not indicate continually increasing BC concentrations (Kaspari *et al.* 2011) suggesting that BC missions have decreased in recent decades.

Carbon isotope analysis ($\Delta^{14}C/\delta^{13}C$) indicated that the contribution of biomass burnings to BC was approximately 54 ± 11 per cent in the Himalayas and more than 60 per cent in the inland TP, while the northern TP was mostly from fossil fuel combustion sources (66±16 per cent) (Li *et al.* 2016), indicating different BC source regions. Community Atmosphere Model 5.0 modeling showed South Asia biomass burning and fossil fuel combustion have the largest impact on BC in the Himalayas and central TP, while East Asia fossil fuel combustion and biomass burning contributed the most to the northeast plateau in all seasons and southeast plateau in the summer; Central Asia and Middle East fossil fuel combustion emissions have relatively more important contributions to BC reaching the northwest plateau, especially in the summer (Zhang *et al.* 2015; Pandey *et al.* 2020; Prabhu *et al.* 2020). The Weather Research and Forecasting (WRF) model coupled with Chemistry modelling demonstrated that the majority of anthropogenic BC over the TP was transported from South Asia, which contributed to 40-80 per cent of surface BC in the non-monsoon season, and 10-50 per cent in the monsoon season; for the northeastern TP, anthropogenic BC from eastern China accounted for less than 10 per cent of the total in the non-monsoon season but can be up to 50 per cent in the monsoon season (Yang, J. *et al.* 2018). These results indicated that accumulated atmospheric BC at the southern foot of the Himalayas can traverse the Himalayas and reach the inland TP region (Kang *et al.*, 2019). Episodic cross-Himalayan pollution was transported through the major south–north valleys and over the Himalayas, and into the inland TP (Lüthi *et al.* 2015; Chen *et al.* 2018). Local meteorological processes, such as mountain peak-valley wind systems, may also facilitate the trans-Himalayan transport of atmospheric BC (Cong *et al.* 2015).

Based on a regional climate model (RegCM4.3.4) coupled with an aerosol-snow/ice feedback module, the surface temperature was simulated to be increased by 0.1-1.5ºC due to the potential radiative feedback of BC aerosol over the TP in 1990-2009 (Ji 2016). However, the anthropogenic BC induced negative radiative forcing and cooling effects at the near surface over the TP (Yang, J. *et al.* 2018). BC deposition and its climate effects profoundly accelerated the glacier and snow melting (Xu *et al.* 2009; Qian *et al.* 2015; Yao *et al.* 2019). With strong light-absorption, BC in snow and ice surface can contribute up to 20 per cent reduction of albedo in the TP based on observations and model estimates (Kang *et al.* 2020). This leads to a radiative forcing of several Watt per square meter (W m^{-2}) in fresh snow to hundreds of W m^{-2} in aged snow (Li, X.F. *et al.* 2017; Li, Y. *et al.* 2021). The annual mean radiative forcing (0.42 W m^{-2}) due to BC in snow outweighs the BC dimming effect (0.3 W m^{-2}) at the surface over the HTP (Zhang *et al.* 2015). Simulation of BC-in-snow resulted the loss of SWE through melting exceeds 25 mm in some parts of the western TP and the Himalayas (Ji 2016). Estimation illustrated that BC can reduce the snow cover durations days by 3-4 days over the TP (Zhang *et al.* 2018). BC on four glaciers in the Pamir region contributed to 6.3 per cent of the glacier melt, corresponding to an increase in summer snowmelt of up to 0.8 mm per day (Schmale *et al.* 2017). Generally, BC can enhance the glacier melting by 15-20 per cent, with snow melt of 9.65 mm per day or 70-204 mm in Himalayas to about 400 mm in the central to northern TP (Yasunari *et al.* 2010; Thind *et al.* 2019; Kang *et al.* 2020; Gul *et al.* 2021; Li, Y. *et al.* 2021). During the past 40 years, the glacier mass loss of glaciers on the TP has been approximately 450 km^3, 20-80 km^3 of which are due to the effects of BC and other light-absorbing impurities (Zhang, Y. *et al.* 2018). Therefore, BC plays an important role in modulating the water availability, snow cover, glacier area and prevailing weather condition all of which directly impacts the TP ecosystem.

3.1.2. Heavy metals

Heavy metals have been increasingly studied throughout the TP to assess their concentration levels, the sources, and their impact on human health and environment. Heavy metals in ice cores drilled from Mt. Everest, Guliya, and Miao'ergou exhibited varied historical changes but showed consistent increases since the mid to late twentieth century (Kaspari *et al.* 2009; Lee *et al.* 2011; Wang, C.M. *et al.* 2016; Sierra-Hernandez *et al.* 2018). This trend coincides with the historical anthropogenic emission of heavy metals in South and Central Asia, which is different from the records in the Arctic and Alps, therefore indicating the impact of regional anthropogenic emission on the TP environment (Eyrikh *et al.* 2017; Sierra-Hernandez *et al.* 2018).

Heavy metals in glacier snow and atmospheric aerosols are mainly from crustal sources where anthropogenic contributions are mostly found at places in the periphery areas of the plateau (Wei *et al.* 2017; Jiao *et al.* 2021), in proximity to heavy anthropogenic emission regions. In the Himalayas, heavy metals such as copper, zinc, and lead showed decreased concentrations with the increase of south-to-north elevation gradient, indicating the impact of South Asia emission on the Himalayan atmospheric environment (Rawat *et al.* 2021).

Mercury (Hg) is a global pollutant of interest because of its persistence in the environment, its ability to bioaccumulate in addition to its toxicity. Due to long range transport, it is often observed in remote areas such as the TP region. Increased Hg concentration in ice cores and lake sediments over the TP since 1950s have been attributed to rising Asian Hg emissions (Yang, H.D. *et al.* 2010; Kang *et al.* 2016). However, current measurements of Hg concentrations in the TP atmosphere, water and soil remain low and are comparable with global reference levels (Kang *et al.* 2016). It should be noted that, indigenous Tibetan fish were found to have Hg levels that exceeded the safety standards for human health due to their slow growth rate, long lifespan and efficient accumulation of the heavy metal along the aquatic food chain, which is indicative of the sensitivity and fragility of Tibetan ecosystems to Hg pollution (Zhang, Q.G. *et al.* 2014).

With respect to Hg in glaciers, although levels were low in accumulation zones (Zhang, Q. G. *et al.* 2012), glaciers were found to cultivate Hg-enriched cryoconites in ablation zones (Huang, J. *et al.* 2019). Whether the melting of glaciers will serve as a source and sink of Hg remains unclear, though increasing studies have stressed enhanced Hg export in glacierized basins (Sun *et al.* 2017). Studies also indicate that the plants in glacier-retreated zones can absorb atmospheric Hg over time (Wang, X. *et al.* 2020).

Overall, the TP remains an area with very low heavy metal concentrations in the diverse environmental matrices. However, biological samples with elevated Hg in the environment suggests that it is important to continuously monitor heavy metal pollution and assess its potential impact on human health and ecosystems (Kang, S. *et al.* 2019). Meanwhile, with the rapid decline of the cryosphere due to changing climate, particularly glacier retreat and permafrost degradation, the role of changing cryosphere in redistributing the heavy metals in the TP's environment remain uncertain and warrants further study and assessment.

3.1.3. Persistent organic pollutants

POPs are a class of semi-volatile organic compounds with persistence, high toxicity, and the potential of long-range atmospheric transport. Due to low temperature, some remote regions such as the Arctic, Antarctica, and the TP accumulate POPs and become their "sink" (Wania and Mackay 1996; Wang *et al.* 2019).

For the TP, the upwind surrounding regions, especially South Asia, are the main contributors of POPs. Although most POPs have been restricted globally, due to the huge historical usage (Yadav *et al.* 2016), the atmospheric concentrations of pesticide POPs, such as dichlorodiphenyltrichloroethanes (DDTs) and hexachlorocyclohexanes (HCHs), in South Asia are on the highest levels globally (Pozo *et al.* 2009; Nasir *et al.* 2014; Pokhrel *et al.* 2018). The record of ice cores showed that the highest atmospheric deposition fluxes of DDTs and HCHs in the Mt. Qomolangma regions occurred in 1970s, matching with the emission peaks of DDTs and HCHs in South Asia (Wang *et al.* 2008), indicating that long-range atmospheric transport (LRAT) from South Asia as one of the primary sources of POPs in the TP.

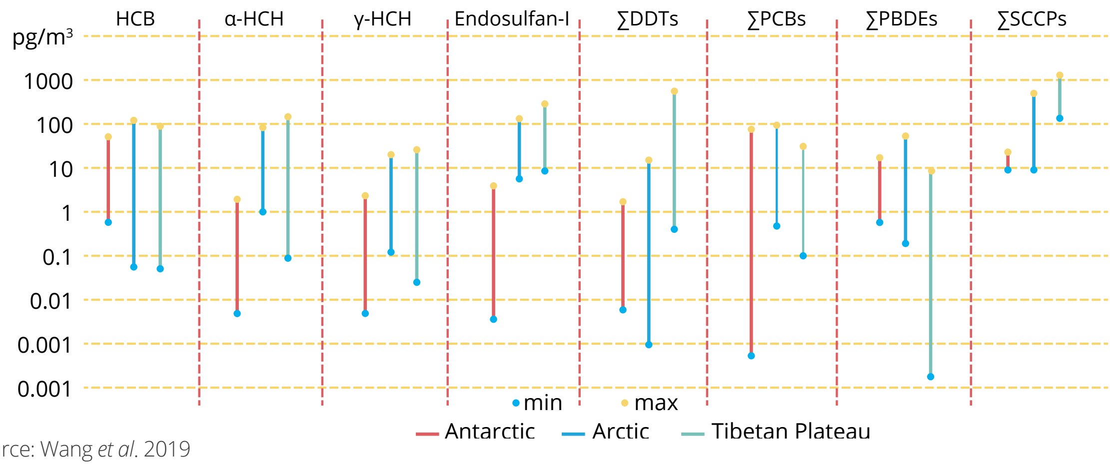
For monitoring the possible transport of POPs to the TP, the long-term plan of POPs observation started in 2007 featuring a 30-site monitoring network over the TP (Wang *et al.* 2019). The annual and seasonal concentrations of atmospheric POPs are collected by passive and active air samplers, and the samples of soil, vegetation, water, snow, and organisms are also collected to estimate the accumulation of POPs in ecosystems. The atmospheric concentrations of POPs such as hexachlorobenzene (HCB, 2.8-80 picogram per cubic metre [pg/m^3]) and HCHs (0.1-36 pg/m^3) in the TP region are as low as the levels measured in the Arctic, while the levels of atmospheric polychlorinated biphenyls (1.8-8.2 pg/m^3) and polybrominated diphenyl ethers (0.1-8.3 pg/m^3) are far less than those found in the Arctic **(Figure 3.2)** (Wang *et al.* 2019). The concentration of DDT over the TP region (5-75 pg/m^3) is higher than that observed over the Arctic and Antarctica, presumably due to the high atmospheric levels of pesticides in South Asia (Wang, X.-P. *et al.* 2010).

The spatial distribution of atmospheric POPs derived from the long-term monitoring network also reveals the sources of POPs in the TP. Generally, relatively higher concentrations of atmospheric DDTs (up to 80 pg/m^3) were observed in the southern TP, the concentrations almost identical to that in South Asia while much more than that in the central or northern TP (2-25 pg/m^3) (Wang, X.-P. *et al.* 2010; Wang, X. *et al.* 2016). It further suggested that South Asia could be source regions of POPs. The Indian monsoon is considered one of the major driving forces for the transport of POPs into the southern TP region, which were revealed by the synchronous fluctuations between Indian

Monsoon Index and the atmospheric DDT concentrations measured in a valley between the TP and South Asia (Sheng *et al.* 2013). Although the Himalayas played a role of hindering the atmospheric transport of POPs from South Asia to the TP, it is estimated that approximately 1–10 per cent of POPs (estimated to be up to 100 tons per year) are transported over the Himalayas into the TP region (Gong *et al.* 2019). In addition, the relatively higher composition of HCB can be found in the northern TP, which suggested that westerlies may load POPs onto the TP, implying possible source regions as in Central Asia (Wang, X. *et al.* 2015).

POPs deposit and accumulate in soil (Ren *et al.* 2019), snow (Wang *et al.* 2019) and biota (Ren *et al.* 2017) when they arrive in the TP. The forest ecosystem in the southeast TP hindered the transported POPs (Ren *et al.* 2014), and the forest soil with high content of organic matters is becoming the POP 'sink', which receive the deposition of atmospheric POPs (Wang *et al.* 2014). From the observation of POPs in vegetation and animals along the terrestrial (Wang, C. *et al.* 2015) and aquatic ecosystems (Ren *et al.* 2017) in the TP, it was found that POPs concentrations could be magnified by 2-4 times along the food chains. Although the levels of POPs in the air, water, and soil are quite low compared with that in the urban, agricultural, and/or polluted regions, the bio-magnifications of POPs along the food chains may still threaten the health of ecosystems and humans. Due to global warming, retreating glaciers in the TP are releasing deposited POPs into rivers and lakes (Chen, M. *et al.* 2019), which is increasing the risks associated with POPs in the TP.

Δ Figure 3.2. Comparison of the concentration ranges of atmospheric POPs in the Antarctica, Arctic, and TP



Δ Source: Wang *et al.* 2019

3.2 Biodiversity is rich and well preserved, but still faces major challenges in the Third Pole

Known as the 'Water Tower' of Asia, the Tibetan Plateau and its adjoining mountain ranges which constitutes the Third Pole is important for biodiversity and global conservation efforts. Its diverse altitudinal gradients and variations in latitude and longitude create many micro climatic zones and a rich biodiversity. It contains a rich variety of flora and fauna with a high proportion of endemism and is the habitat for some of the most charismatic species, including the snow leopard (Panthera uncia), giant panda (Ailuropoda melanoleuca) as well as numerous other ungulates. This region is surrounded by four biodiversity hotspots namely Himalaya, Mountains of Southwest China, Mountains of Central Asia and Indo Burma (Favre *et al.* 2015). The TP has witnessed a number of successful conservation efforts with an increase in populations of some species and expansion of protected areas (Fu *et al.* 2021). However, in recent decades, there has been growing concern in relation to the prevalent drivers of change such as climate change. This chapter highlights the global importance of the TP in terms of biodiversity and some protective practices while identifying some gaps in conservation efforts and makes some recommendations. Due to the scarcity of data, the analysis of species data is mainly limited to the Third Pole in China.

3.2.1. Research on Biodiversity in the Third Pole

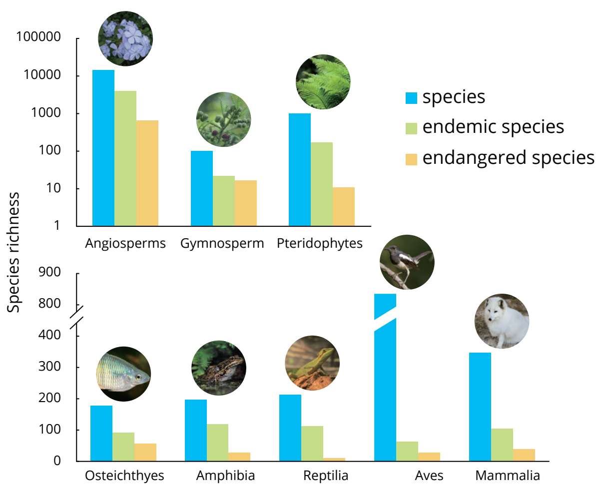
The TP, characterized by the world's largest elevational gradients developed through Cenozoic evolution, has complex micro-climatic and soil conditions which has resulted in ecosystem diversity with great faunal and floral uniqueness, abundance and rarity (Zhang, Chen and Li 2002; Chettri *et al.* 2012; Mosbrugger, Favre and Muellner-Riehl 2018; Zu *et al.* 2019). The biodiversity of the TP has been shaped by a long and complicated evolutionary history of colonization, agriculture and land use practices, local recruitment and in situ diversification driven by ancient orogenic and climate changes (Che *et al.* 2010; Miehe *et al.* 2014; Chen, F.H. *et al.* 2015; Deng *et al.* 2020; Ding *et al.* 2020; Xu *et al.* 2021). The biodiversity of the TP ranges from micro-organism to iconic species along with diverse flora, birds and other organisms (Smith and Foggin 1999; Chettri *et al.* 2012; Adhikari *et al.* 2019; Zu *et al.* 2019). As one of the most biologically diverse regions in the world, conservation of TP biodiversity is of global importance and widely acknowledged at regional (IPBES 2018) as well as global levels (Bongaarts 2019). However, the changing land use pattern, human population, infestation by invasive species, pollution and increasing threats from climate change are adding challenges for maintenance of the rich natural heritage of TP (Li *et al.* 2018; Gillespie *et al.* 2019; Luan and Li 2021).

3.2.2. Current status of biodiversity

The TP has one of the most diverse ecosystems in the world (Favre *et al.* 2015). Overall, 1,763 vertebrate species are found in this region, including mammals, birds, reptiles, amphibians, and fish **(Figure 3.3)**, which encompass five classes, 39 orders and 157 families. These account for 45.8 per cent of the total terrestrial vertebrates and freshwater fish found in China (Jiang *et al.* 2016). In addition, around 40 per cent (14,634 species) of the vascular plant species in China are found in this area, including pteridophytes, gymnosperms and angiosperms **(Figure 3.3)**, which belong to 2,047 genera and 249 families.

The species richness reaches its peak in the southern and south-eastern part of the TP in the Himalaya and Hengduan Mountains (Chettri 2010; Wu *et al.* 2013; Manish *et al.* 2017; Rana, Price and Qian 2019). About 60 per cent of mammals and over 80 per cent of birds are found in this area. Animal species richness is greatest at the middle elevations of

Δ Figure 3.3 Richness of species, endemic species and endangered species of vertebrates and vascular plants in the TP.



Δ Source: Fu *et al.* 2021

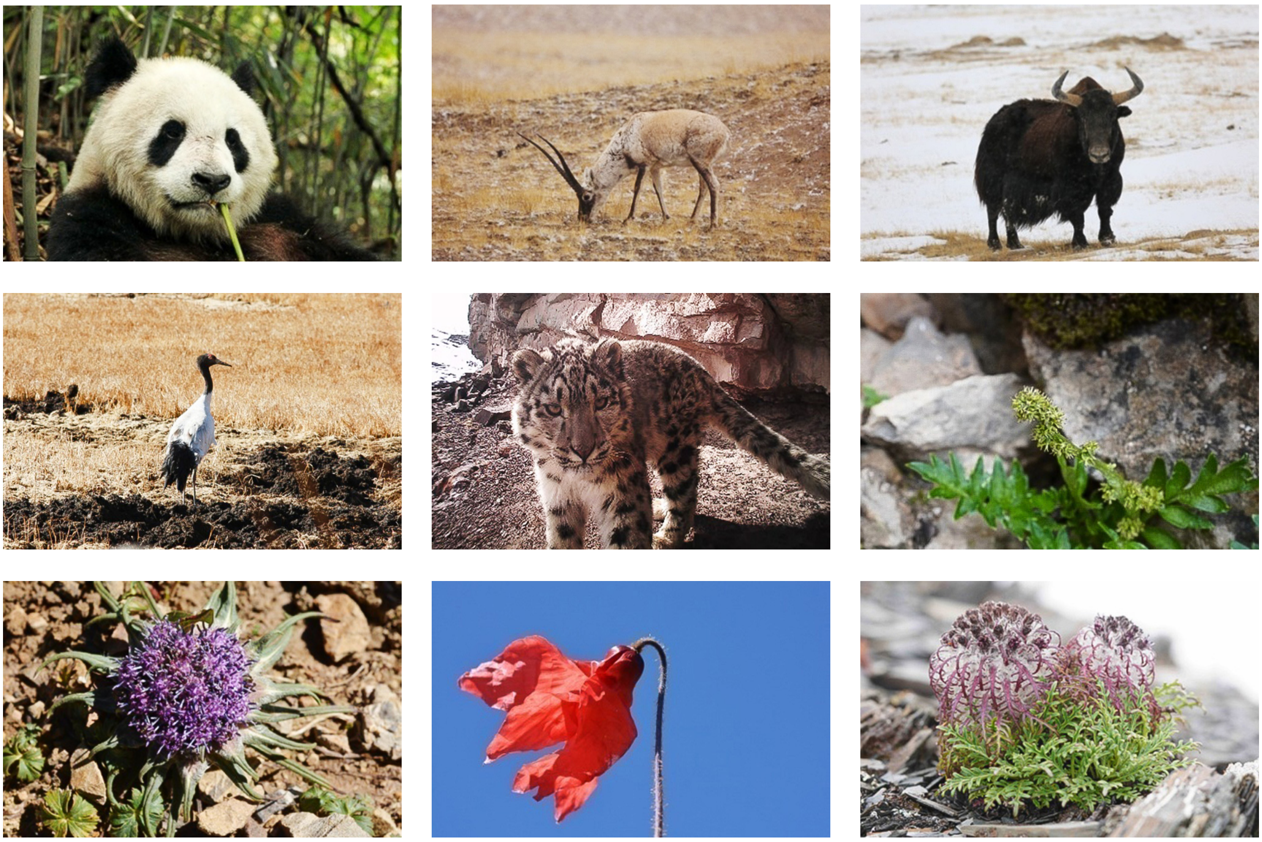
this area (Acharya *et al.* 2011; Wu *et al.* 2013; Price *et al.* 2014; Hu *et al.* 2017), with amphibian species richness in particular peaking between 1,200 metres and 1,400 metres and reptile species richness peaking between 1,100 metres and 1,300 metres (Fu *et al.* 2006; Fu *et al.* 2007; Khatiwada *et al.* 2019; Chettri and Acharya 2020).

The TP is also a region of high endemism for animals and plants **(Figure 3.3).** Endemic animal species comprise 28 per cent of the total in this region, with amphibians having the highest rate of endemism (59.9 per cent), followed by reptiles (53.3 per cent), fish (51.7 per cent), mammals (30.3 per cent) and birds (8 per cent). More than 4,000 endemic Chinese plant species (including varieties, subspecies taxon) also occur in this region, most of which are angiosperms (3,818 species), with the rest comprising pteridophytes (165 species) and gymnosperms (21 species). The TP also has 3,764 species of endemic seed plants, which account for 24.9 per cent of all endemic plants in China (Yu *et al.* 2018). Endemism varies across altitudes, with endemic mammals peaking between 2,500 and 3,000 metres (Hu, Liang and Jin 2018) and the maximum number of endemic plant species occurring at high elevations (Shrestha and Joshi 1996).

The TP is well known for its variety of rare and endangered animals and plants **(Figure 3.4).** These include charismatic species such as the giant panda (*Ailuropoda melanoleuca*), snow leopard (*Panthera uncia*), Tibetan antelope (*Pantholops hodgsonii*), Przewalski's gazelle (*Procapra przewalskii*), snow lotus (*Saussurea laniceps*), black-necked crane (*Grus nigricollis*), *Rhodiola crenulata, Saussurea wellbyi* and *Meconopsis punicea*. The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (2020) includes 169 animal species from this region , accounting for 9.6 per cent of all animal species in the TP, identifying 16 Critically Endangered, 66 Endangered and 87 Vulnerable species. Among the animal species, 71 per cent of the ungulates are highly threatened with 55 per cent of them included in the Convention on International Trade in Endangered Species of Wild Fauna and Flora list (Jiang *et al.* 2018).

There are also 662 Threatened and Extinct plant species in the region, which contain around one-fifth of China's Threatened and Extinct vascular plant species (3,701 species). These belong to 284 genera and 110 families, including pteridophytes (10 species), gymnosperms (16 species) and angiosperms (636 species). The China Species Red List (2015) indicates that 2.7 per cent of the TP's vascular plant species (~398) are Vulnerable, 190 (1.3 per cent) are Endangered, 69 (0.5 per cent) are Critically Endangered, 1 is regionally Extinct and 4 are Extinct.

Δ Figure 3.4 Charismatic species in the Third Pole



Δ Note: Top row, left to right: giant panda *(Ailuropoda melanoleuca)*, Tibetan antelope *(Pantholops hodgsonii)*, domestic yak *(Bos grunniens)*; middle row, left to right: black-necked crane *(Grus nigricollis)*, snow leopard, *Sinadoxa corydalifolia*; bottom row, left to right: Saussurea wellbyi, *Meconopsis punicea* and *Saussurea leucoma*.

Δ Photos: © The Second Tibetan Plateau Scientific Expedition and Research.

3.2.3. Biodiversity conservation efforts

About 20 per cent of the world's vertebrates and plants are vulnerable to threats and face extinction (Baillie and Zhang 2018). In the past 40 years, the global population sizes of mammals, birds, fish, reptiles and amphibians has decreased by around 60 per cent on average (World Wide Fund for Nature 2018). However, the TP region has not been affected to the same extent, with only 9.6 per cent of vertebrates and 4.5 per cent of plants threatened in total, reflecting a much lower extinction rate than the global average. It has been also noted that some of the iconic species and more taxa in the TP have been studied more than other regions (Kandel *et al.* 2016). Populations of some flagship species are even increasing in the region. For example, a recent survey revealed that the population of Przewalski's gazelle experienced a 20-fold increase from 130 to more than 2,900 from 1999 to 2020 (Administration of Qinghai Lake National Nature Reserve 2020). Furthermore, the number of kiangs (Equus kiang), which was about 56,000 in 1989, increased to nearly 90,000 in 2000, with its population continuing to grow slowly thereafter.

The favourable conservation status of many organisms and resulting biodiversity benefits are the result of the joint efforts of the Chinese government's regional administrations and scientific institutions. This has produced conservation practices that include credible policies, legal systems, ex-situ and in situ conservation programmes and strengthened environmental impact evaluations. Historically, overhunting has been recognized as the primary driver behind decreases in large herbivore populations (Schaller and Liu 1996; Leclerc *et al.* 2015). To tackle this, the Chinese government's regional wildlife protection administrations have issued a series of regional laws and regulations. Over the last four decades, the Qinghai provincial government has implemented strong law enforcement for ecological and environmental protection and patrolling, resulting in reduction of illegal poaching. The effect of these actions is most evident in the Hoh Xil region, where zero illegal hunting events have been reported in the last 10 years (Sanjiangyuan National Park Administration and Qinghai Meteorological Bureau 2020). National nature reserves have also been established for crucial areas to protect endangered species and key habitats. There are currently eleven national nature reserves, 12 national forest parks and 4 national reserves of aquatic germplasm resources in the TP. To date, protected areas cover 59 million hectares (ha) in the TP region, including 33.1 per cent of the total land area, which is much higher than the global average of 14.7 per cent (Pringle 2017; Boakes Fuller and McGowan 2019). The conservation efforts by the neighbouring countries such as Bhutan, Nepal, India, Pakistan, Tajikistan and others have also contributed to improve the biodiversity of the TP (Sharma, Chettri and Oli 2010; Kaewkhunok 2018; Adhikari *et al.* 2021).

Strengthened practices have boosted biodiversity conservation of endemic and endangered species in TP (Sharma, Chettri and Oli 2010; IPBES 2018). A succession of rigorous field surveys and research projects have been conducted, especially for endemic and endangered species, preventing further population decline and extinction. In recent years, Chinese scientists have developed a conservation concept known as 'plant species with extremely small populations' (PSESP) as a conservation priority in China (Ren *et al.* 2012; Ma *et al.* 2013; Sun 2013). PSESP focuses on species that face an elevated risk of extinction, characterized by small remaining populations in restricted habitats and exposure to serious human disturbance (Sun, Ma and Blackmore 2019). Species qualify as PSESP if they are less than 5000 mature individuals in total and fewer than 500 individuals in each isolated population (Sun 2013; Sun, Ma and Blackmore 2019), and especially for those species of less than 1000 or even 100 mature individuals are the most priority for taking an urgent rescuing actions (Sun, Yang and Dao 2019). Follow-up actions for species conservation of comprehensive field surveys, creating in situ conservation sites (micro-reserves) for the species or populations or scattered individuals distributed outside the nature reserves, mass propagation and cultivation, establishing near situ and ex situ populations, population reinforcement and reintrodution have all been carried out from the national and provincial levels to the local level (Sun, Yang and Dao 2019). At present there are about 100 extremely threatened plant species (over 40 families) in the TP, half of which are included in the PSESP category. For example, *Acer yangbiense*, a newly identified species of maple in 2003, was found to have only five individuals left in the wild. To ensure the species' survival, almost 50,000 seedlings have been propagated since this discovery, with around 2,000 reintroduced to the species' native habitat and another 4,000 conserved either ex-situ or near-situ at conservation bases in Yunnan (Sun and Yin 2009; Sun, Yang and Dao 2019).

Conservation of the Tibetan antelope (*Pantholops hodgsonii)* provides a striking example of how endemic species can be successfully protected through the adoption of comprehensive practices. The population of Tibetan antelope was decimated in the last decade of the twentieth century (Xia *et al.* 2007; Yang and Xia 2008; Leslie, Groves and Abramov 2010), with human activities, including habitat fragmentation, illegal poaching and smuggling, accounting for around 90 per cent of the decline (Schaller and Liu 1996). In 1997, the Hoh Xil National Nature Reserve was established and further protection activities were implemented, such as banning the trade of Tibetan antelope (including products), cracking down on poaching and carrying out rescue work (Du *et al.* 2016). These efforts were very effective, and the Tibetan antelope population has now recovered, increasing from less than 20,000 individuals to more than 60,000 in Hoh Xil National Nature Reserve (Zhao *et al.* 2020). In 2016, the IUCN down-listed the Tibetan antelope from Endangered to Near Threatened, with the Chinese Red List of Vertebrates assessing the species as Near Threatened (Jiang *et al.* 2016). There has also been an increase in the genetic diversity of the Tibetan antelope population (Chen, J.R. *et al.* 2019). However, despite the positive progress made, the Tibetan antelope and other species are now facing new threats related to severe climate change (Luo, Jiang and Tang 2015; Negi *et al.* 2017; Pei *et al.* 2019; Penjor *et al.* 2021).

Similarly, the population of giant panda *(Ailuropoda melanoleuca)* has also begun to recover. The wild population size dropped to its lowest in 1990 with just 1,112 individuals, gaining IUCN Endangered status. However, thanks to decades of joint efforts of international non-governmental organizations, universities and the Chinese government to protect this species' habitat, their number has increased, with the number of wild individuals growing to 1,864 in the 2010s (Wei *et al.* 2018) and captive individuals reaching 600 worldwide in 2019. The IUCN has therefore down-listed the extinction risk of the giant panda from Endangered to Vulnerable. Conservation efforts for this species include establishing a network of giant panda reserves, constructing giant panda corridors to connect fragmented populations, boosting sustainable development with local communities to mitigate habitat degradation, and setting up captive breeding centres. Conservation efforts on ungulates in Pakistan through 'Trophy hunting' programme incentivised local community to recover the population of a number of species (Adhikari *et al.* 2021).

Environmental impact evaluations of major infrastructure construction have also been strengthened. Carrying out an environmental, especially ecological, impact evaluation is the first step before beginning any project construction and can provide precise feedback for wildlife protection (Korosi *et al.* 2017). At the first stage of the Sichuan-Tibet railway design process, wildlife conservation was listed as the major target of the project's environmental impact assessment. Before construction, an automatic wildlife monitoring network of infra-red cameras was established at 150 monitoring sites along 1,000 km of the railway line, which informed designs that protect animal passages along, over or under the rail routes, as well as other wildlife protection strategies. This network provides constant data for wildlife conservation in the construction of railways and offers detailed feedback on the effectiveness of environmental protection facilities during railway operation. The established Qinghai-Tibet railway set a good example of adopting ecological impact evaluation results and implementing various conservation practices, such as grading roadbeds, establishing wildlife corridors, introducing warning signs and suspending vehicle traffic during wildlife migration periods (Yang and Xia 2008). These measures have increased the protection of animals when they pass through railway routes.

3.2.4. Challenges for biodiversity conservation

Although some progress has been made in conserving the TP's biodiversity, there are significant challenges. There are gaps in systematic and long-term research for relevant knowledge, information and baseline data that still pose significant challenges for conservation efforts. Comprehensive understanding of the region's biodiversity, especially of species richness and abundance, is therefore incomplete. For example, since 2000, around 72 new species of vertebrates have been discovered throughout the region, including two primate species, the Myanmar snub-nosed monkey (*Rhinopithecus strykeri*) (Geissmann *et al*. 2011) and the white-cheeked macaque (*Macaca leucogenys*) (Li, Zhao and Fan 2015), a new amphibian genus (*Nasutixalus*), and a new amphibian family (Ceratobatrachidae) (Tietze *et al*. 2013). However, such researches have been sporadic, short term and limited to certain high biodiversity areas such as protected areas and reserves. Gaps do exist for research on agro-biodiversity, micro-organisms, and lower vertebrates among others (Kandel *et al.* 2016; IPBES 2018; Basnet *et al.* 2019; Rana *et al.* 2021).

Another challenge lies in the transboundary nature of biodiversity conservation in the TP. Biodiversity conservation, especially biodiversity hotspots and ecoregions, which provide critical habitats for threatened species, are more difficult to manage across transboundary landscapes, due to the different approaches to conservation carried out by various political and governmental entities in their respective areas. These transboundary areas are often subject to strict military control as a result of cross-border conflicts, weak governance, limited understanding and physical barriers (Kotru *et al*. 2020; Shi *et al*. 2021). Such challenges have increased the difficulty of conserving biodiversity in the TP. Wildlife and plant species are rarely confined within national boundaries (Liu *et al.* 2020; Sharma *et al.* 2020), indicating that successful transboundary conservation depends on international exchanges and cooperation, which need to take place urgently. The snow leopard (Panthera uncia) is one example of a large transboundary mammal, with one-third of its suitable habitat located less than 50–100 km from the international borders of its 12 range countries. In 2013, the 12 range countries issued a joint declaration for snow leopard conservation, transboundary management and awareness-raising (Li *et al*. 2014), setting a positive example for transboundary biodiversity conservation. Conservation diplomacy based on such transboundary species could be explored for regional cooperation and conflict resolutions (Dong, Chettri and Sharma 2017; Marsden 2019; Maheshwari 2020; Sharma *et al*. 2020). Some initiatives with guiding principles of regional cooperation at transboundary landscapes are emerging from the TP (Gurung *et al.* 2019; Yang, Y. *et al.* 2019; Kotru *et al.* 2020; Uddin *et al.* 2020; Shi *et al.* 2021) However, increased international cooperation in wildlife conservation practices is still needed in the transboundary areas in order to tackle issues related to illegal trade, transboundary management and law enforcement.

Another important challenge stems from anthropogenic activities associated with major infrastructure projects, alien species invasion and human disturbance. Major infrastructure projects, such as highways, railways, airports and hydropower projects, are likely to traverse multiple habitats and cause large-scale habitat fragmentation and regional ecosystem degradation. Even though improved environmental impact evaluations have decreased the loss of biodiversity from major infrastructure projects, the long-term impact of such projects is still not clear. As is clear in China's experience with ecological civilization, which seeks to bring about harmony between human development, conservation and nature, future conservation practices must place greater effort on maintaining and reversing biodiversity loss, including long-term monitoring, systematic scientific research and the application of new theories, methodologies and technologies.

Alien species invasion is emerging as a major threat impacting on the structure and functions of local ecosystems (Lamsal *et al.* 2017; Li, S. *et al.* 2017; Thapa *et al.* 2018). Alien freshwater fish and many alien species of amphibians and reptiles have invaded the TP, occupying most exorheic systems. Alien species invasion have a strong negative influence on the abundance of aquatic communities (Gallardo *et al.* 2016). In the last two decades, the number of alien fish species and their distributions has expanded into water bodies of higher altitudes and more remote areas (Li, S. *et al.* 2017). About 35 alien fish species have been found, resulting in the rapid deterioration of native fish populations. Alien fish species now outnumber native species in some rivers (Tang and He 2015; Fan *et al.* 2016; Liu *et al.* 2017; He *et al.* 2020). Once the resources of these native fish species are destroyed, it is extremely difficult to recover their populations largely due to their slow growth, long recruitment periods and low tolerance to environmental changes (Chen *et al.* 2004). Several alien herpetofauna and commensal rodents, such as the American bullfrog (*Rana catesbeiana*), red-eared slider (Trachemys scripta elegans), black-spotted frog (*Pelophylax nigromaculatus*), house mouse (Mus musculus), brown rat (Rattus norvegicus) and Asian house rat (R. *tanezumi*), have also been found in the plateau (Mi *et al.* 2014; Fan *et al.* 2016; Wang *et al.* 2017). To better protect the region's native species, enhanced regulations for harvesting native species should be adopted, and a stronger legal framework to prevent the introduction of invasive species should be implemented. To ensure the early detection of introduced species, a strong system should be established that incorporates frequent monitoring and citizen science for reporting invasive species. Scientific models that predict the potential distribution of invasive species should also be developed, as this will help target specific areas for monitoring.

Humans may unconsciously drive evolution, a concept that must be considered when dealing with threatened species (Law and Salick 2005), such as snow lotus (*Saussurea laniceps*), a rare plant endemic to the eastern Himalayas that is often used in traditional Chinese and Tibetan medicine. Overharvesting of this plant is a significant disturbance that may put it at greater risk of extinction (Law and Salick 2005), an effect also evident in other species, such as *fritillaria, oreosolen* and *rhodiola*. The slow-growing flagship plant Rheum *nobile* in particular requires further protection (Song *et al.* 2020). In the future, management for sustainable use of these plants is urgently needed.

Climate change also threatens biodiversity conservation efforts in the TP. Climate change and associated extreme events affect species change in phenology, population distribution, population sizes and the timing of reproduction or migration (Shrestha and Bawa 2014; Lamsal *et al.* 2017). Over the past half-century, the average annual surface temperature of the Qinghai-Tibet Plateau has increased by 1.5ºC, which was significantly higher than in other parts of China (Wu *et al.* 2013; Wang, X. *et al.* 2020). A recent study used ecological models to project that global warming would significantly increase the extinction risk of the toad-headed lizard (*Phrynocephalus*) (Sinervo *et al.* 2018). Climate change-related changes in water levels, glacier river diversions and river capture are also threatening the survival of some rock lizard (*Laudakia* sp.) populations. Conservation efforts are therefore needed along with evidence-based management options that are explored based on comprehensive studies and research on climate change impacts.

In the recent years, additional challenges are emerging, largely due to habitat fragmentation, disruption of corridors used for seasonal migration and increasing frequency of human wildlife conflicts (Liang *et al.* 2018; Dai *et al.* 2020; Xu, Wei and Jin 2020; Bhattacharya *et al.* 2021; Liang *et al.* 2021) .

3.3 Summary

The concentrations of key pollutants such as BC, mercury, and POPs over the TP still remain low. However, observation and modelling results clearly indicate the exogenous influence of surrounding sources of air pollution through long-range transport. Based on the historical trends reconstructed from ice cores and lake sediments, BC and heavy metals like mercury show a dramatic increase since 1950s, which reflect the enhanced emissions of air pollutants in South Asia. The pollutants entered and deposited into the TP further incorporate in the biogeochemical cycle at a multi-sphere scale, exerting negative impacts on the cryosphere and ecosystem. BC can accelerate the melting of glaciers and snow cover, and at the same time, the melting of glaciers can release the deposited POPs and heavy metals into the water body, further threatening the aquatic environment.

Decline in diversity in the TP is not as significant as elsewhere in the globe with just 9.6 per cent of vertebrates and 4.5 per cent of plants vulnerable to threats and face extinction. Populations of some flagship species are even increasing in this region, such as Przewalski's gazelle and the Tibetan wild ass. Nevertheless, due to knowledge gaps, the region's transboundary nature, anthropogenic activities and climate change, the TP still faces great biodiversity conservation challenges. There is therefore a need to collect biodiversity baseline data, enlarge cross-border conservation efforts, increase general community protection awareness, further improve monitoring and management, strengthen law enforcement, advance the effectiveness and pertinence of protection actions, build an alarm system to alert against introduced species, relieve ecological impacts of climate change and recover conditions necessary for survival in key areas.

4 Projected environmental changes in the Third Pole

This chapter uses various models, such as the recent model projections from version 6 of the Coupled Model Intercomparison Project (CMIP6), to assess changes in climate, water bodies, permafrost and ecosystems throughout the 21st century. Using the current status during 1995–2014 as reference, these projections consider several scenarios, with a special focus on climate model projections over the Third Pole from the Scenario Model Intercomparison Project (ScenarioMIP) of the Coupled Model Intercomparison Project Phase 6 (CMIP6) (O'Neill *et al.* 2016). CMIP6 provides multi-model climate projections driven by a set of combinations of different Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (O'Neill *et al.* 2016). The Scenario provides future projections of climate, water and vegetation changes from multiple Earth System Models that are forced by Shared Socioeconomic Pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5) (Tebaldi *et al.* 2021). SSP1-2.6 is a sustainable socio-economic pathway where the radiative forcing peaks at 2.6 W m^{-2} before 2100; SSP2-4.5 belongs to the "middle of the road" socio-economic family with the radiative forcing peaking at 4.5 W m^{-2} before the year 2100; SSP5-8.5 represents a high fossil-fuel development world with the radiative peaking at 8.5 W m^{-2} before 2100 (Gidden *et al.* 2019; Meinshausen *et al.* 2020). All those three scenarios represent, respectively, low, medium and high levels of future forcing of climate pathways.

4.1 Climate is projected to get warmer and wetter in the 21st century in the Third Pole

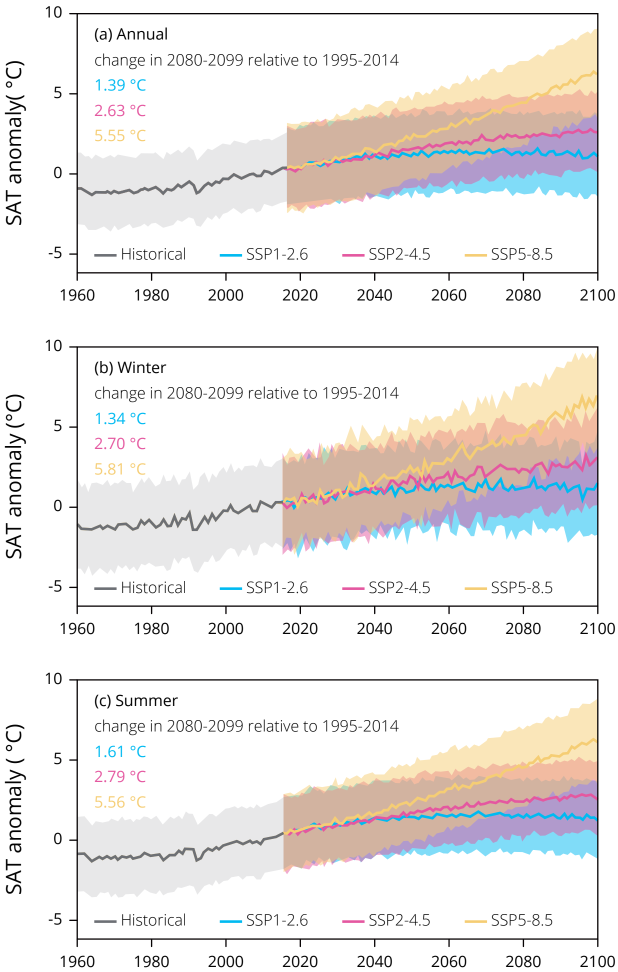
4.1.1. Temperature

Under CMIP6 SSP scenarios, warming will continue in the TP throughout the 21st century. The temperature increase is almost the same for SSP scenarios before 2030, diverging thereafter against a longer timescale **(Figure 4.1)**, with the increase highest under SSP5-8.5 (0.8°C per decade), followed by SSP2-4.5 (0.2°C per decade). In contrast, under SSP1-2.6, the warming rate peaks in the middle of 21st century before declining. Specifically, in the CMIP6 model ensemble, the increase in annual mean temperature under SSP1-2.6 will stay below 1.5°C relative to the 1995–2014 reference period throughout the 21st century. Under SSP2-4.5, the warming will exceed 2°C at around 2060. In contrast, the increase in annual mean temperature will exceed 2°C at an earlier date (around 2040) and could even exceed 6°C under SSP5-8.5 by 2099, which is in qualitative agreement with previous studies using CMIP5 RCP4.5 and RCP8.5 scenarios (Chen and Frauenfeld 2014). The seasonal temperature is projected to follow a similar pattern as the annual mean, with warming increasing 1.6–5.6°C in summer and 1.34–5.81°C in winter by 2080–2099 relative to 1995–2014. Larger temperature increases are expected under higher emission scenarios **(Figure 4.1)**. Projected warming in the TP is greater than the global average, which is related to enhanced downward longwave radiation and surface albedo feedback (Ghatak, Sinsky and Miller 2014; Pepin *et al.* 2015; Su, Duan and Xu 2017). According to the latest CMIP6 projections, the rise in surface air temperatures in the TP will be 1.2–1.4 times greater than the global average by 2080–2099 relative to 1994–2015.

The temperature increase is not spatially uniform in the TP. Under SSP1-2.6, 57.4 per cent of the TP is projected to stay below 1.5°C in temperature change, a proportion that only becomes 2.8 per cent and zero in 2080–2099 (relative to 1995–2014) under SSP2-4.5 and SSP5-8.5, respectively. Based on SSP2-4.5 and SSP5-8.5, warming above 4°C will affect 1.8 per cent and 97.6 per cent of the TP's area, respectively. Intense warming is projected to occur mainly in the central part of the TP under all the three SSPs, which is consistent with previous studies using CMIP5 model simulations (Hu, Jiang and Fan 2015). Such spatial warming patterns based on mean annual temperature are also found using winter and summer temperatures **(Figure 4.2)**. The projected warming could significantly change the TP's atmospheric heat source/sink, which would further impact Asian monsoon systems.

The EDW is projected to continue into the future (Krishnan *et al.* 2019). Based on CMIP5 GCM ensemble analysis a 1.5°C end of the century scenario would mean 1.8 ± 0.4°C averaged over the HKH region. Looking solely at the mountain ranges, this enhanced warming is even more pronounced. For example, for the Karakoram it would imply regional temperature increases of 2.2°C ± 0.4°C.

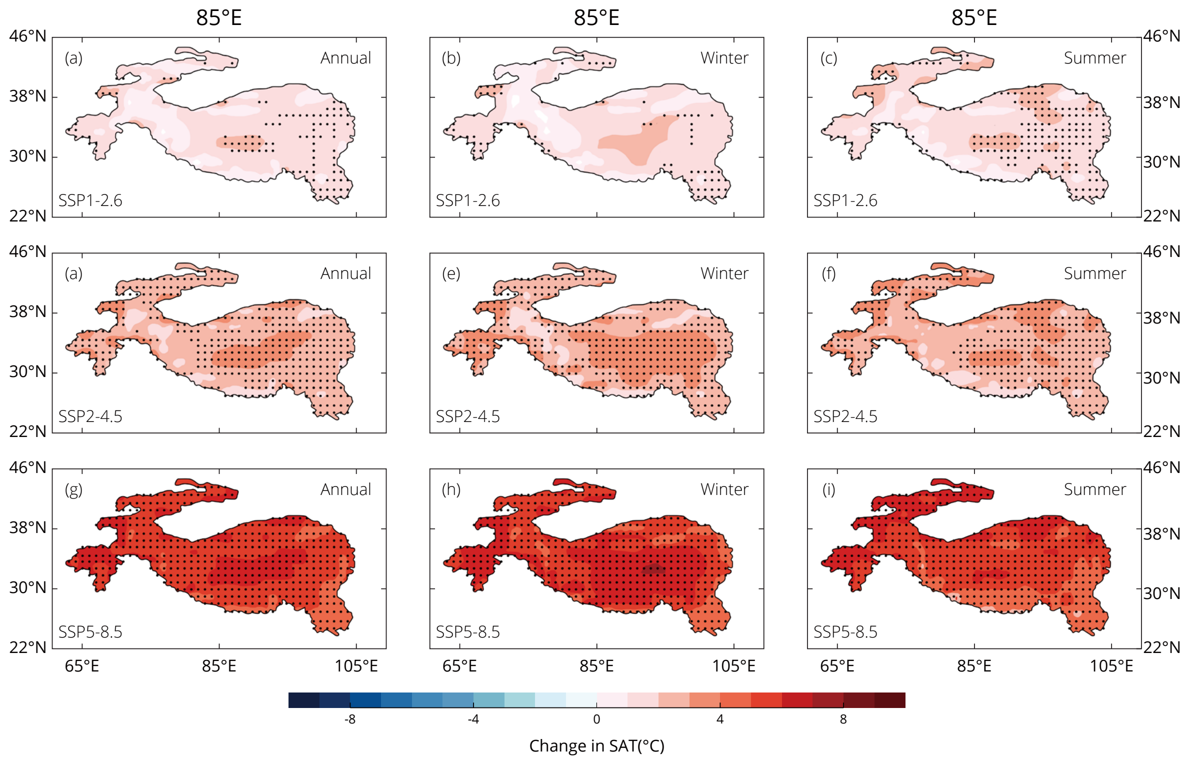
Δ Figure 4.1 Projected time series of (a) annual, (b) winter, and (c) summer surface air temperature anomalies



Δ Notes: Changes are relative to 1995–2014 from CMIP6 SSPs experiments. Projections are shown for each SSP for the multi-model mean (solid lines) and one standard deviation across the distribution of individual models (shading). For SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, 16, 15 and 14 models were used, respectively.

Δ Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

Figure 4.2 Spatial patterns of annual, winter and summer surface air temperature anomalies



Notes: Annual = images a, b and c; winter = images, d, e and f; summer = images g, h and i. Changes averaged from CMIP6 models for 2080–2099 relative to 1995–2014 using SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. For SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, 16, 15 and 14 models were used, respectively. Dotted points denote the significant change at 95 per cent confidence level.

Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

4.1.2. Precipitation

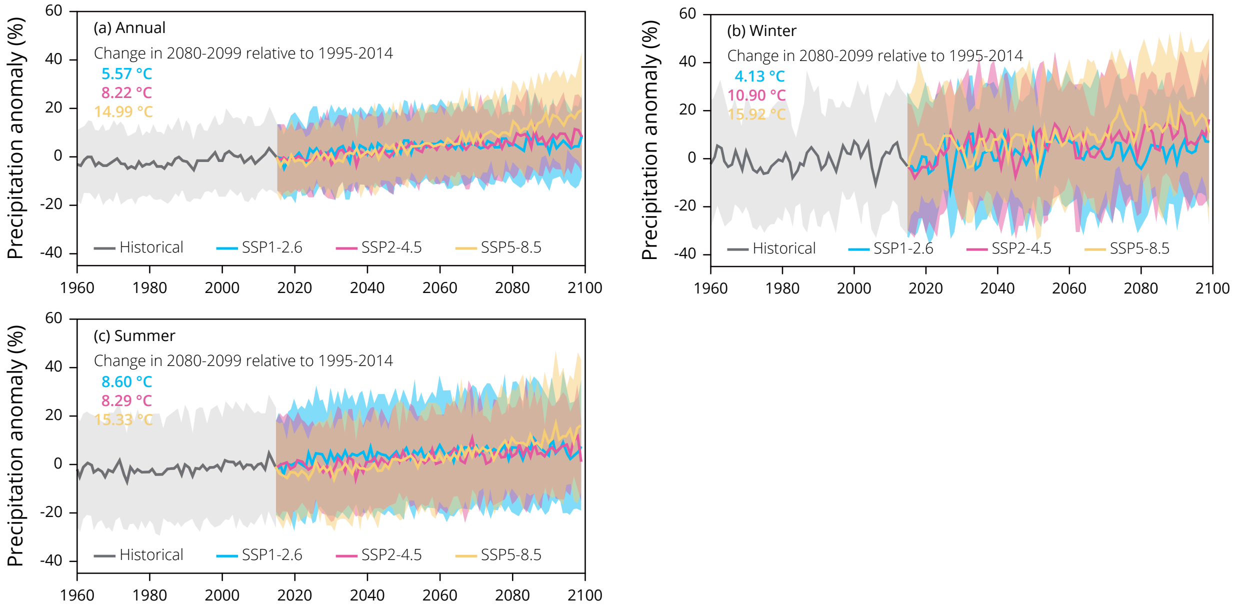
Precipitation across the Third Pole is expected to increase despite the wide variation in the extent of the change based on different models. CMIP6 models on average project a gradual increase in the TP's annual precipitation throughout the 21st century, with the increase exceeding 5.6 per cent, 8.2 per cent and 15.0 per cent in 2080–2099 relative to 1995–2014 under SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively **(Figure 4.3)**. The precipitation increase will also vary widely across the area and in different seasons. Winter precipitation is predicted to increase in Tian Shan, Kunlun Mountains and Qilian Mountains but decline in the central Himalayan region.

Regional climate models generally perform better than coarse GCMs. CORDEX RCM indicates a likely increase by 4–12 per cent in the near future (2036-2065) and by 4–25 per cent in the long term (2066-2095). Winter precipitation is projected to increase by 7–15 per cent in the Karakoram, but to decline slightly in the central Himalaya.

The general pattern of precipitation change indicates that only part of north-western region, which accounts for around 20 per cent of the TP, will experience a significant increase in 2080–2099 relative to 1995–2014 under the worst-case scenario SSP5-8.5 **(Figure 4.4)**. A similar spatial pattern is also obtained under CMIP5 RCP8.5 scenario (Jia *et al.* 2019). A spatial contrast of precipitation changes between winter and summer is also likely. The westerlies-dominated area, which includes the Tian Shan, Kunlun Mountains and Qilian Mountains, will experience greater increases in precipitation during winter **(Figure 4.4d, e and f)** than summer **(Figure 4.4g, h and i)**. The percentage increase is largest under SSP5-8.5, with the value ranging from 30 to 75 per cent **(Figure 4.4f)**. In contrast, the south-western area, which is strongly affected by Indian summer monsoons, will witness a higher precipitation increase in summer **(Figure 4.4g, h and i)** than in winter **(Figure 4.4d, e and f)**. The spatial patterns of annual, winter and summer precipitation projections under SSP1-1.6 and SSP2-4.5 are almost identical to that under SSP5-8.5, except that there is a much smaller variation in magnitude.

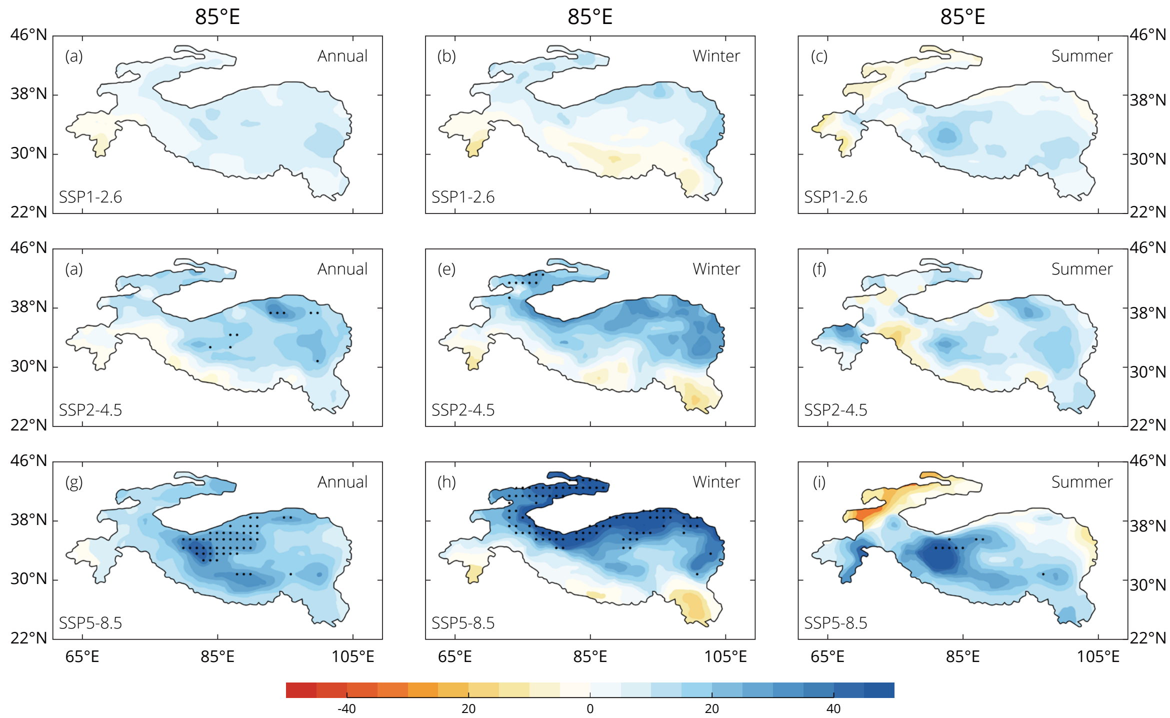
Compared with the temperature increase, t, the main reasons of the large model spread in precipitation changes are not fully understood. The sources of uncertainties in projected precipitation changes could be possibly related to the representation of atmospheric circulation responses to climate forcing in climate models, as large-scale atmospheric dynamics mainly control precipitation in the TP (Duan, Yao and Thompson 2006; Yao *et al.* 2013). Other factors, including the parameterization of convective-scale activities (Sun, Miao and Duan 2015) and the representation of orographic lifting and climate feedback from the cryosphere and vegetation, could also play a role.

Figure 4.3.Projected time series of (a) annual, (b) winter, and (c) summer total precipitation anomalies



Notes: Changes relative to 1995–2014 from CMIP6 SSPs experiments. Projections are shown for each SSP for the multi-model mean (solid lines) and one standard deviation across the distribution of individual models (shading). For SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, 14, 10 and 12 models were used, respectively.

Figure 4.4 Spatial patterns of annual, winter and summer total precipitation anomalies



Notes: Annual = images a, b and c; winter = images d, e and f; summer = images g, h and i. Changes averaged from CMIP6 models for 2080–2099 relative to 1995–2014 using SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. For SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, 14, 10 and 12 models were used, respectively. Dotted points denote the significant change at 95 per cent confidence level.

Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

4.2 Water bodies will be expanding and more variable in the Third Pole

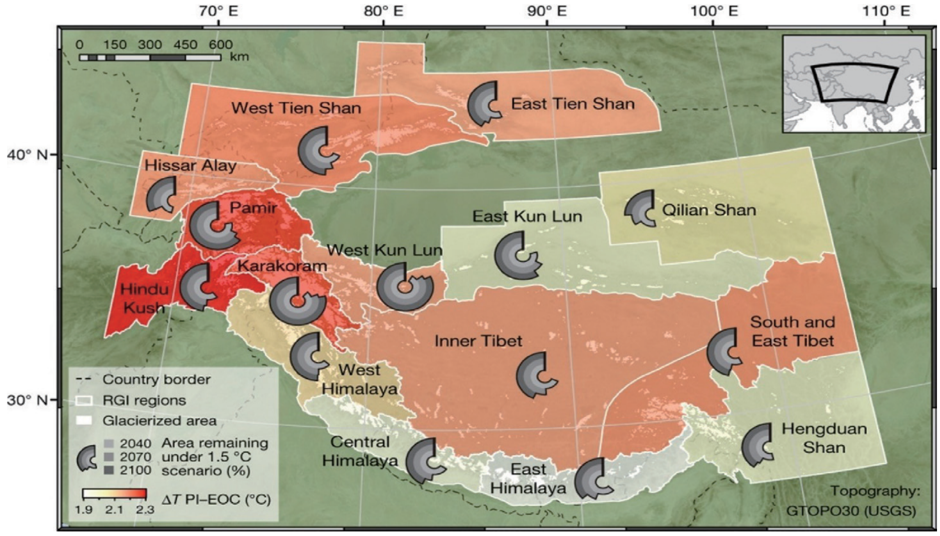
4.2.1. Glaciers

Glacier types (Shi and Liu 2000), glacier size (Ren *et al.* 2012), spatial heterogeneity and glacier response time to climate change (Ren *et al.* 2006) should all be considered when projecting future glacier change. Some studies project future glacier change (e.g. glacier terminus, glacier area and ice volume) for several individual glaciers using sophisticated glacier dynamic models. For Urumqi No. 1 Glacier in Tian Shan, the simulation shows that the glacier terminus will retreat slowly and thin dramatically before 2040, then accelerate after 2040 (Duan *et al.* 2012). For the continental Qiangtang No.1 Glacier on the Tibetan Plateau, losses of 11–18 per cent in area and 19–30 per cent in volume are predicted by 2050 under the warmer RegCM3 scenario (Li, Y. *et al.* 2017). Simulations of two well studied individual glaciers in the Nepal and Indian Himalayas suggest their complete demise between 2050 and 2100 (Adhikari and Huybrechts 2009; Kathayat *et al.* 2017).

For regional projections, different model simulations may lead to different projected glacier changes, yet all projections point to continuous area shrinkage and mass loss of glaciers across the Tibetan Plateau. Based on the relationship between climate change and glacier shrinkage since the Last Glacial Maximum, Shi and Liu (2000) quantified the shrinkage rates for 2030, 2070 and 2100 as 12 per cent, 28 per cent and 45 per cent, which correspond to temperature rises of 0.4–1.2°C, 1.2–2.7°C and 2.1–4.0°C, respectively. Based on surface mass balance-elevation parameterization and various volume-area scaling approaches (Zhao, Ding and Moore 2014), projections indicate that the total area loss for the Tibetan Plateau by 2050 will be 22–35 per cent of the total area compared with the year 2000, contributing 5 mm to global sea level rise. Regional simulations of glaciers in the Everest region suggest that under RCP4.5 84 per cent of the ice volume will have disappeared by the end of the century, while for the RCP8.5 95 per cent will disappear, with large altitudinal variability and heterogeneous mass loss due to the presence of debris on glacier tongues (Shea *et al.* 2015). Kraaijenbrink *et al.* (2017) found that a global temperature rise of 1.5°C will lead to a warming of 2.1°C in the TP region, with 36 ± 7 per cent of glacier mass and 36 ± 8 per cent of glacier area disappearing by 2100. Projections for RCP4.5, RCP6.0 and RCP8.5 reveal that much of the glacier ice is likely to disappear, with projected mass losses of 49 ± 7 per cent, 51 ± 6 per cen tand 64 ± 5 per cent, respectively, by the end of the century. The projected glacier area revealed a heterogeneous pattern with dramatic area shrinkage throughout most of the TP, except for the western Kunlun Mountains, Karakoram and Pamir Mountains, where there will be relatively less shrinkage **(Figure 4.5)**. As a result glacier melt, river runoff but also seasonality of flow are expected to increase until 2050 in the Himalaya-Karakoram region (Azam *et al.* 2021), followed by a decrease after peak flow has been reached (Huss and Hock 2018; Nie *et al.* 2021).

As glacier tongues retreat, over-deepening result in present lakes expanding and new lakes forming (Linsbauer *et al.* 2016), resulting in an increased threat of GLOFs which are expected to triple by the end of the century (Zheng *et al.* 2021).

Δ Figure 4.5 Regional temperatures and projected glacier area associated with a 1.5°C increase



Δ Note: The map shows the mean temperature increase at the glaciers between pre-industrial (PI) years (1851–1880) and the end of century (EOC, 2071–2100) for the global 1.5°C increase scenario, aggregated by RGI subregions. The circular graphs depict the projected reduction in glacierized area within each region for the 1.5°C scenario for three points in time.

Δ Source: Kraaijenbrink *et al.* 2017

4.2.2. Snow

Snow is a crucial component of the TP's water balance and therefore has the potential to impact ecosystems (Wang *et al.* 2018) and water resources (Kraaijenbrink *et al.* 2021). There is increasing evidence to show that the snow in the TP will experience substantial changes throughout the 21st century as the climate warms (Chen, D. *et al.* 2015; You *et al.* 2020; Kraaijenbrink *et al.* 2021). According to the latest CMIP6 model projections, annual mean SWE will consistently decrease in the TP under each of the three scenarios **(Figure 4.6)**. The mean SWE will reduce by around 8.4 kilogram per square metre (kg m^{-2}) (34.5 per cent) in 2080–2099 relative to 1995–2014 under SSP1-2.6, and about 13.0 (41.6 per cent) and 20.3 kg m^{-2} (60.0 per cent) under SSP2-4.5 and SSP5-8.5, respectively **(Figure 4.6a and e)**. SWE will decrease significantly from 2015 to 2099, with multi-model mean slopes of -0.3, -0.7, and -1.9 kg m^{-2} per decade under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively.

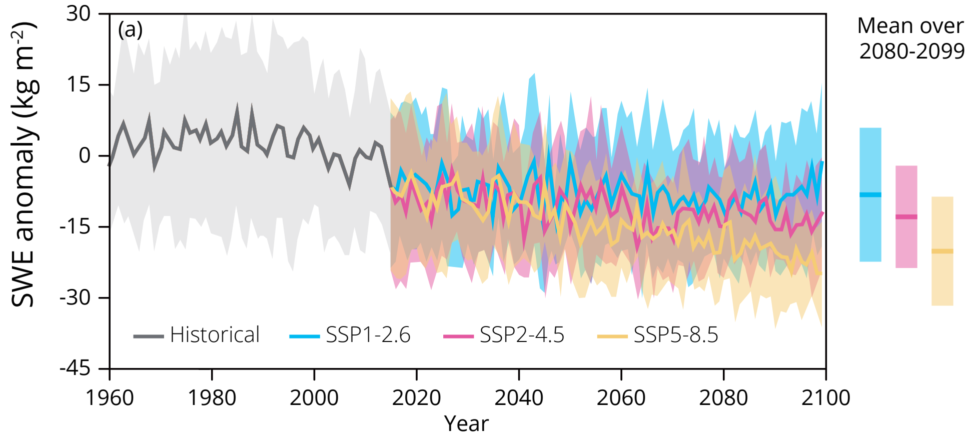
The spatial pattern of projected changes in annual mean SWE in 2080–2099 relative to 1995–2014 exhibits a general reduction but to varying degrees. Under SSP1-2.6 and SSP2-4.5, there are more notable declines in SWE across the central and south-eastern parts of the TP and the Hindu Kush (exceeding 40 per cent) **(Figure 4.6b and c)**. Under the SSP5-8.5 scenario, the decrease in SWE is much stronger across the Tian Shan, Hindu Kush, Himalayas and south-eastern part of the TP, with reduction levels exceeding 60 per cent. The Karakoram is an exceptional case, with snow changes appearing relatively stable under all three scenarios **(Figure 4.6b, c and d)**. This anomalous phenomenon in the Karakoram could be linked to its unique seasonal cycle and winter precipitation, making the snow less sensitive to warming (Kapnick *et al.* 2014) or an increase in snow fall suggested earlier (de Kok *et al.* 2018). Nepal *et al.* (2021) suggested a substantial decrease in snow cover area towards the end of the century in the small watershed in the Indus basin under warm-dry climatic conditions of RCP8.5 scenarios.

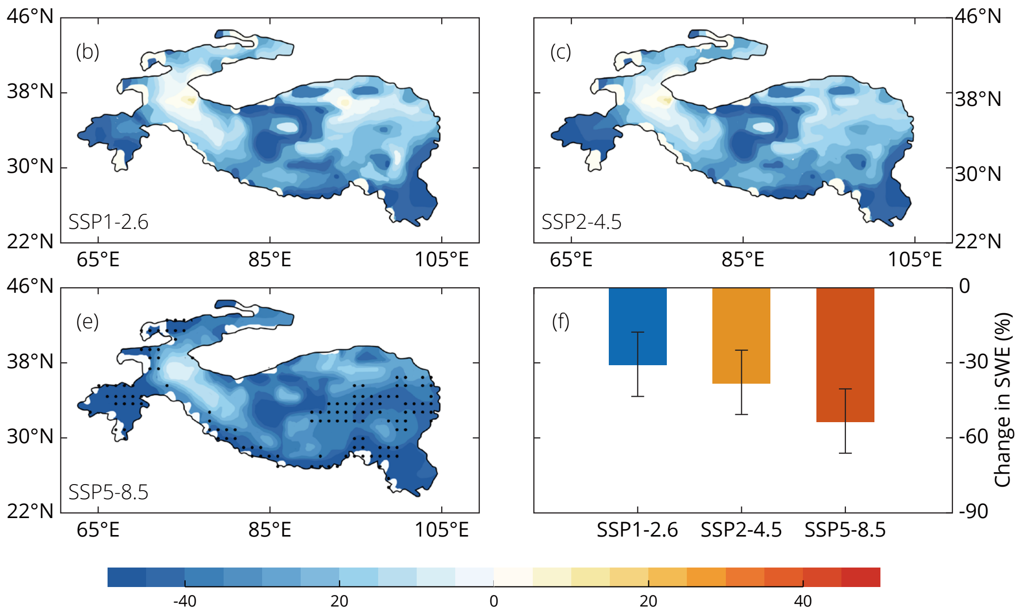
Snow depth also exhibits a consistent and robust decreasing trend, with multi-model mean trends of -0.08, -0.24, and -0.65 centimetres per decade under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, respectively. These changes are consistent with previous CMIP5 model projections, though decreasing rates are greater under RCP2.6, RCP4.5, and RCP8.5, at -0.8, -0.8, and -1.1 centimetres per decade, respectively (Wei and Dong 2015). Snow cover duration will also decline substantially with warming. For example, Shi *et al.* (2011) used the RegCM3 model to show that snow cover days in the TP will decrease at the rate of 11 days per decade during 2021–2099 under the IPCC A1B emission scenario. Modelling evidence suggests that the TP's seasonal snow will continue to reduce throughout the 21st century as surface temperatures rise.

Δ Table 5.1 Changes of SWE averaged over TP under three scenarios.

Scenarios	Reduction of SWE in 2080–2099 relative to 1995–2014		Trends of SWE during 2015- 2099 (kg m^{-2} $decade^{-1}$)
	Amount (kg m^{-2})	Percentage (per cent)	
SSP1-2.6	8.4	34.5	-0.3
SSP2-4.5	13.0	41.6	-0.7
SSP5-8.5	20.3	60.0	-1.9

Δ Figure 4.6. CMIP6 multi-model ensemble simulated changes in annual mean SWE in the Third Pole





- Notes: Image (a) Time series of average SWE anomaly relative to 1995–2014. The shaded areas denote the inter-model standard deviation for each ensemble mean. Images (b)–(d) Spatial patterns of the relative change in SWE during 2080–2099 (percentage, relative to 1995–2014) under three scenarios. The dotted area denotes the SWE change significant at 95 per cent confidence level. Image (e) Area mean of relative change in SWE during 2080–2099 throughout the TP.
- Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

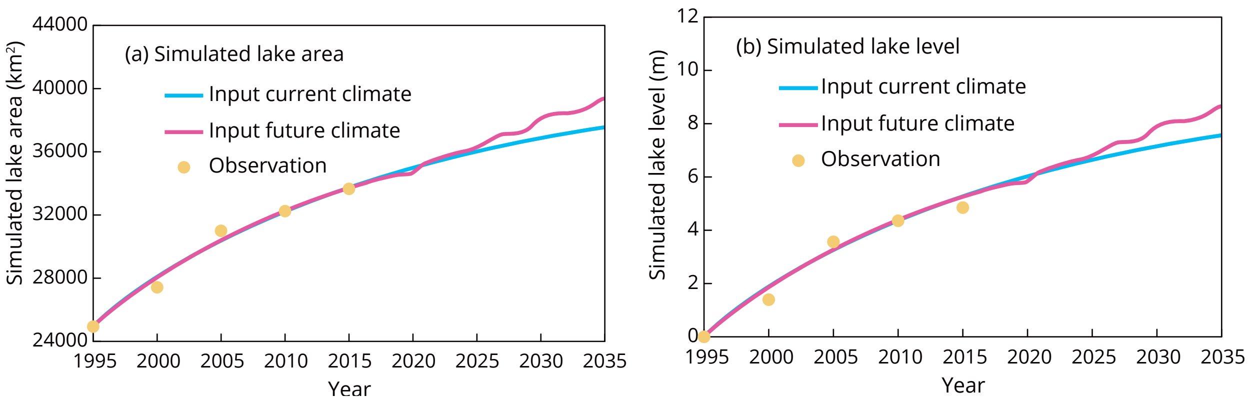
4.2.3. Lakes

Over the past three decades lakes have expanded extensively throughout the Tibetan Plateau (Zhang, G. *et al.* 2013; Mao *et al.* 2018; Yang, K. *et al.* 2018; Qiao,Zhu and Yang 2019; Zhao, Q. *et al.* 2019).The question of whether this increase will continue in the future has gained increasing attention. The area and volume of Tibetan Plateau lakes are expected to increase in the coming decades (Yang, K. *et al.* 2018; Zhao, Q. *et al.* 2019; Zhu,Peng and Zhang 2020). For example, (Yang, K. *et al.* 2018) applied a lake mass balance model to project that the region's total lake area will expand by 8,000–10,000 km^2, with the lake level rising by 7.6 ± 0.6 m from 2015 to 2035 under the CMIP5 RCP4.5 scenario **(Figure 4.7)**. The simulated expansion and lake level rise were linked to increased precipitation and warming-induced glacier meltwater (Yang, K. *et al.* 2018).

Besides lake area and level, studies of lake temperature responses to climate change could improve understanding of climate change impacts on lake ecosystems. Under RCP2.6 and RCP6.0 scenarios, warming is projected to reduce the duration of winter ice cover by 5–15 per cent and 30–40 per cent and increase lake temperatures by 0.6–1.4°C and 2.5–3.5°C (Woolway and Merchant 2019). However, it should be noted that such warming, and even warming exceeding 4°C, is not sufficient to shift the winter ice cover of TP lakes from annual to intermittent (Sharma *et al.* 2015). There is a growing recognition that reduced winter ice cover and increased lake temperatures could alter lake mixing regimes, which transport nutrients and oxygen between surface waters and deep water and can thus indicate climate change impacts on lake ecosystems. The mixing regime for lakes throughout the TP can be mainly classified as dimictic as they have two seasons of vertical mixing (Woolway and Merchant 2019). By running a one-dimensional numerical lake model with input climate data from RCP2.6 and RCP6.0 scenarios, there is little possibility that TP lake regimes will shift from dimictic to other regimes (Woolway and Merchant 2019).

Projections of lake changes, especially lake area and level in the TP, are limited. There is also still a large knowledge gap about whether projected lake expansion will persist in the near future or accelerate throughout the 21st century. Current short-term predictions of lake changes (2015–2035) (Yang, K. *et al.* 2018) assume that there will be no changes in lake evaporation, though this will change in the long-term with future climate change. In glacier-fed lakes, accelerated glacier melt is also contributing to lake expansion. Increasing evidence suggests that glacier melt will peak at a point in the future, before declining due to reduced glacier area. In addition, since the TP contains ice-rich permafrost, warming-induced permafrost degradation **(Figure 4.9)** affects the levels of water flowing to lakes (Walvoord and Kurylyk 2016). Model projections therefore need to be conducted throughout the 21st century under different climate scenarios and should be updated frequently to include new scientific insight and improved lake models.

Figure 4.7 Projected lake area and level increases for current climate status and future climate scenarios



Source: Yang *et al.* 2018

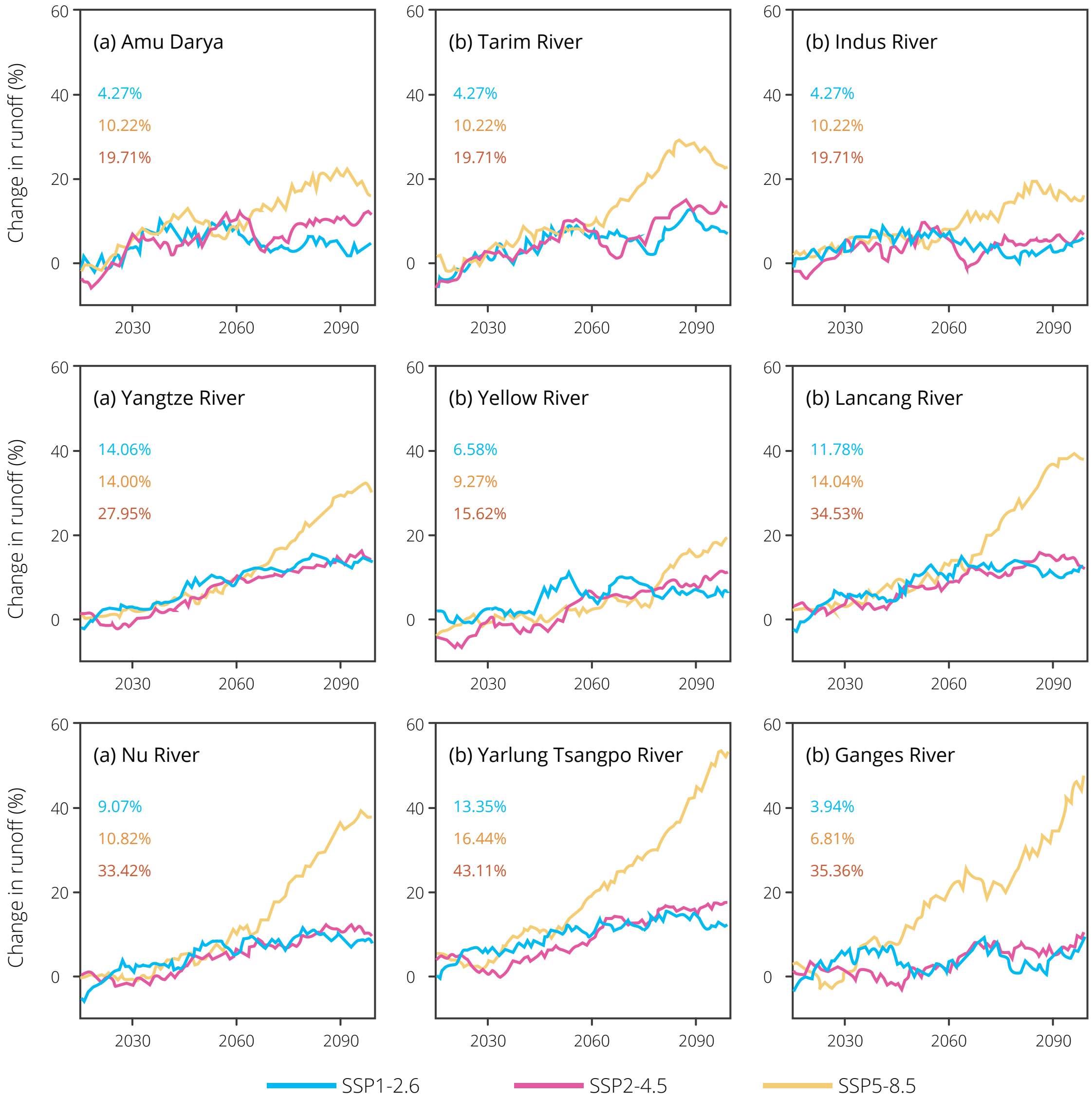
4.2.4. Rivers

The total run-off from the TP rivers will consistently increase in the 21st century based on CMIP6 multi-model ensemble **(Figure 4.8)**, which was consistent with previous studies that used other climate and hydrological models (Lutz *et al.* 2014; Su *et al.* 2016; Luo, Y. *et al.* 2018; Zhao, Q. *et al.* 2019; Azam *et al.* 2021; Khanal *et al.* 2021). The magnitude of the increase in total run-off by the end of this century is greatest in the highest emission scenario (SSP5-8.5), as observed through the percentage increase projected for 2080–2099 relative to the 1995–2014 reference period (28.4 per cent) compared with that of SSP1-2.6 (8.4 per cent) **(Figure 4.8)**. The percentage of run-off increase in monsoon-controlled river basins is also expected to be larger than that of westerlies-controlled basins, with the total projected run-off of the Nujiang River, Yarlung Tsangpo and Ganges basins (37.3 per cent) almost double that of the Amu Darya, Tarim River and Indus River basins (20.8 per cent) **(Figure 4.8)**. This difference is linked to the fact that changes in run-off mainly result from precipitation increases in monsoon-dominated basins, compared with the more controlled levels of run-off from glacier meltwater in westerlies-dominated basins (Li, F.P. *et al.* 2013; Lutz *et al.* 2014; Su *et al.* 2016; Zhao, Q. *et al.* 2019). Khanal *et al.* (2021) also suggested contrasting response of climate change on high mountain Asia (HMA) rivers, in which earlier onset of melting causes a shift in the magnitude and peak of water availability to earlier in the years. Both large and small basins have a predicted overall increase in total runoff in Indus (Wijngaard *et al.* 2017), Ganges (Nepal 2016; Bajracharya *et al.* 2018; Kaini *et al.* 2021).

In glacier-fed river basins, future run-off will typically rise until a maximum is reached, before steadily declining thereafter because warming-induced glacier shrinkage can no longer sufficiently support rising meltwater (Bliss, Hock and Radic 2014; Sorg *et al.* 2014; Huss and Hock 2018; Azam *et al.* 2021; Nie *et al.* 2021). The timing of this turning point depends on warming rates, the glacier area of the basin and its geographical location (Bliss, Hock and Radic 2014; Huss and Hock 2018). Based on CMIP6 model simulations, the turning point is only expected to occur in the upper Amu Darya, Indus River and Tarim River basins, which have relatively large glaciers and high glacierization under the worst-case scenario SSP5-8.5, occurring slightly earlier in the Indus and Tarim rivers (around 2080) than in Amu Darya (around 2090) **(Figure 4.8a, b and c)**. In contrast, turning points are not expected for these basins throughout the 21st century under lower scenarios, such as SSP1-2.6 and SPP2-4.5. However, the peak water in headwaters in Ganges river basin is projected to be in the 2050s, but in Brahmaputra, it has already passed or is close to doing so (Huss and Hock 2018; Azam *et al.* 2021).

There is a general consensus that run-off will increase throughout the 21st century, but the magnitude of this increase differs significantly based on different models. Immerzeel, Pellicciotti and Bierkens (2013) used a glacio-hydrological model to show that run-off from the upper Indus River and Ganges will increase by 88 per cent and 96 per cent, respectively, during 2071–2100 under CMIP5 RCP8.5, which are substantially larger percentages than 16.6 per cent and 35.4 per cent under CMIP6 SSP5-8.5 **(Figure 4.8c and i)**. Run-off from the upper Brahmaputra River, Salween River and Mekong River will increase by 5.0 per cent, 9.1 per cent and 11.0 per cent, respectively, during 2041–2050 under CMIP5 RCP4.5 (Lutz *et al.* 2014). Using a different hydrological model (Zhao, Q. *et al.* 2019), they will instead increase by 16.8 per cent, 12.6 per cent and 21.1 per cent. Khanal *et al.* (2021) suggested a variable response of rivers to climate change in HMA. For example, the annual total runoff from the upper Indus River in warm-wet scenario will increase by 23 per cent but decline by 20 per cent in cold-dry scenario. Such discrepancies are linked to the expected result of different model structures, input climate forcing and downscaling methods, which suggests that the focus of future research should be to further refine model parameterizations and develop high-resolution projections over the complex terrain area.

Δ Figure 4.8 Time series of run-off anomalies (relative to 1995–2014) from nine major rivers originating from the Third Pole under the three CMIP6 scenarios



Δ Notes: The three CMIP6 scenarios are SSP1-2.6, SSP2-4.5 and SSP5-8.5. The values of run-off change (in percentage) averaged over the 2080–2099 period are also shown.

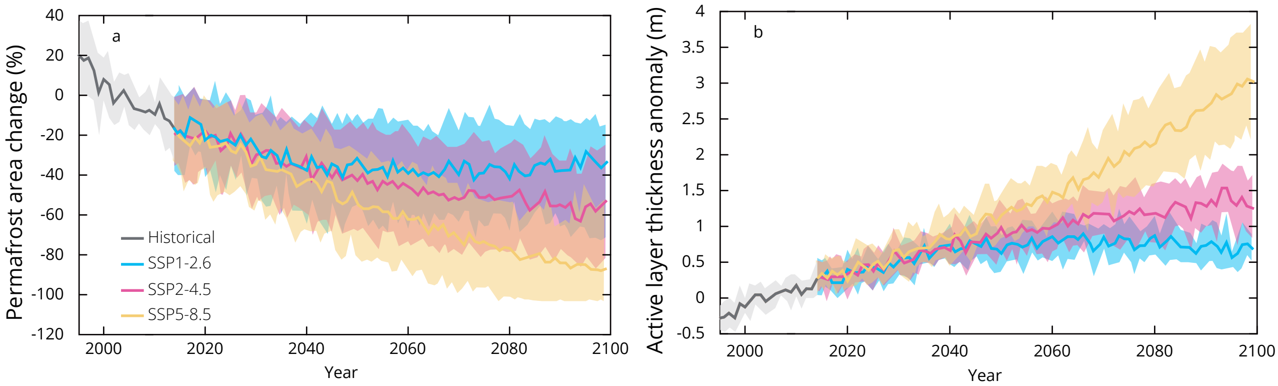
Δ Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

4.3 Active layer thickness of permafrost is projected to increase in response to climate warming in the Third Pole

The active layer thickness of permafrost deepens in thaw depth in response to warming. According to the latest model projections from CMIP6, the active layer thickness of permafrost in the TP will increase by 70 ± 19 cm under SSP1-2.6, 126 ± 47 cm under SSP2-4.5 and 303 ± 83 cm under SSP5-8.5 by 2099 relative to the 1995–2014 reference period **(Figure 4.9b).** Active layer thickness in the TP increases at a faster rate than Arctic permafrost in warmer climates (Peng *et al.* 2018), due to the fact that the TP's permafrost is close to 0°C and is higher than Arctic permafrost (Wu, Zhang and Liu 2010).

Although land surface models participating in CMIP6 are beginning to incorporate the physical process of permafrost dynamics (Lawrence *et al.* 2008; Gouttevin *et al.* 2012; Koven *et al.* 2013), large uncertainties still exist in permafrost simulations. Some processes that could accelerate permafrost thaw, such as thermokarst, are omitted or poorly represented in current models (Jorgenson, Shur and Pullman 2006; Olefeldt *et al.* 2016), which highlights the need to update permafrost projections using improved permafrost modules in the future.

Δ Figure 4.9 Projected changes in (a) permafrost area, and (b) active layer thickness relative to the 1995–2014 reference period, based on CMIP6 model simulations



Δ Sources: Burke *et al.* 2013; Chadburn *et al.* 2017

4.4 Ecosystem carbon cycle is projected to accelerate in the Third Pole

Climate change, specifically warming and increase in precipitation will lead to expansion of vegetation growth in the Third Pole. The temperature increase will not only expand the area of vegetation to a higher altitude but also change the growth season with leaf growth beginning earlier and lasting longer each year. Changes in plant phenology and vegetation growth will jointly affect future ecosystem carbon cycle.

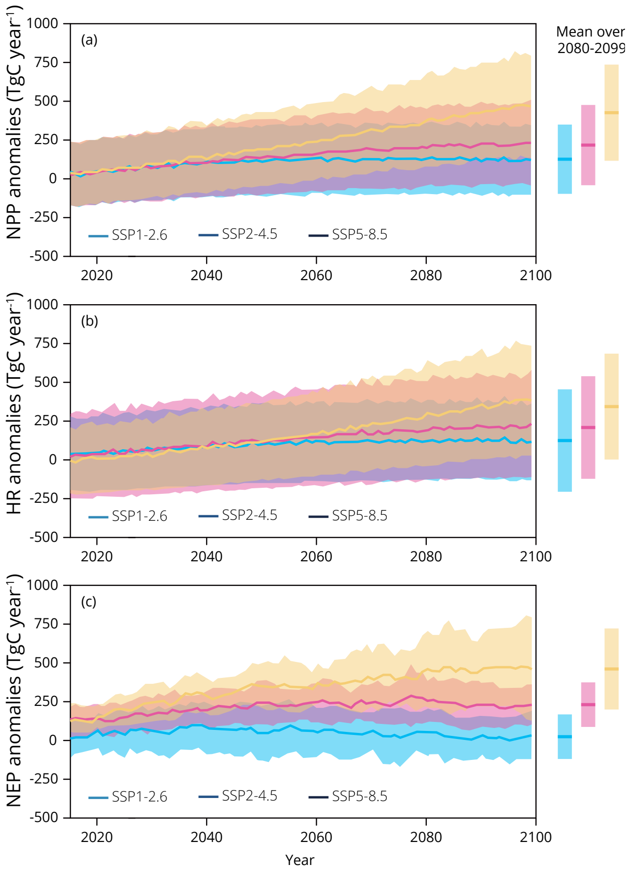
Climate change is significantly influencing alpine vegetation growth across the Tibetan Plateau (Luo, Z. *et al.* 2018). Vegetation expanded by 33,566 km^2 (1.3 per cent) of the total area of this plateau and is positively correlated with increasing precipitation and warming (Wang, Z.P. *et al.* 2020). Temperature variation is the primary climatic driver of change in terms of NPP in the TP during the 21st century under RCP4.5 projected by CMIP5 Earth system models (Li *et al.* 2015). Terrestrial NPP is set to increase by 126.8 ± 225.63 TgC(1 TgC = 10^{12} g of carbon) per year under SSP1-2.6, 220.23 ± 259.92 TgC per year under SSP2-4.5 and 420.20 ± 311.49 TgC per year under SSP5-8.5 in CMIP6 models during 2080–2099 relative to 1995–2014 **(Figure 4.10a)**. Such enhancement of alpine terrestrial NPP is partly due to changes in vegetation phenology and photosynthesis rates (Natali, Schuur and Rubin 2012; Wang, Z.P. *et al.* 2020).

First, the mean first leaf date of alpine vegetation across the TP is projected to advance by 15.8 days under RCP4.5 and 34.1 days under RCP8.5 during 2071–2100 relative to 1950–2005 (Zhu, L. *et al.* 2019). During 2015–2100, the length of the tree-ring growing season is expected to extend by 2.1 days per decade, 3.6 days per decade and 5.0 days per decade under the RCP2.6, RCP6.0 and RCP8.5, respectively (He *et al.* 2018). Second, the ecosystem-scale optimum temperature for photosynthesis was 13 ± 3°C during 2000–2013, which was higher than the growing season average daily maximum air temperature for alpine grasslands in the TP (Huang, M. *et al.* 2019). This indicates that there is potential for photosynthesis enhancement due to climate warming (Natali, Schuur and Rubin 2012). CMIP6 simulations also show that there are apparent spatial patterns in NPP changes for alpine ecosystems under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios during the 21st century **(Figure 4.10a, d and g)**. The enhancement of NPP decreases from east to west **(Figure 4.10a, d and g)**, similar to the spatial pattern of precipitation (Bliss, Hock and Radic 2014). Unlike (Gu *et al.* 2017), it seems that the spatial pattern of NPP change in alpine ecosystems during the 21st century is jointly influenced by changes in both temperature and precipitation (Jia *et al.* 2019; Wang, T. *et al.* 2020). Increasing precipitation is positively correlated with the vegetation expansion rate for the arid and semi-arid northwest Tibetan Plateau whereas, warming contributed to vegetation expanding in the semi-humid southeast Tibetan Plateau (Jia *et al.* 2019; Wang, T. *et al.* 2020).

Terrestrial heterotrophic respiration (HR) in the TP is projected to increase by 124.4 ± 252.4 TgC per year under SSP1-2.6, 209.3 ± 329.0 TgC per year under SSP2-4.5 and 339.7 ± 340.5 TgC per year under SSP5-8.5 in CMIP6 models during 2080–2099 relative to 1995–2014 **(Figure 4.10b)**. The increase in NPP completely cancels such HR enhancement, thereby enhancing the alpine ecosystem carbon sink in the TP. Terrestrial net ecosystem productivity (NEP) is expected to increase by 18.1 ± 30.6 TgC per year under SSP1-2.6, 56.0 ± 32.1 TgC per year under SSP2-4.5 and 99.4 ± 52.9 TgC per year under SSP5-8.5 in CMIP6 models during 2080–2099 relative to 1995–2014 **(Figure 4.10c)**. The spatial pattern of NEP change during the 21st century is dominated by NPP change, rather than HR change. The response of ecosystems to different magnitudes of climate warming and corresponding precipitation changes during the last few decades may provide an important reference for predicting the magnitude and trajectory of NPP in the future **(Figure 4.11)**.

Nevertheless, care should be taken when interpreting these results, as permafrost is not explicitly considered in most CMIP6 models. A machine learning analysis showed that permafrost carbon stock throughout the Tibetan Plateau is set to decrease ~1.86 ± 0.49 PgC(1 PgC = 10^{15} g of carbon) and ~3.80 ± 0.76 PgC under RCP4.5 and RCP8.5, respectively, by 2100 relative to 2006–2015, which would largely offset increases in carbon uptake in alpine ecosystems (Andreu-Hayles *et al.* 2020; Wang, T. *et al.* 2020). It is therefore possible that enhancement of terrestrial net ecosystem productivity in the TP could be overestimated in CMIP6 models. Clarifying the mechanism that drives permafrost degradation is essential to better predict the evolution of alpine terrestrial ecosystem carbon cycling under future climate change (Natali, Schuur and Rubin 2012; Piao *et al.* 2017; Myers-Smith *et al.* 2020). For accurate estimation of terrestrial ecosystem productivity, it is important to represent the known biogeochemical processes and their mechanisms, as well as the effects of interactions among multiple factors on the carbon cycle in ecosystem models (Andreu-Hayles *et al.* 2020). In addition, it is also crucial to monitor the land cover change and explore its responses to climate change, particularly in the high latitudes and elevations, where the land is undergoing a higher warming rate and the vegetation might play a role of forerunner and feedbacks (Piao *et al.* 2017; Myers-Smith *et al.* 2020).

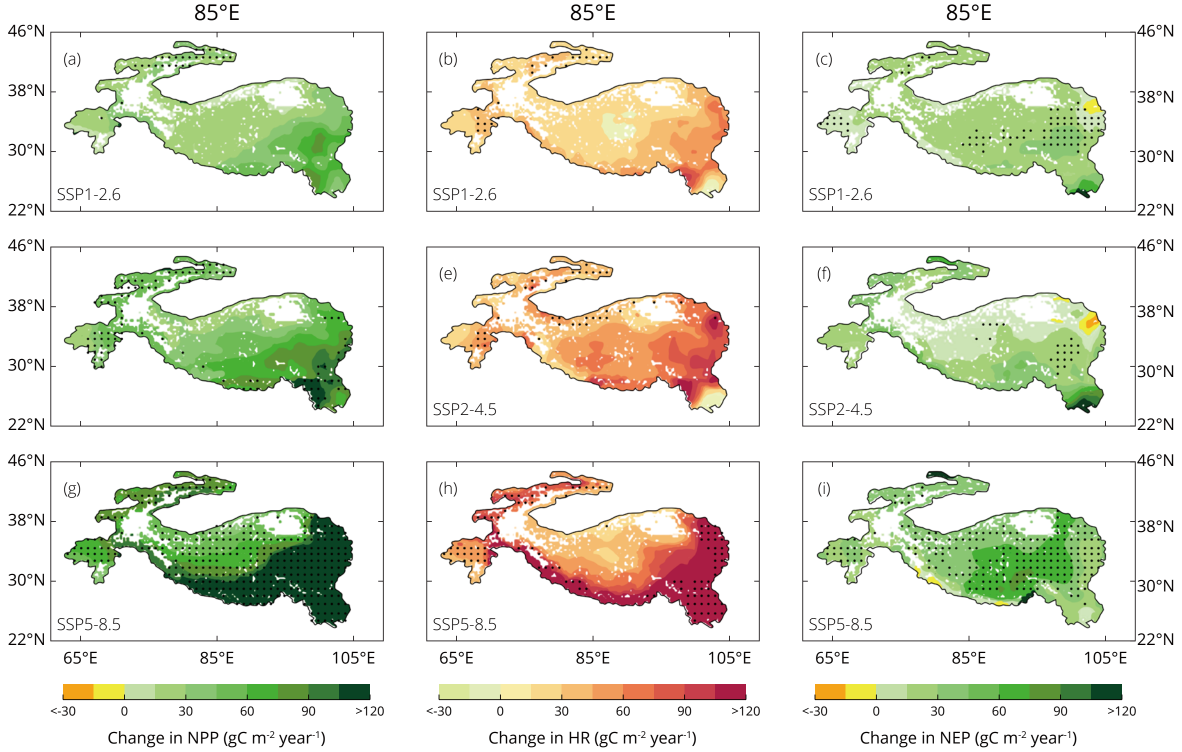
Δ Figure 4.10 Changes in (a) NPP, (b) HR, and (c) NEP, relative to 1995–2014 in the Third Pole



Δ Notes: Based on CMIP6 multi-model ensemble under three scenarios: SSP1-2.6, SSP2-4.5 and SSP5-8.5. The lines show the averages of multi-model ensemble for the same SSPs, while the shading shows inter-model standard deviation. The coloured bars on the right-hand side show the projected NPP range by 2100 (mean value for 2080–2099) under the three scenarios.

Δ Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

Figure 4.11 Spatial distributions of projected changes in NPP, HR and NEP



Notes: Based on CMIP6 multi-model ensemble means for 2080–2099 and 1995–2014 under SSP1-2.6, SSP2-4.5 and SSP5-8.5. Dotted points denote a statistically significant value at P< 0.05.

Source: CMIP6 data acquired at https://esgf-node.llnl.gov/search/cmip6/

4.5 Summary

Surface air temperature is projected to increase in the TP, particularly in the late 21st century. Compared with the latter half of the twentieth century, the late 21st century will witness an average temperature rise by 1.4–5.6°C. The increase in temperature in 2080–2099 relative to 1994–2015 is expected to be 1.2–1.4 times greater than the global average. Precipitation is also expected to generally increase, reaching 5.6–15 per cent by the end of the 21st century. Precipitation changes will contrast in winter and summer periods, with the westerlies-dominated area experiencing greater precipitation increases during the winter.

Glacier mass and area are projected to significantly decline in most regions of the TP, but will shrink much less in the western Kunlun Mountains, Karakoram and Pamir Mountains. The regional annual mean SWE and snow depth will also decrease throughout the 21st century, with pronounced reductions expected to occur mainly in the Tian Shan, Hindu Kush, Himalayas and south-eastern part of the TP. Little changes are expected in the Karakoram, even under the worst-case scenario.

Total lake area will likely expand by 8,000–10,000 km^2, with lake levels rising by 7.6±0.6 m from 2015 to 2035 under CMIP5 RCP4.5 scenario. It is therefore urgent to conduct model projections throughout the 21st century under different climate scenarios, updating these frequently to include new scientific insight and improved lake models.

Total run-off is expected to generally increase, with a higher increase in monsoon-controlled basins than in westerlies-controlled ones. But the runoff from glacier-fed river basins increase to a peak value and then decline thereafter.

Permafrost over the TP is projected to deepen in active layer thickness, and the alpine permafrost is projected to degrade faster than Arctic permafrost.

Alpine terrestrial net primary productivity is projected to increase, which will enhance the TP's alpine ecosystem carbon sink. The projected net ecosystem productivity change should be carefully interpreted due to the uncertainty of possible warming-induced carbon release by permafrost degradation.

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