

An aerial photograph of a high-altitude Himalayan valley. In the foreground, a small village with blue-roofed buildings is situated on a rocky slope. A large, turquoise lake winds through the valley, surrounded by dark, rugged mountains. In the background, majestic snow-capped mountain peaks rise against a clear blue sky with light clouds. The overall scene is one of a stark, high-altitude environment.

Climate Change on the Third Pole

Causes, Processes and Consequences

A Working Paper by the Scottish Centre for Himalayan Research
for the Scottish Parliament's Cross-Party Group on Tibet

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“The Tibetan Plateau (TP), with an average elevation of over 4000 m, is the highest and the largest highland in the world and exerts a great influence on regional and global climate through its thermal forcing mechanism. The TP and its surroundings contain the largest number of glaciers outside the polar regions, which are at the headwaters of many prominent Asian rivers. In the context of global warming, climate and cryospheric change in the TP are well evident, including glacier shrinkage, expansion of glacier-fed lakes, permafrost degradation, shortened soil frozen period and thickening of the active layer. Moreover, more than 1.4 billion people depend on water from the Indus, Ganges, Brahmaputra, Yangtze and Yellow Rivers, and the warming in the TP may lead to reduced water resources for the downstream regions in the future. Therefore, climate change in the TP is of societal importance to both the local and surrounding people.” (You, Min, and Kang 2016)



“Despite uncertainties, one thing is absolutely clear: global warming is real and poses a significant threat to civilizations worldwide, and reducing emissions of greenhouse gases can mitigate the problem. The process of climate negotiation has been frustratingly slow, but it's encouraging that the world has committed to a goal of keeping temperature increases to less than 2 °C. Both developed and developing countries must work together to share the obligation of emissions reduction. We must act now. This is our moral responsibility towards future generations.” Qin Dahe, Cold and Arid Regions Environment and Engineering Research Institute, Lanzhou, China; Co-Chairman of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) at the International Symposium on Changing Cryosphere, Water Availability and Sustainable Development in Central Asia, Oct 2011)



“All projections point towards increased cryospheric changes in the coming decades and centuries in the extended Hindu Kush-Himalaya. Decreased snowpacks, accelerated glacier mass loss, and changes in permafrost, rivers, and lakes will occur in response to increased temperatures. These cryospheric changes will directly affect populations both within and downstream of the mountains through changes in hydrology, natural hazard risks, and potential infrastructure losses. Notwithstanding the uncertainties in both the climate projections and the model formulations, high-emission scenarios will result in greater cryospheric impacts than low-emission scenarios.” (HKH Assessment, ICIMOD, 2019, p.245).



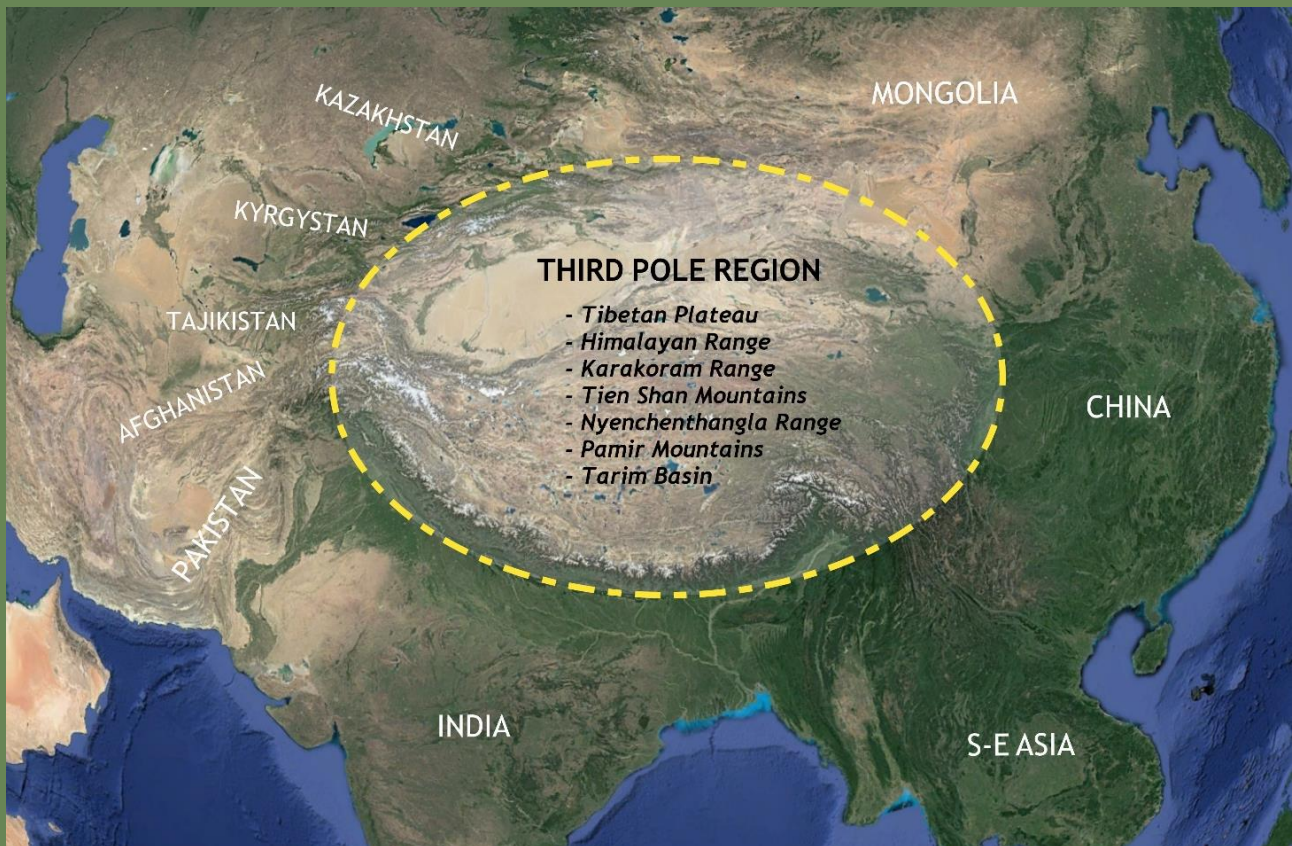
“By 2025, if present consumption patterns continue, about five billion people will be living in areas where it will be difficult or impossible to meet all their needs for fresh water. Half of them will face severe shortages.” (United Nations IAEA Commission Report OBV/267, 22 March 2002)

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EXECUTIVE SUMMARY



1. The Third Pole Region (TPR) is a high-altitude massif at the heart of Asia comprising the Tibetan Plateau and its surrounding mountain ranges: the Himalaya, Karakorum, Pamir and Tien Shan Ranges (see Fig.1) amongst others. Nearly the size of Europe and at an average altitude of 4,000 meters above sea level, the Plateau's glaciers, snow and permanently frozen ground (permafrost) – its *cryosphere* – contains within it the largest mass of frozen freshwater outside of the polar regions, leading to it often being called “The Third Pole”.
2. The TPR cryosphere depends on snowfall and freezing winters, storing frozen freshwater at high altitude. Its gradual melting throughout the rest of the year, augments river flow in spring and summer, regulating the overall water supply to the surrounding region. The cryosphere's ‘buffering’ of Asia's water cycles thus provides the region's rivers with consistent supplies of freshwater throughout the year. The headwaters of ten major rivers are found in the TPR uplands: the Yellow & Yangtse Rivers feeding to the east; the Mekong, Salween, Irrawaddy & Brahmaputra to the south; the Ganges, Sutlej & Indus Rivers to the west; and the Tarim River to the North. In total, 1.9 billion people live within the watersheds of these rivers and depend upon them directly for freshwater supplies, and some 4.1 billion people are fed by agriculture and industry dependent upon these supplies – more than half the world's present population.
3. There is clear evidence that temperatures across the TPR are increasing at a rate between two and four times the global average, a process that has been underway for more than half a century. This primarily involves an increase in minimum winter temperatures, compromising the region's capacity to maintain

a viable cryosphere: glaciers are reducing in size, permafrost is melting, snowfall is turning to rain: the overall pattern is for the Tibetan Plateau in particular to become progressively warmer and wetter. The causes of these changes include global atmospheric warming, regional pollution, local land-use patterns and a growing range of complex feedback processes, but undoubtedly the most substantial driver is global atmospheric warming. Indeed, the conditions for the loss of the majority of glaciers and permafrost across the TPR are already established at present temperatures.

4. Without significant changes to the present direction of global climate change, the impact of these changes over the next fifty years include: increased flooding south of the Himalayas; escalating disruption of human infrastructure in permafrost areas; the desertification of high-altitude river headlands and grasslands in eastern Tibet; and the loss of freshwater supplies to mountain communities and urban centres downstream of the TPR, particularly those in India, Pakistan and Xinjiang that depend on glacial meltwaters. Along the same timetable, this would involve a destabilization of year-round freshwater resources to inland regions around the TPR. Local access to significant freshwater supplies is a hard adaptation limit for human communities, agriculture and industry, and its destabilization would have a direct impact on the population maintenance, agriculture and industry of 220 million people and the continent's resilience to desertification.
5. Several major policy lessons can be learnt from Asian states' struggles to both mitigate and understand these changing environmental conditions:
 - a. Many of the systemic changes that are only now impacting human populations have already been underway for decades and are already *well-established* at present global temperatures.
 - b. Many climate change effects (such as glacier and permafrost melt) depend on non-negotiable physical and biological *thresholds* (such as the 0°C threshold between ice and water), crossing which may precipitate abrupt ecological shifts.
 - c. Climate change processes often *combine* in ways that produce complex and counterintuitive effects, at odds with the abstracted ecological models and precedents for individual processes. Transferring mitigation policies from one ecological zone to another ignores these complex local interactions and may well produce damaging and counterproductive results.
 - d. Some of these effects (such as upland desertification) may prove *transitional*, appearing and disappearing as climate change progresses through distinct stages. Long-term mitigation strategies need to take this into account.
 - e. Realistic projections of the effect of climate change require regional assays of specific ecologies, based on a stronger weight of *on-the-ground empirical data* (as opposed to mathematical modelling) than is presently available. International data sharing is an essential component of this.



RATIONALE

This working paper is the product of the ongoing *Third Pole Climate Inquiry* at the Scottish Parliament's Cross-Party Group on Tibet (CPGT), carried out by the Scottish Centre for Himalayan Research at the University of Aberdeen. The inquiry was prompted by the findings of the CPGT's previous briefing paper, [Mass Relocations and Resettlement on the Tibetan Plateau](#) (published in October 2018), which examined the relocation of up to 2.3million Tibetans during the first two decades of the 21st Century, many of which occurred under the People's Republic of China's Ecological Migration Policy (生態移民政策; *Shēngtài yímín zhèngcè*). While both local and international observers have expressed deep concerns regarding the Eco-Migration scheme itself, the fact that the PRC is facing an ever-deepening environmental crisis is clear – a crisis shared by other countries abutting the wider Third Pole Region – India, Nepal, Bhutan and Pakistan amongst others.

While some of the burgeoning environmental challenges faced by the People's Republic of China since the 1970s (such as urban air pollution) are well-known, the most urgent and overwhelming – expanding desertification and compromised freshwater availability – remain muted on the international stage, despite the absolute limits they place on the country's economy, and their effect on the PRC's capacity to feed its own population. These problems largely centre on the transforming nature of the Third Pole Region, and the growing fragmentation of its traditional capacity to supply reliable year-round fresh water to its neighbouring regions. While this is widely understood in Asia itself and amongst the scientific community, many of its exact causes and mechanisms remain politically contested, and its consequences buried in lengthy scientific papers.

There are therefore three main objectives to this working paper:

The first is to introduce policymakers and the general public to the dynamics of climate change in the Third Pole Region, and its present and potential repercussions – in particular, its repercussions for wider freshwater availability, and therefore of the long-term human carrying capacity of the Asian continent. While the paper involves some discussion of specific policy responses by different countries in the region, this is a huge topic in itself, and will be dealt with in a separate upcoming paper.

The second is to examine some of the larger scientific and policy lessons learnt from facing such crises. Understanding and anticipating the specific on-the-ground effects of climate change over the last fifty years – as well as the manner in which science develops and is deployed – is the basis for preventing threats, mitigating damage, and perhaps even identifying opportunities in a changing world.

The third lies in opening up a discussion around the present limits of the public understanding of climate change in the UK, Europe and the US. In particular:

- i) **To emphasise the degree to which human communities depend on natural processes that are now changing dramatically.** The manner in which intervening urban technologies – from underground pipes through to filtration works – obscure the depth of our collective reliance on *natural* processes. Most particularly here, our almost complete dependence - for both basic survival and the support of industry and agriculture – on the natural water cycles of evaporation, condensation, precipitation and run-off that surround us. At the moment, largely through expensive desalination plants, we can replace just less than 1% of this natural supply.
- ii) **To widen public and policy awareness of the range of natural processes effected by climate change.** Secondly, the almost exclusive concentration in public and media discussions on the impact of climate change, and in particular global warming, on weather and oceanographic phenomena, in

particular sea level rise and heatwaves. With no wish to minimise the potentially catastrophic importance of these possibilities, it nonetheless remains the case that the principal impact of climate change will be on the *land quality and freshwater availability* in continental areas such as Asia, and the subsequent impact this has on our ability to produce enough food to feed a burgeoning human population over the course of the next century.

- iii) **To emphasise the importance of local complexity in understanding climate change predictions.** An equally important (and problematic) tendency lies in the manner in which scientific insights are simplified for the wider public and indeed policymakers. While the need to keep public information on climate change processes clear is vital, this often occurs by explaining its basic scientific principles. This tends to privilege the understanding of *individual* processes – glaciologists explaining how glaciers melt, permafrost specialists explaining methane feedback processes, etc. As educational as this is, the climate change realities that both the public and policymakers will face over the coming years and decades (such as desertification, forest fires, freshwater availability issues) are the product of *complex interactions between multiple processes in particular regions*.

In this last respect, the segmentation of scientific explanations of climate change militates against the creation of publicly available regional assays that identify the unique *combined challenges* that face specific regions. Such assays are essential for national governments to come to terms with those challenges and plan appropriately in terms of mitigation and preparation. With regard to the Third Pole Region itself (that is, the Tibetan Plateau and its surrounding mountainous areas), a major exception to this is ICIMOD's 600-page *Hindu Kush-Himalaya Assessment* (Springer/Cham, 2019 – publicly available on the web) – and this report very much follows their lead in this regard.

Nonetheless, this paper emerges from a review of almost nine hundred scientific papers on climate change, meteorology, glaciology, hydrology and permafrost studies carried out by scientists and research teams around the world, most especially by the Intergovernmental Panel on Climate Change (IPCC), the Chinese Academy of Sciences (CAS), the International Centre for Integrated Mountain Research (ICIMOD, Kathmandu), and the Environment Desk of the Tibet Policy Institute (Dharamsala). We are thankful to these organisations, as well as other research and media organisations, and individual scientists, for the research they have produced, the evidence they have provided, and the time they have given up in consultation and discussions with the Cross-Party Group. The Scottish Centre for Himalayan Research is particularly grateful to Prof. Pete Smith (Chair in Plant and Soil Science, University of Aberdeen), Prof. Brice Rea (Chair in Geography and Environment, School of Geosciences University of Aberdeen), Gabriel Lafitte (rukor.org) and Tempa Gyaltzen Zamlha (Senior Fellow/Executive Head, Environment Desk, Tibet Policy Institute) for peer-review and comments, and to the University of Aberdeen for support in producing this paper.



THE THIRD POLE CRYOSPHERE CORE OF THE ASIAN WATER CYCLE

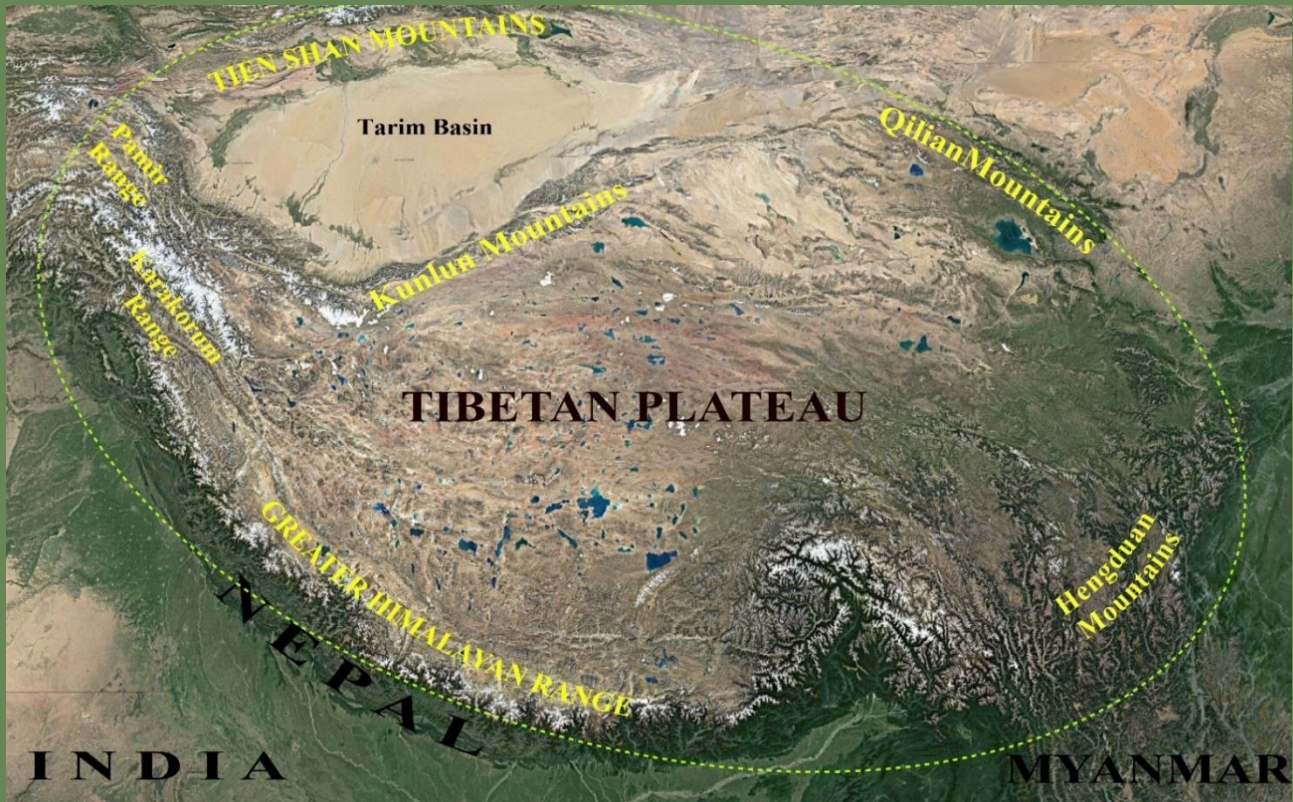


Fig.1: The Third Pole Region, its major rivers and mountain ranges.

The Third Pole Region (TPR) – that is, the Tibetan Plateau and its surrounding mountain ranges (see diagram above) are the heart of Asia’s water cycle and supply almost all the continent’s major rivers. The glaciers, icefields and permafrost of the TPR act as a cryosphere – a domain of ice – whose gradual melting across the year ensures continuity of freshwater supply to population centres in South, East and Central Asia – one of the most densely populated areas of the planet.

The Tibetan Plateau is a high-altitude massif at the heart of Asia, formed 50 million years ago by the tectonic collision of the Indian subcontinent with the Eurasian Plate. This collision raised the seabed some five kilometres, forming both the Plateau itself and its surrounding mountain ranges: the Himalaya, Karakoram, Pamir, Kunlun and Tianshan Ranges. Combined, these cover more than three million km² – roughly the size of Western Europe. Most of the Plateau is located within People’s Republic of China, but also includes all of Nepal and Bhutan, and large areas of India, Bangladesh, Pakistan and Afghanistan.

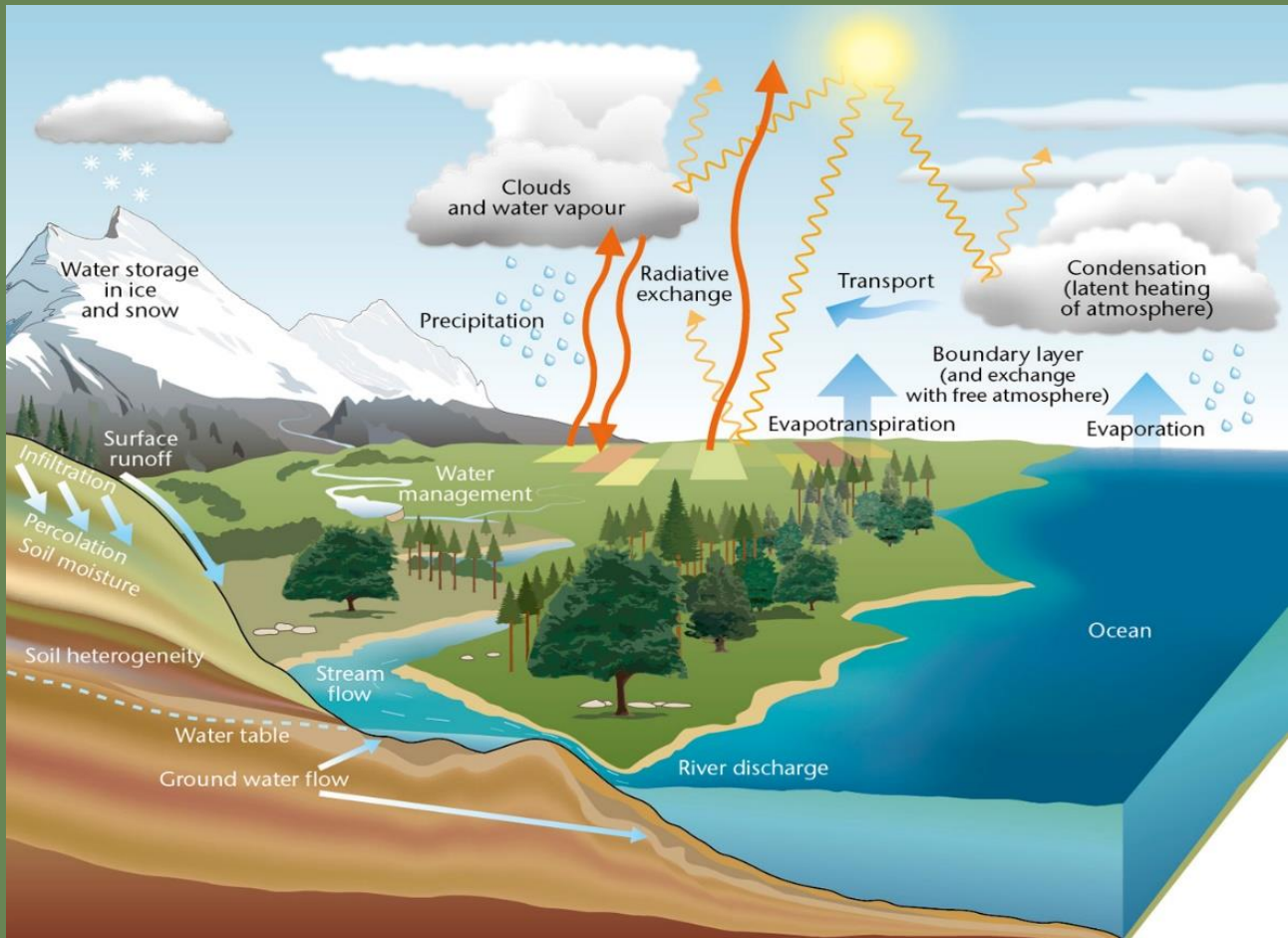


Fig.2: The Water Cycle: Courtesy of the UK Met Office.

In combination with its distance from the sea, the height of the Plateau has made it a cold and desolate land for most of human history, acting as a *cryosphere* – a storehouse of snow, glaciers and permafrost. Its glaciers alone are estimated to hold more than six thousand cubic kilometres of ice, making it the “Third Pole” – the largest reservoir of frozen fresh water outside the Arctic and Antarctic.

This makes the Third Pole Region an indispensable part of the Asian water cycle, a process that sustains all human populations on the continent, no matter how technologically developed. The Plateau’s high altitude and historically low temperatures combine with its position on the northern boundary of the tropics to create a fragile balance of ice accumulation in the winter and gradual melting in the spring and summer months. During the summer, moist air is drawn off the oceans by the heating of the land, where it rises and turns into rain. As this moist air is drawn eventually to the higher mountainous regions of the Third Pole Region, it falls as rain and snow, compacting and accumulating as ice and percolating into the ground. Residual heating of the land during warmer days and on sun-facing slopes causes this ice to gradually melt and congregate around headlands, forming the upper reaches of the continent’s vital rivers.

This melting makes the Tibetan Plateau in particular the source of all of Asia’s major rivers, with the Indus, Sutlej and Brahmaputra headlands located within the southern Himalayas and the Yellow, Yangtze, Mekong and Irrawaddy Rivers finding their sources in the upper grasslands of eastern Tibet. Running back out of the Region under the force of gravity, these meltwaters are augmented by seasonally dependent rain and runoff from lower-level watershed lands. The spring and summer meltwaters from this cryosphere feed into the headlands of most of Asia’s major rivers, providing year-round consistency of water supply, especially during

dry seasons. These rivers provide direct freshwater supplies for 225 million people in the immediate environs of the Third Pole Region, and augment freshwater resources for a total of 1.9 billion people. The areas they help irrigate provide food sources for 4.1 billion people – more than half the world’s population. While these rivers are also fed by rainfall throughout the rainy season, it is the slow melting of Tibetan glaciers, permafrost and snow throughout the rest of the year that provides a baseline for human habitation, agriculture and industry in Asia since the time of the earliest human civilizations in the Indus Valley and Yellow River areas of India and China.



THE WARMING PLATEAU

Overwhelming evidence now exists that the Third Pole Region’s longstanding balance of slow year-round melting replenished by winter snows has undergone a major shift since the 1970s. The region has seen a consistent movement towards a warmer and wetter climate. This will significantly destabilise the TPR’s capacity to regulate regional water supplies across the year, undermining regional water security of the wider continental area. Almost all projections for future climate across the TPR project further dramatic increases in temperature, accompanied by an increase in summer precipitation.

Like many other areas of the world, the analysis of ice cores, tree rings, lake changes and cave sediments reveals significant fluctuations in the climate of the Tibetan Plateau during the period of human habitation. This included, for example, a mini-ice age between 1560 and 1750. Nevertheless, there is consensus that the Tibetan Plateau is presently undergoing a significant warming period, and overall has experienced higher average temperatures during the late 20th Century than at any other period over the last one thousand years (Krishnan, Raghavan; Shrestha 2019; Gou, Wang, and Li 2012; Liu et al. 2009; K. Yang et al. 2014; Kang et al. 2010; X. Xu et al. 2008; You et al. 2010; Ran, Li, and Cheng 2018a; T. Yao et al. 1995; Lau et al. 2010; G. Wang et al. 2011; Wu, Yu, and Jin 2017; Rangwala, Miller, and Xu 2009; Shrestha et al. 1999).

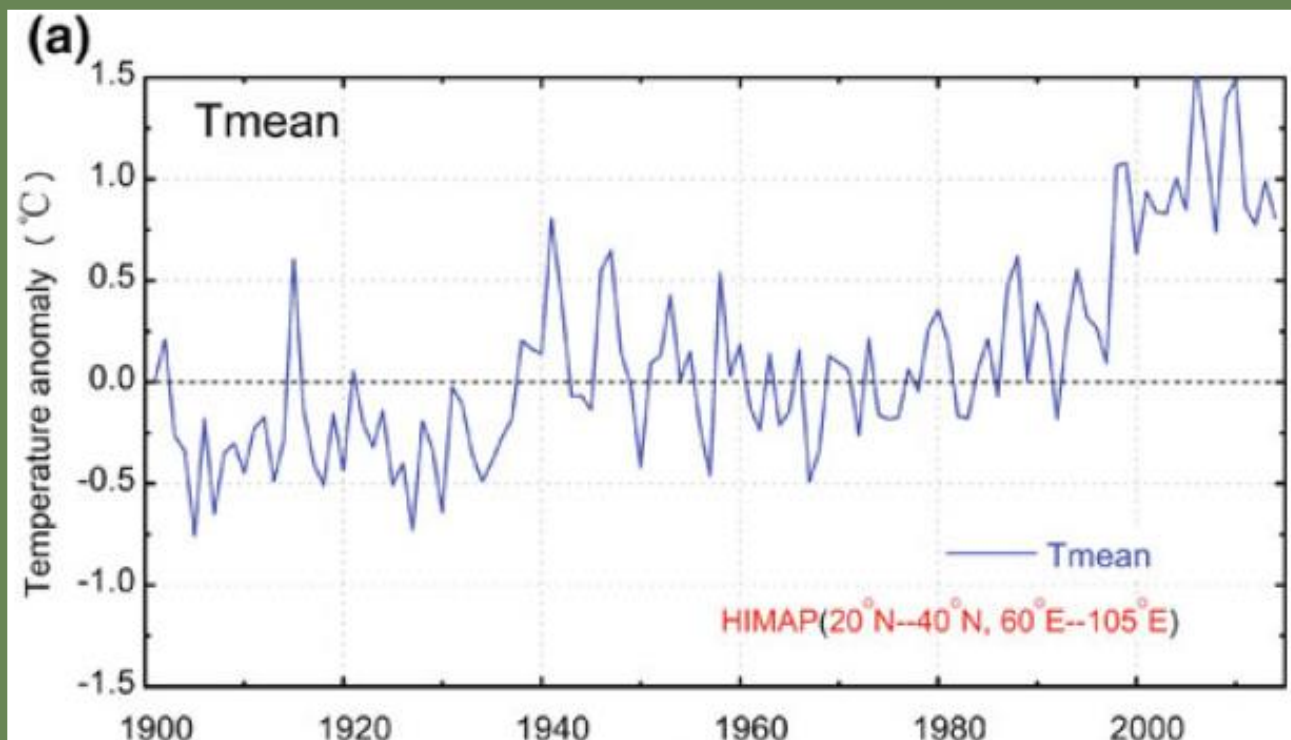


Fig.3: Mean temperature changes on the Tibetan Plateau across the last century.
 Source: Khrishnan et al. 2019: 66

While temperatures have varied by decade (see Fig.3) – with 1900-1930 being relatively stable and 1940-1970 showing an overall cooling in line with a significant drop in temperature across the northern hemisphere (You et al. 2010, 2013; Kang et al. 2010) – the 1970s onwards saw a marked increase in temperatures (Tang and Ren 2005; Shrestha et al. 1999). This warming slowed somewhat from 1998-2014 (again consistent with

global temperature changes – Trenberth et al. 2014), but nonetheless witnessed some of the warmest years on record (2007 and 2010 respectively – Ren et al. 2017), with mean temperatures on the Plateau increasing during this period by between 0.28°C–0.61°C per decade (You, Min, and Kang 2016; Cheng and Wu 2007a; Yan, L. B., & Liu 2014). A joint report by the Chinese Academy of Sciences (CAS) and the Tibetan Provincial Government in August 2014 placed this temperature rise at an average of 0.4°C per decade (Qiu 2014).

Such temperature changes generally follow the overall warming patterns identified for the northern hemisphere as a whole, but are significantly greater in magnitude, being more than twice the global average for warming (Liu and Chen 2000) and generally increasing with altitude (see next section). Some CAS results report temperature increases in the river headlands of the upper mountains of eastern Tibet as much as four times the global sea level average (Liu et al. 2009).

These temperature changes are, moreover, *asymmetrical*: while they show a general increase in mean temperature, this is largely driven by a *larger increase in minimum* temperatures – that is, a *reduction in the number of cold and very cold days* (Fan et al. 2015; Krishnan, Raghavan; Shrestha 2019; Rangwala, Sinsky, and Miller 2013; Rangwala, Miller, and Xu 2009; Ding, Wang, and Lu 2018; Liu et al. 2009). In this regard, warming on the Plateau mainly occurs during the winter months and early spring (Ran, Li, and Cheng 2018b; D. Guo, Wang, and Li 2012), reducing the region’s capacity to accumulate ice and snow. At the same time (as illustrated in Fig.3), the effect of these increases is disproportionate to their size because they generally resolve around 0°C – the melting point of ice and threshold of viability for the Third Pole’s cryosphere.

Projections of Third Pole Climate Change, 2035-2100

Climate change projections presented by the International Panel on Climate Change have undergone several modifications as the range of possible factors – industrial and population expansion, carbon fuel use, carbon dioxide emissions, environmental feedback processes, etc. – has been refined and integrated. The latest 2014 IPCC report simplified these possible futures into four potential *representative concentration pathways* (RCP), defined simply in terms of the concentration of greenhouse gases (measured against carbon dioxide concentrations) in the atmosphere *from whatever source*. The four projected RCP pathways are RCP 2.6 (greenhouse gas emissions peaking in 2010-2020 and declining thereafter); RCP 4.5 (peaking around 2040, declining thereafter); RCP 6.0 (peaking at 2080, declining thereafter); and RCP 8.5 (continuous expansion at present rates). Just as medical understanding develops with the emergence of a new disease, the global scientific community have systematically improved theory and modelling when predicting future climate change. Advances in these models usually involves what is called “coupled” models, which co-ordinate existing models from multiple disciplines (meteorology, hydrology, glaciology, permafrost studies, geology, etc.), as our understanding of the interrelationships and feedback mechanisms between the many aspects of the natural world develop. The following projections come from the IPCC’s CMIP5 (*Coupled Model Intercomparison Project 5*) work completed in 2013. For the sake of simplicity, in what follows we will look at the predicted changes in temperature and precipitation (rain and snowfall) for Representative Concentration Pathways RCP 4.5 and RCP 8.5.

Temperature Changes

These two pathways have dramatically different effects, and those effects impact upon the Third Pole Region differentially depending on location. Fig. 4, from the recent *Hindu Kush Himalaya Assessment* results that co-ordinate the results of twenty-four international CMIP5 models (ICIMOD 2019, 88), project the following distribution of winter temperature rises for RCP 4.5 and RCP 8.5 up to the end of this century:

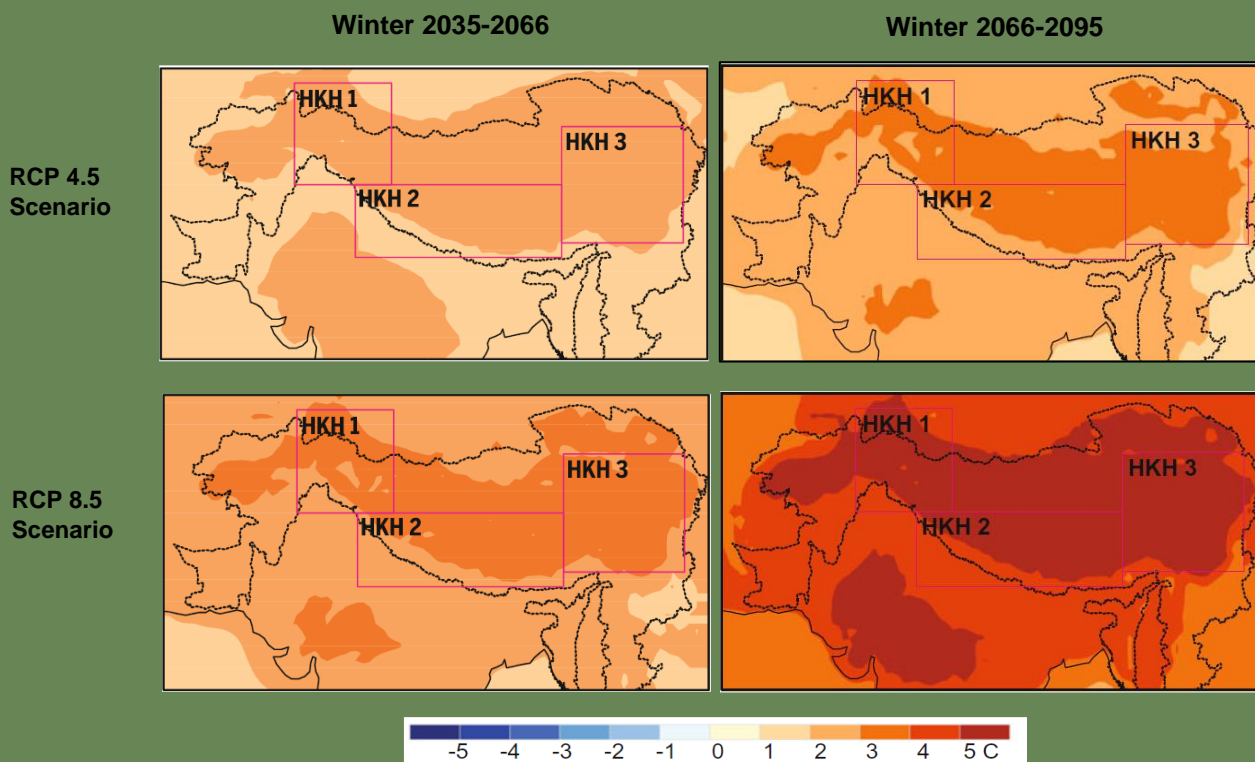


Fig.4: Projected temperature rises across the Tibetan Plateau and surrounding areas under IPCC scenarios RCP 4.5 and 8.5 during the winters of 2035-2095. Compared against baseline temperatures for 1976-2005.

Source: Hindu Kush Himalaya Assessment (2019): 81

NOTE: The Paris Agreement of December 2015, which bound its 196 signatory countries to stabilising global temperature rises to well below 2°C (with a goal of 1.5°C), constitutes a further pathway of RCP 1.9, with dramatic cuts in carbon production worldwide. For the Third Pole Region, a 1.5°C rise would mean an *average* temperature increase of 1.8 ± 0.4 °C. Amongst the region’s various mountain ranges, this would mean a 2.2 °C (± 0.4 °C) rise in the Karakoram Range and a 2.0 °C (± 0.5 °C) rise in the central and south-eastern Himalaya, respectively (ICIMOD 2019, 83).

Precipitation Changes

Projecting future patterns of precipitation (rain and snowfall) is significantly harder than predicting temperature changes. At the moment, these are largely based on CORDEX (*COordinated Regional climate Downscaling EXperiment*) models, which have key limitations: in particular, the influence of local micro-conditions such as the impact of mountain ranges, and the inherent instability of key meteorological events such as the summer monsoons, make such changes harder to predict (Maussion et al. 2014; ICIMOD 2019; Dong et al. 2016).

Nonetheless, almost all such models point towards a general increase in precipitation across most of the Third Pole Region, particularly in the east and north of the Tibetan Plateau (see Fig. 5, below). The persistence and strengthening of westerly winds coming across Afghanistan means that these increases will be matched by a decline in precipitation in the west (that is, Pakistan, Afghanistan and Tajikistan), with this imbalance becoming more marked as the century progresses.

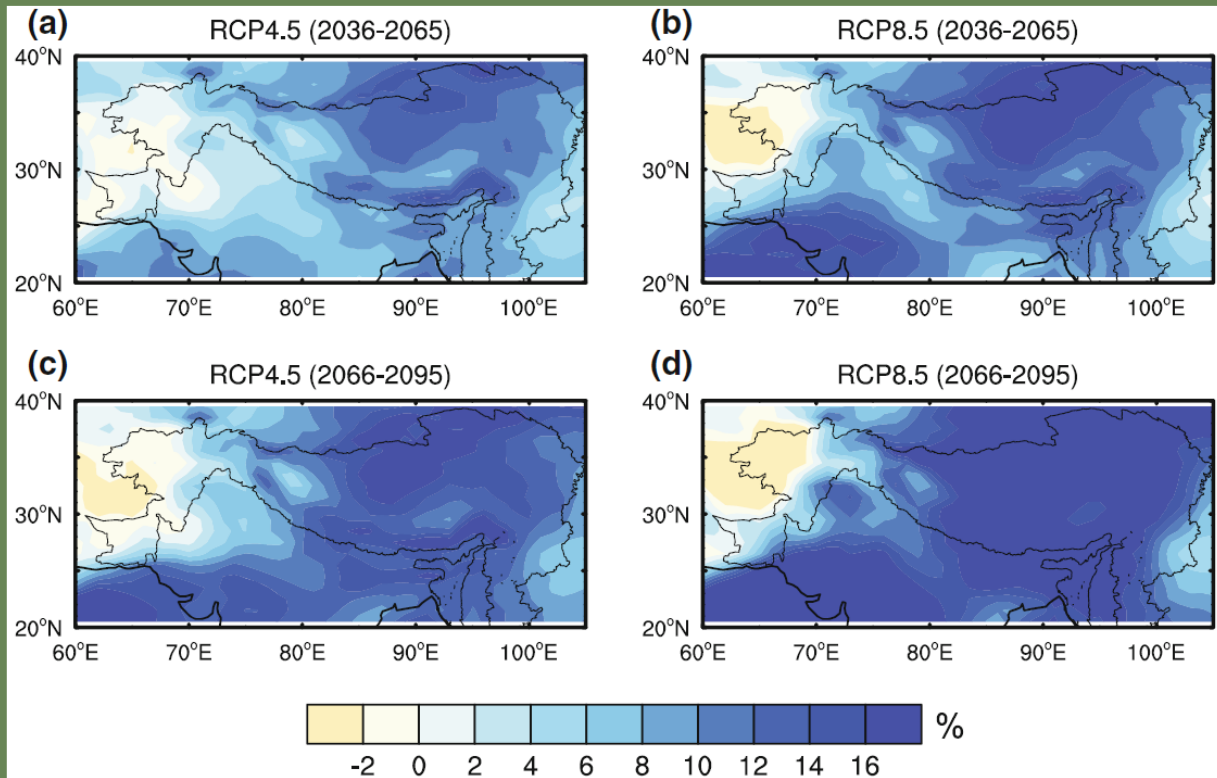


Fig.5: Projected increases in precipitation under RCP 4.5 and 8.5 for years 2036-2065 and 2065-2095.
Source: Hindu Kush Himalaya Assessment (2019): 85



GLACIER LOSS

Along with most other glacial areas around the world, the Third Pole Region has seen a pronounced reduction of the overall 'mass balance' and retreat of its glaciers in almost all areas since the 1950s. This is largely a product of overall atmospheric warming and black carbon pollution deposits from regional urbanisation and industrialisation. At present rates, it is estimated that the majority of the TPR's glaciers will have disappeared by the end of the century, and with them the crucial year round fresh water support they provide to major Asian industry, agriculture and population centres.

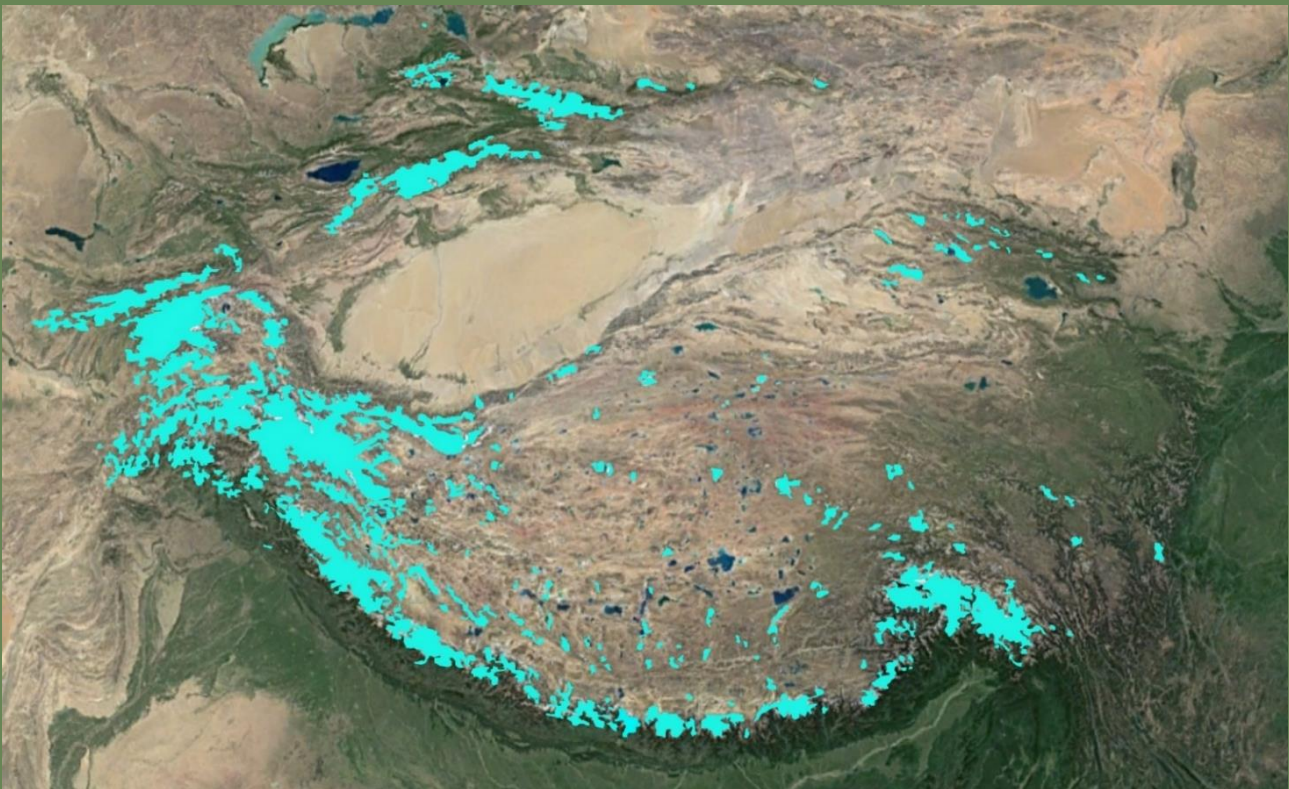


Fig. 6: Present distribution of large glaciers across the Third Pole Region. From Zhang 2017.

The glaciers of the Third Pole Region – spread across the western half of the People's Republic of China, northern India, Nepal, Bhutan, Pakistan and Tadjikistan (see Fig .6) – cover almost 59,425 km² and contain some 5,600 cubic kilometres of ice, a frozen freshwater supply held inside some 27,024 documented glaciers of different sizes (Shi, Liu, and Kang 2009). Since the 1970s, however, surveys of glacial mass in the region have highlighted a persistent reduction in both the size and number of the region's glaciers. This overall loss of 'mass balance' has been witnessed across the globe in a wide number of mountain ranges, as well as the polar regions (see Fig 7). In the Third Pole Region itself, this decline has been measured since the 1970s (Gertler et al. 2016; T. Yao et al. 2007; Kang et al. 2010; Zheng, Xu, and Shen 2002; Krishnan, Raghavan; Shrestha 2019; Ageta and Kadota 1992). By the mid-2000s, glaciers within the People's Republic of China had shed 586.9 billion cubic metres of ice, a 15% decline in overall glacial mass over fifty years. In regions such as Xinjiang (the desert basin to the north of the Tibetan Plateau), that figure is between 21-27% (CHEN 2017). Under a conservative warming scenario of RCP 4.5 (see above), most studies show a loss of between 45-63% in glacial mass by the end of this century, with some estimates being much higher (ICIMOD 2019, 231).

The loss of the Third Pole’s glacial mass is far more than an aesthetic issue, a loss of one of nature’s wonders; far more importantly, such a loss will profoundly destabilise Asia’s year-round supply of fresh water, and its capacity to maintain industry, agriculture and population centres. To appreciate the magnitude of this problem, we need to understand how glaciers help regulate continental freshwater supply.

Despite their size and age, glaciers are highly dynamic phenomena (see Fig. 7), constantly moving and intimately linked to climate through precipitation (snow and rainfall, which leads to the accumulation of ice) and temperature (which leads to the melting of ice). A glacier acts like a conveyor belt: ice accumulates, year on year, in the upper part (the accumulation zone); the weight of the ice and the steep slopes makes the ice flow continually downhill and; in the lower part (the ablation zone), the snow and ice melts. Glaciers release most of their meltwater in the spring and summer driven by warm air temperatures. As they are located at the highest elevations in a catchment they provide meltwater later in the hydrological year and thus keep rivers flowing in dry season and when snow at lower elevations has all melted. In addition, glaciers can lead to cooling of the surrounding air, leading to local precipitation or fog, both of which can augment snow accumulation, in a positive feedback loop (Ayala, Pellicciotti, and Shea 2015). However, when melting exceeds accumulation, glaciers gradually reduce in size, reducing their capacity to provide water supplies in the summer months.

Annual melting is thus a normal part of glacial processes, and a vital contributor to mountain ecosystems, river support and supplies of freshwater for downstream agriculture, industry and population centres. For some areas around and within the Third Pole Region – such as those populations and agriculture in the Chinese province of Xinjiang around the Urumqi River and much of Pakistan, agriculture, industries and cities depend almost entirely on glacial meltwater in the summer (J. Yao et al. 2018; Jilani, Haq, and Naseer 2007; Khan, Koch, and Tahir 2020). In other areas, such as the northern and western provinces of the Chinese mainland, this meltwater is an essential source of support for the first of its two main growing seasons.

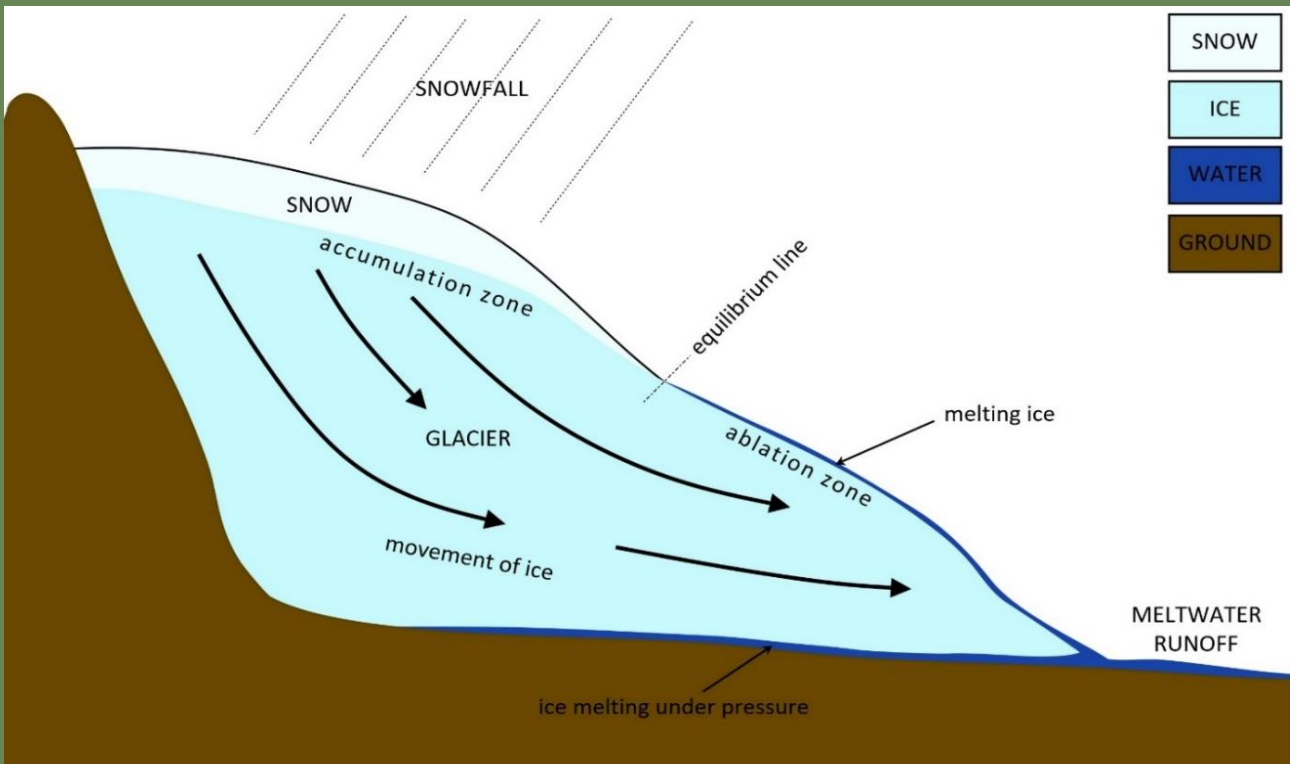


Fig. 7: Dynamics of glacial ice formation, movement and melting.

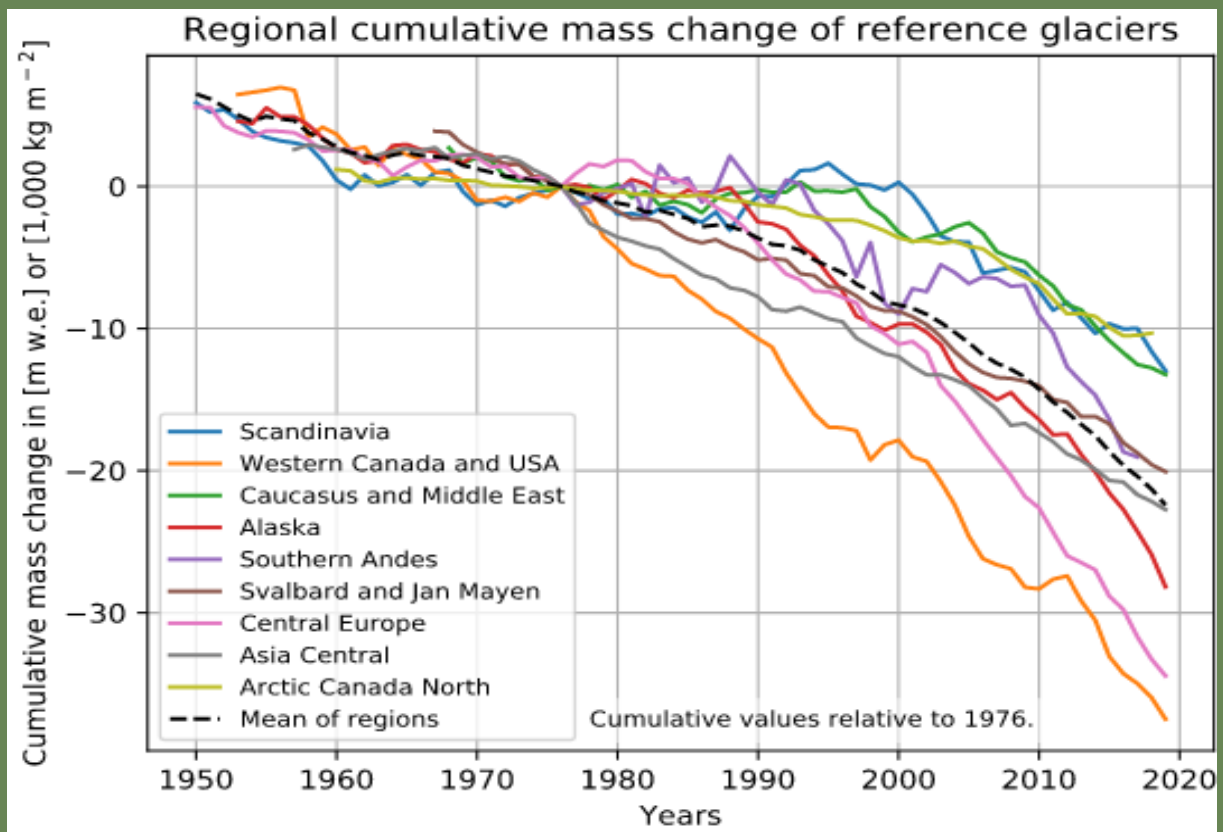


Fig. 8: Comparison of the decline in glacial mass balance across the world.
The Third Pole Region is the grey line ('Asia Central').
Source: World Glacier Monitoring Service, 2020.



The Causes and Consequences of Glacial Loss

Glacial mass loss is caused by several factors: increases in ambient air and ground temperatures; reduction in precipitation; the effects of particulate pollution (particularly black carbon); and feedback mechanisms.

- **Increases in ambient air temperature:** These can be caused either by global factors such as general atmospheric warming (see above), regional factors such as meteorological changes; or local factors such as the expansion of nearby towns or industrial centres (Jianping et al. 2003). As we have seen above, temperatures across the TPR have progressively increased for the last fifty years and are set to continue rising, in line with overall global warming.
- **Changes in precipitation:** The sheer size of the Third Pole Region means that its various areas are the subject of different wind and weather patterns: the south-eastern section of the TPR (effectively, the Himalayas and southern Tibetan Plateau east of the Sutlej River) is strongly affected by changes in the Indian summer monsoon; the north (such as the Tien Shan, Qilian and Kunlun mountain areas) by the Siberian high-winter monsoon; the west (particularly around the Karakorum and Pamir ranges) by the westerly winds that enter the TPR across Afghanistan and Pakistan; and the east by the summer monsoon that passes over southern China. On the Tibetan Plateau, the cooling of the summer monsoon winds creates snowfall which both adds mass to the glaciers and increases their capacity to reflect sunlight. Increased warming of this monsoon, both in the last fifty years and in the projected future (see above), is causing a progressive shift from snowfall to rain, promoting snow and ice melt (Fujita and Ageta 2000; Fujita 2008).
- **Regional black carbon pollution:** When carbon is incompletely burnt, it can plume to an altitude of 5 kms and travel trans-continental distances in aerosol form (as black carbon, or soot). Brought by wind onto glaciers, it falls in precipitation, progressively blackening the glaciers so they reflect less sunlight and melt faster (Kopacz et al. 2011; Gertler et al. 2016; Lüthi et al. 2015; Fujita 2007). Black carbon aerosol emerges mainly from human activities, primarily the burning of fossil fuels, biofuels and biomass, and is itself a major contributor to overall global warming, second only in impact to carbon dioxide (Ramanathan and Carmichael 2008). Black carbon pollution in the TPR predominates along the south-western, southern and eastern boundaries of the Tibetan Plateau (R. Zhang et al. 2015; C. Li et al. 2016; Werner et al. 2013; Q. Y. Wang et al. 2015): pollution along its southwestern borderlands being transported mainly from the Indo-Gangetic Plains of Pakistan and India but, carried by high westerly winds, can come from as far away as East Africa; along its southern Himalayan borders, from the North Indian Plains; and on the eastern Tibetan Plateau, from the conurbations of mainland China. Much of this pollution is seasonal, peaking in the early spring months when human burning of fossil fuels and household fires is greatest.
- **Positive feedback mechanisms:** As glaciers reduce in mass, their cooling effect on the surrounding atmosphere (see above) reduces, allowing water vapour to pass over them without turning into cloud, rain or snow. Since they draw less cloud cover and cold precipitation to them, accumulation rates reduce and ablation increases, increasing melting and mass loss. As the glacier melts further, ponds grow in its surface, which absorb energy from the environment fourteen times faster than the glacial ice itself, speeding melting further (Miles et al. 2018). These positive feedback mechanisms promote runaway glacial loss.

The impact of sustained increases in glacial melt has generally been understood in terms of the 'peak water' model: that is, as glaciers melt, the relationship between their surface area and their overall mass means that the meltwater running off them increases slowly (over many decades) to a peak, and then declines rapidly. This model gained prominence from research in the Andes in the early 2000s (Pouyaud et al. 2005) and has been usefully deployed in a wide variety of cases around the world. In the TPR, it has reasonably accurately

described changes in meltwater runoff from the southern Himalayan range area (feeding the Indus, Sutlej and Brahmaputra Rivers) and the northern Kunlun Mountains (feeding the rivers of the Tarim Basin). The upper Indus, Sutlej and Brahmaputra Rivers in particular have seen an increased incidence of flooding events, leading ultimately to an overall decline in river output. For such rivers, particularly in their upper reaches, the long term projection is that they will become seasonal, rendering affected areas comparatively uninhabitable and prone to soil erosion and desertification (Barnett, Adam, and Lettenmaier 2005; Kehrwald et al. 2008).

However, the 'peak water' model is itself attended by certain anomalies, especially along the boundaries of the eastern Tibetan Plateau, where extensive glacial loss seems to have been attended by *reductions* in water flow from east and south-east facing rivers such as the Yellow, Yangtze and Irrawaddy Rivers, many of whose headlands have witnessed increasing early-stage desertification. Growing evidence suggests that this anomaly is related to the disintegration of permafrost (see below), one of the most important, but hidden, elements of the Third Pole cryosphere.



PERMAFROST DISINTEGRATION

The warming of the Third Pole Region has also affected its vast reservoir of permafrost, which has demonstrated persistent thawing since the 1960s. In the immediate to medium term (0-30 years), permafrost melt will trigger localised landslides, undermine road and rail links, and compromise urban and industrial infrastructure. In the immediate to long term, it is projected that permafrost thawing will significantly affect the region's water cycle, expanding desertification around the key headlands that source major outflowing rivers, with significant effects on downstream water security across Asia. In the long term (100+ years), local non headwater areas (especially northwest Tibet) will see a flourishing of agricultural and forest capacity.

If glaciers are the public face of climate change, permafrost – land that remains frozen throughout the year for two or more consecutive years – is its hidden leviathan. Permafrost covers more than 25% of the world's landmass, mainly in the Arctic circumpolar regions, parts of the Antarctic continent and the Third Pole Region. The TPR's permafrost layer is an integral part of its cryosphere: recently estimated to contain almost ten thousand cubic kilometres of frozen freshwater – more than that held in the Third Pole's glaciers. As with other areas, persistent warming has caused a widespread disintegration of subterranean permafrost across the TPR, with the majority of existing permafrost expected to disappear by the end of the century.

Public perception of the impacts of melting permafrost largely revolves around the potential release of methane (a potent greenhouse gas) causing a positive feedback loop to overall greenhouse warming. This appears also to be the case in the Third Pole Region (Cheng and Wu 2007b; N. Zhang 2017) but it remains only one of the many impacts of widespread permafrost warming, which can have a dramatic and unpredictable impact on the region's water cycle, infrastructure and the overall habitability of the land.

To understand this, it is necessary to appreciate how permafrost is structured, and how it affects water flow in mountainous regions. Far more than simply frozen ground, permafrost separates the soil into layers (see Fig.10):

- **Active Layer:** Permanently frozen ground (permafrost) is generally concealed beneath an “active layer” of seasonally-warmed surface earth, generally somewhere between 50cm–2m deep, which melts during the summer (B. Wang and French 1995; Wu and Zhang 2008; Cheng and Wu 2007b).
- **Permafrost Layer:** Beneath the active layer is a permanently frozen layer of soil, rock and ice. The depth of this permafrost layer can vary considerably and has been known in areas of northern Siberia to penetrate to depths as great as 1500m; on the Tibetan Plateau, results so far show it varying from 10 to 300m, with an estimated average depth of 39m (Wu and Zhang 2008; Wu, Zhang, and Liu 2010; Weiming et al. 2012).
- **Unfrozen bedrock:** Beneath the permafrost layer is unfrozen bedrock or sediment, warmed by geothermal heat from the Earth's interior.

Permafrost dynamics profoundly affect the way in which water flows in regions where it is dominant and the permafrost layer is continuous (Song et al. 2020). Simply put, ice is waterproof, and the existence of a continuous layer of permafrost acts as a barrier, preventing water runoff from snow, rain and glacial melt from sinking into underlying unfrozen soil and bedrock. As a consequence, meltwater from snow and glacial melt tends to flow close to the surface, seeping through the active layer towards river headwaters (see Fig 10), supplementing river flow and supplying moisture to nearby grass and vegetation growing on a thin active layer.

The decline in the underlying permafrost layer in the Third Pole Region – particularly on the Tibetan Plateau (see Fig.9) – has been noticed since the 1960s, but only studied systematically since the late 1970s (B. Wang and French 1995). In 1980, permafrost was estimated to be spread across 1.2 million km² of the Tibetan Plateau (D. Guo, Wang, and Li 2012), with most of the rest being seasonally frozen soils (P. Zhang et al. 2018). At present levels of warming, however, it is projected that by 2030-50, this area will almost have halved to 749,000 km², and almost entirely gone by the end of this century, turning into soil that is either unfrozen or seasonally frozen (T. Yao et al. 2019; Cuo et al. 2014; Ran, Li, and Cheng 2018a).

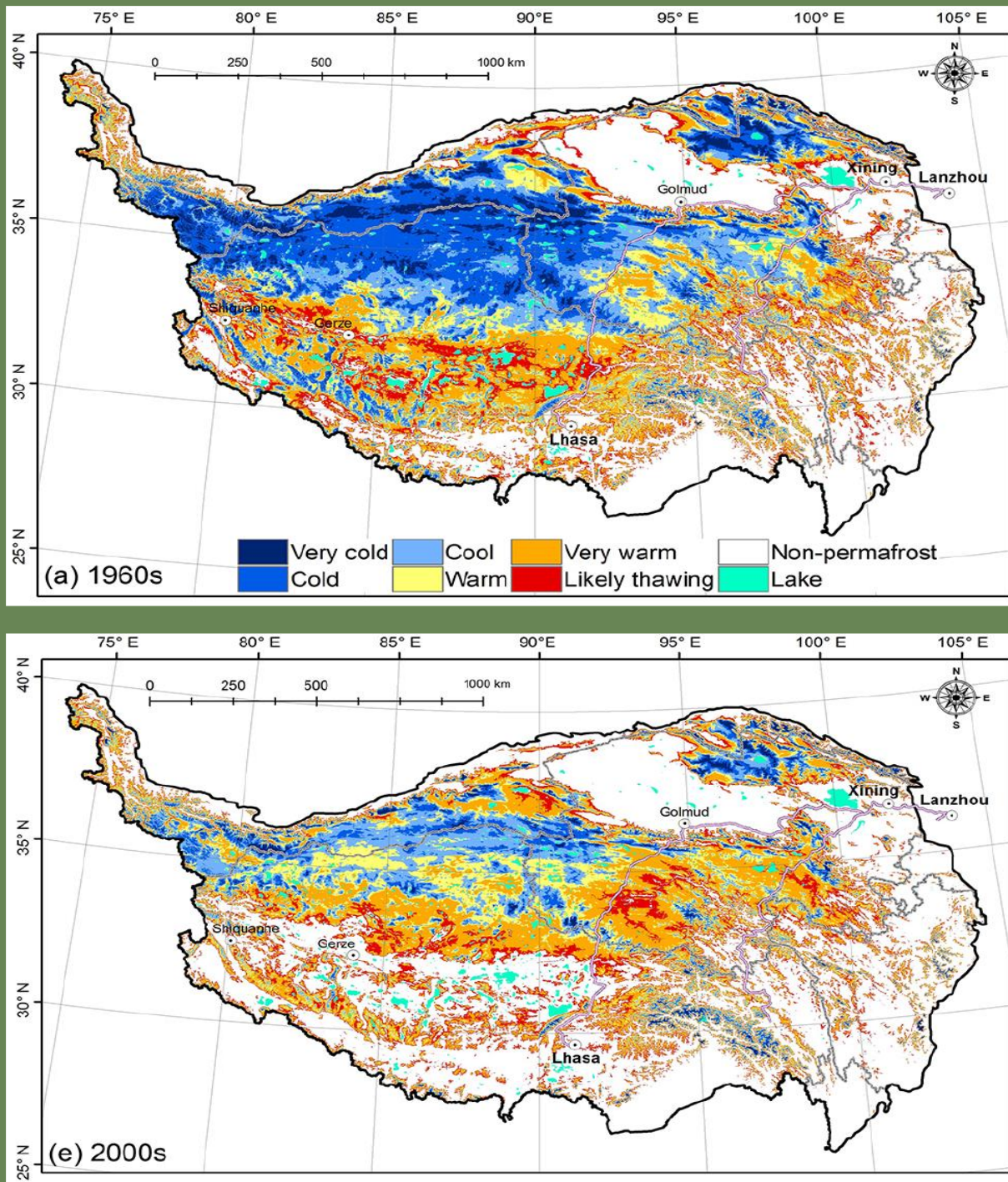


Fig. 9: Permafrost warming and degradation on the Tibetan Plateau between 1960 – 2000.
 Source: Ran, Li, and Cheng 2018a

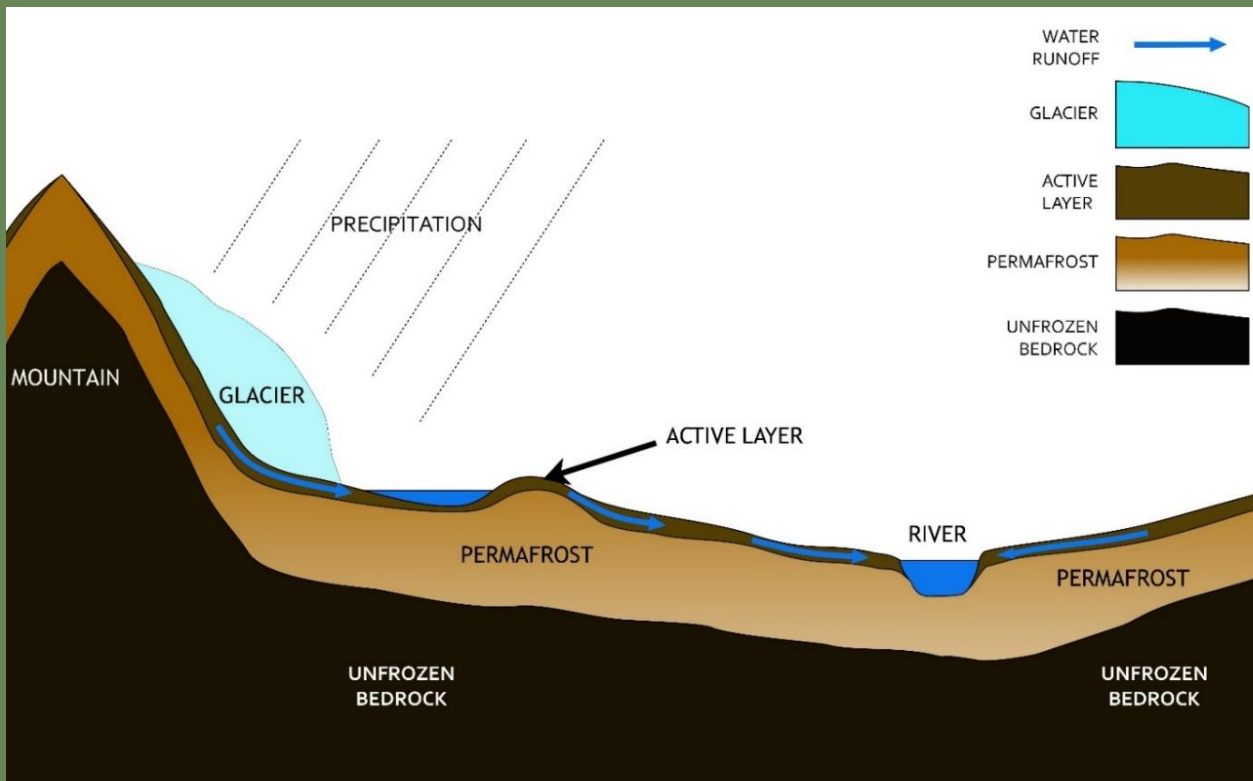


Fig.10: Pre-thawing - water run-off in high mountain conditions, with a continuous permafrost layer.

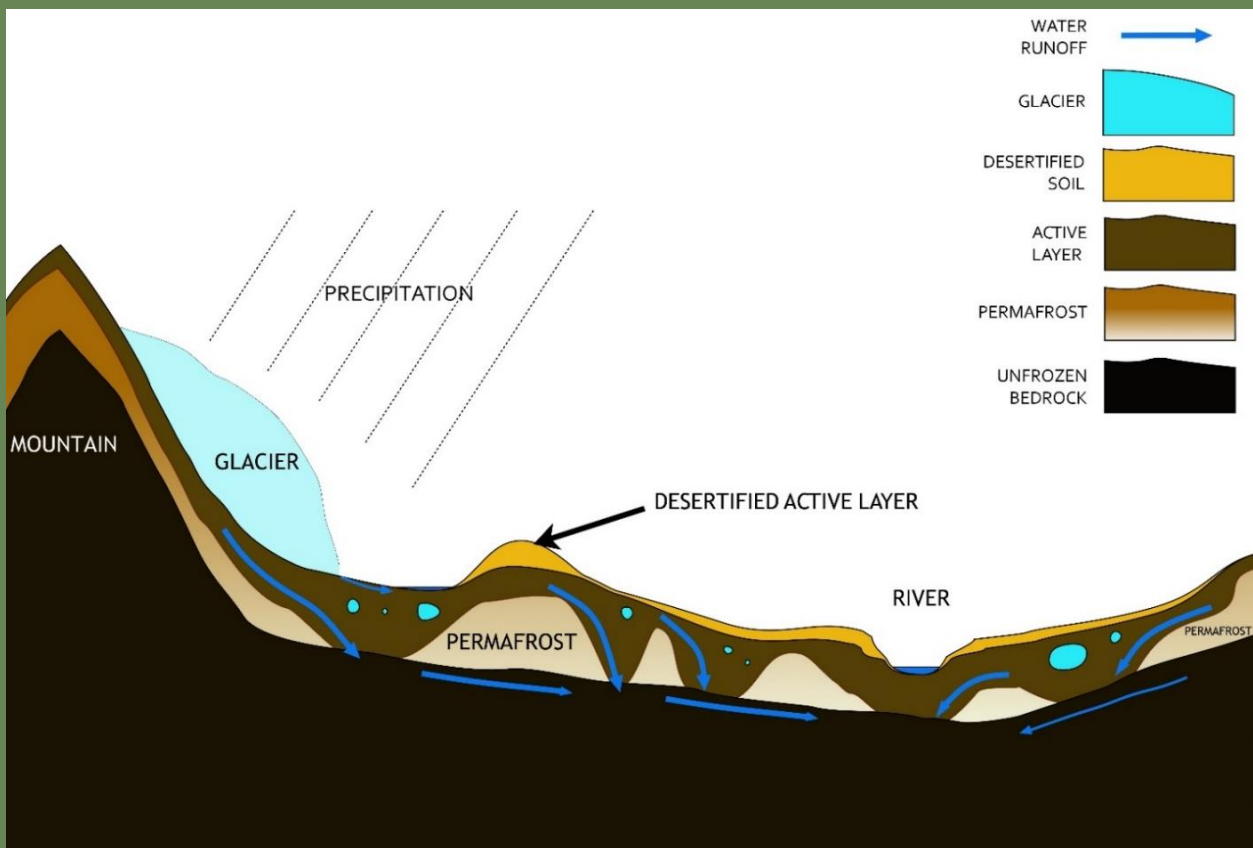


Fig.11: Post-thawing - water run-off in high mountain conditions, with discontinuous permafrost.

Impacts of Permafrost Degradation

While mountain areas such as the TPR present unique challenges, evidence from comparable warming of the permafrost regions of Siberia and Alaska shows that the degradation of permafrost due to warming involves several processes (see Fig 11). Each of these has significant consequences on the surrounding landscape, ecology and hydrology:

- **Deepening Active Layer:** The melting of the permafrost layer is attended by the deepening of the active layer above. There is considerable variation in the speed of this process, from as little as 2 cm per annum to as much as 20 cm (D. Guo, Wang, and Li 2012; Cheng and Wu 2007a; Wu et al. 2015; Pang et al. 2012).
- **Water Release:** Because the permafrost layer contains large quantities of frozen water, this is released upon melting, and begins to redistribute below the ground under the effects of gravity, producing transient flooding and lake increase at lower elevations – often at some considerable distance from the region of degrading permafrost (Huissteden 2020).
- **Methane Release:** The considerable mass of organic material trapped within the permafrost layer decomposes as it melts, releasing methane into the atmosphere. A potent greenhouse gas, methane release over such a large area would contribute considerably to overall atmospheric warming. Recent estimates place the quantity of methane trapped in the permafrost within the Tibetan Plateau at 120 billion and 240 trillion cubic meters (M. Yang et al. 2010; D. F. Chen, Wang, and Xia 2005).
- **Subsidence:** Combined with the fact that water expands upon freezing and reduces upon melting, permafrost melting quickly generates subsidence in permafrost areas, concomitant with the thickness of the melted permafrost and its original ice content (Wei et al. 2006; Shan et al. 2013; 2015; Cheng and Wu 2007b; N. Chen 2018). Moreover, water that is released from melting permafrost can effectively liquefy the soil, causing it to shift and collapse under gravity. This can have dramatic effects on local landscapes (see below).
- **Lowered Water Table:** Where the permafrost melts enough to become discontinuous, the water released from thawing and from nearby precipitation can sink deeper into the ground (see Fig.11), soaking through into the underlying unfrozen soil and bedrock (Qiu 2012; Zhao et al. 2019; D. Zou et al. 2017). This can significantly lower the area's water table, affecting nearby vegetation and crops and changing the chemical composition of river runoff.

What do these changes mean for local and regional communities?

The early impacts on human infrastructure of permafrost melting around the world has been widely charted in recent years. Roads, railways, cities and oil and gas pipelines built on permafrost ground have faced persistent and catastrophic subsidence. This has already been seen in Siberia and Northern Canada: in Yakutsk, one of the coldest cities in Siberia, where temperatures have risen 2.5°C in the last decade, housing blocks are splitting and subsiding as the ground beneath them melts. The massive economic costs of this are already estimated in the billions annually (Fedorinova 2020; Shiklomanov, Streletskiy, and Kokorev 2016).

In the Third Pole Region, four kilometres above sea level, melting soil and water can redistribute radically. The most immediate effect of permafrost thaw is the destabilisation of mountain slopes and loss of integrity of cliffs, leading to landslides and avalanches (Wei et al. 2006; Ouimet et al. 2007; Petley 2018). Indeed, the eastern Tibetan Plateau region has witnessed a systematic increase in landslide activity over the last fifty years (Lin and Wang 2018). In an area as geologically active as the Tibetan Plateau, this will exacerbate the existing tendency for landslides to destroy road and rail links, and to block major rivers (Huggel 2009). Since



much of the region’s population growth in recent decades – from Pakistan in the west to Sichuan province in the east – has been located in steep valleys, these are at high risk from such hazards.

In 2017, the Tibet Policy Institute in Dharamsala reported on the growing number of such incidents across the Tibetan Plateau and the impact that this is having particularly on population centres in East Tibet:

“On 30 August 2017, a massive landslide buried nine people in Golok Machen region of north eastern Tibet. The horrifying disaster occurred in the early hours of the day (4:30am) while residents were still in bed. The day could have been, otherwise, a beautiful summer morning with nomadic melodies echoing across the valley as residents carry on their daily chores. But life on the Tibetan plateau is no longer the same. According to Science Daily (9 December 2016), climate change may now be affecting the once stable regions of the Tibetan Plateau. The impact of climate change is evident with unprecedented number of natural disasters across the plateau since 2016,



Photo: Golok Machen Rab

mostly floods and landslides due to torrential rainfall. As such in 2016, an unusual glacial avalanche in (Aru) Ruthok County of Ngari killed nine people and buried more than 110 yaks. Mud floods and landslide in Labrang, Sangchu, Tsolho and other regions of Amdo injured more than 30 people and caused huge damage. This clearly signals drastic shift in the climatic pattern on the Tibetan Plateau. The shift was apparent as 2017 saw simultaneous floods in many parts of Kham in Tibet.” (Zamlha Tempa Gyaltzen 2017)

Such collapses can affect populations and water resources both in the immediate area as well as upstream and downstream. On 17 October 2018, for example, an ice avalanche precipitated a major landslide at the Sedongpu Basin of the Yarlung Tsangpo River (the Tibetan Plateau section of the Brahmaputra River) dammed the main course of the river for 2.3 km with 40-60 million cubic metres of debris. As water from the Yarlung Tsangpo river quickly backed up behind the landslide dam, creating a lake of more than 500 million cubic metres that stretched 27 km upstream. This inundated the local Gyalha Village, requiring the evacuation of 6,000 residents and affecting livelihoods for 20,000 locals. The growing lake breached the top of the landslide on the afternoon of the 19 October, quickly slicing through the accumulated dam and causing a five-metre rise in water levels in downstream Arunachal Pradesh province in north-east India. The landslide damming of the Yarlung Tsangpo River has dramatically increased in regularity over the last twenty years, having occurred more than ten times since 2010, but only once on record in the fifty years before that (C. Chen et al. 2020).

Subsidence has also begun to impact state infrastructure projects in the TPR. The famous Lhasa-to-Beijing railway has been identified as one of the more immediate casualties of permafrost thawing on the Tibetan Plateau (Lustgarten 2009; Ma et al. 2011; D. Guo and Sun 2015). Opened in 2005, the railway was laid over 550 kms of permafrost in the section between Golmud and Lhasa. Previously, such a feat had been nearly impossible because railways transfer considerable heat into the ground, causing permafrost to melt and rail lines to buckle. At a cost of five billion dollars, the railway deployed a variety of new engineering technologies (from ammonia heat-transfer tubes and raised bridges to crushed rock embankments) to insulate the underlying permafrost from melting.

However, the engineering triumph of the railway could not counter the melting of the underlying permafrost due to ambient atmospheric warming as a consequence of climate change. A recent structural engineering review by the Chinese Academy of Sciences estimated the onset of permafrost collapse, which has already begun in several areas along its length. The Chinese Academy of Sciences team working on hazard onset timing for permafrost notes that, because of the depth of the underlying frozen ground in the region, melting – and consequently continued instability – would last between two and six decades, depending on the severity of overall climate warming, and the height and location of the particular stretch of track (D. Guo and Sun 2015).



THE DESERTIFICATION PARADOX

One of the major lessons to be learnt from the enormous shifts occurring in the TPR is the dangers of transferring environmental policies and programmes from one ecological context to another without the aid of a comprehensive and open assessment of its conditions. The challenges of desertification on the high altitude Tibetan Plateau are a clear example of this warning, with growing scientific debate over causes.

China has suffered from desertification issues throughout its recent history, particularly in its northwest lowland provinces, the cause of which was generally ascribed to intensive local land-use in dry, cold environments – a view widely shared across the international scientific community (Geist and Lambin 2004). The early 2000s saw a dramatic expansion of desertification across the Tibetan Plateau: wetlands around river sources dried up, and grasslands turned to desert (Qian et al. 2006; Cuo et al. 2020; Gabriele Lafitte 2020; M. Yang et al. 2004). This particularly effected river headlands located in the Sanjiangyuan (三江源, “Three River Source”) Nature Reserve – an area roughly the size of France – on the eastern Tibetan Plateau, which supplies the Yellow, Yangtse and Mekong. This combined with a general pattern of declining water run-off on the eastern Tibetan Plateau into rivers such as the economically vital Yangtse and Yellow (Lu 2017).

This presented both a scientific and policy paradox, since it was occurring at a time when extensive glacial melting in the area should, according to the ‘peak water model’ (see above), have led to an *increase* in water run-off, something that had certainly been seen in south- and west-facing rivers of the TPR, such as the Indus (Shen 2004; ICIMOD 2019). From the 1990s to the present, major shifts in the scientific consensus have occurred regarding the causes of this desertification and the appropriate policy to tackle it.

During the late 1990s and early 2000s, the established policy response to such environmental degradation was to focus on land use patterns, particularly in marginal pastoral communities, who had long been portrayed as “irrational exploiters of their resource base” (Goldstein, Beall, and Cincotta 1990). At this point, the impact of land-use and overgrazing on water run-off changes to, for example, the Yellow River, were placed as high as 90% (S. Wang et al. 2012; Qian et al. 2006; Fang 2013). In line with policies elsewhere in the PRC starting in the early 2000s, 2003 saw the introduction of the Ecological Migration Policy on the Tibetan Plateau, which relocated nearly 100,000 nomads away from the Sanjiangyuan region, which was subsequently transformed into a National Nature Reserve (see [Mass Relocations and Resettlement on the Tibetan Plateau](#)).

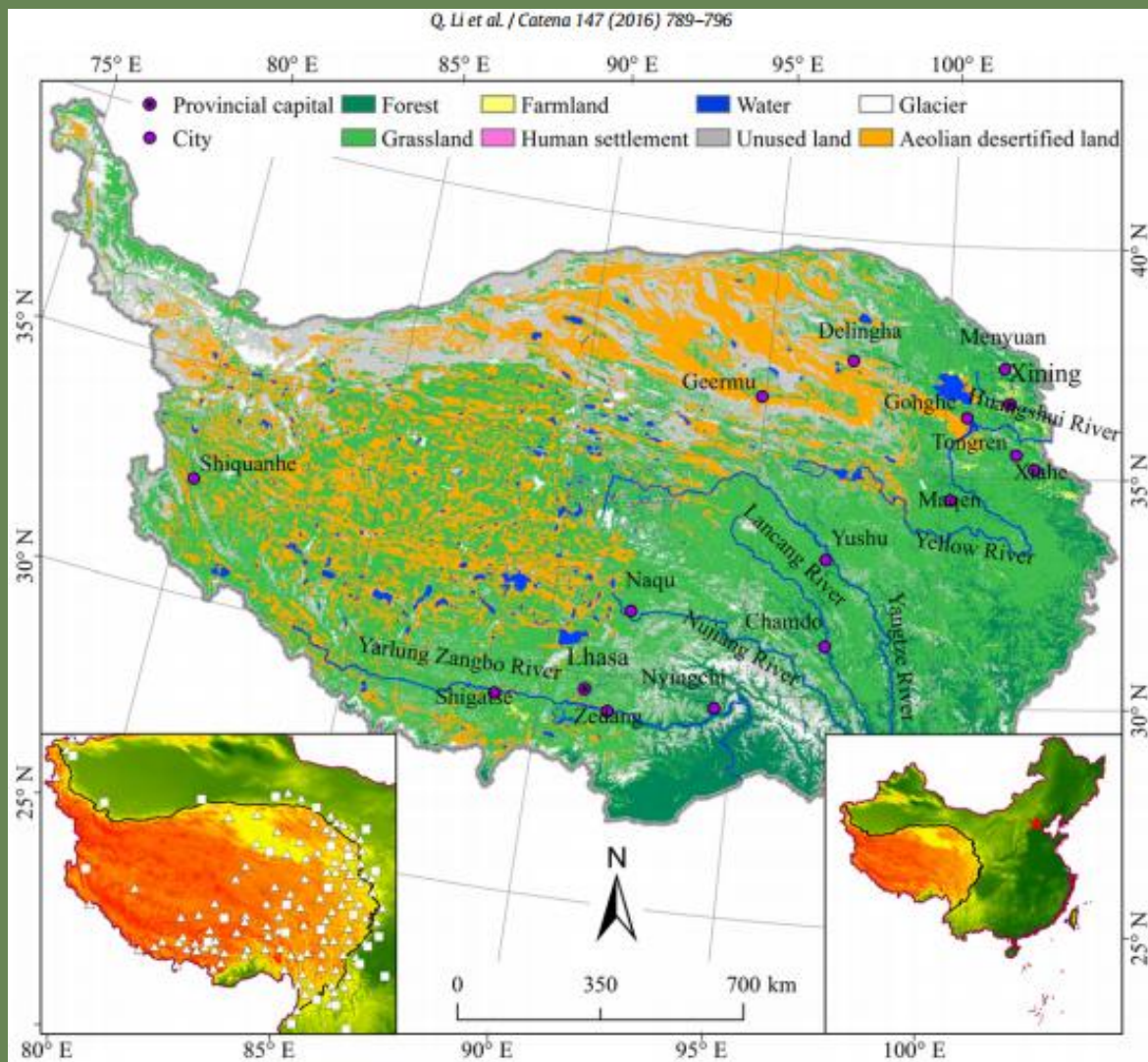


Fig. 12: Distribution of land cover types in 2000.
 Source: Li et al, 2016: 791

The problems with this policy became quickly evident. Not only were the mass relocations met with widespread international criticism (Norbu 2011; 2012; Dhongdue, Lafitte, and Bradshaw 2019; Gabriel Lafitte 2019), but there were clear empirical inconsistencies on the scientific front. First and foremost, grassland and headland desertification was occurring very widely, often starting in sites where nomads did not graze their livestock – indeed, in many cases, where there was nearly zero human land-use at all. Secondly, more detailed meteorological research demonstrated that the effect of overall precipitation changes had been vastly under-estimated (Cuo et al. 2020), and while these did not explain the entirety of the desertification effect, it became clear that in an area with such a low population density as the Tibetan Plateau, rural land-use patterns were actually having only a secondary or tertiary impact on land quality (Kang et al. 2010; Q. Li et al. 2016). Last, but by no means least, the trajectory of desertification underwent a reversal in the late 2010s, with a significant reduction of desertified land (Cuo et al. 2020; B. Xu et al. 2015). While certain sources put this down to the success of government policies (Z. Wang et al. 2016; Lafitte 2020), it remained the case that these reversals were also in areas unaffected by those policies.

This last change in particular has lent increasing credence to the hypothesis, now shared by a wide variety of scientists, that desertification on the Tibetan Plateau was in large part a *transitional* phenomenon that spoke to deeper changes. At the heart of this was the introduction of permafrost dynamics under climate change to the overall picture (L. Zhang et al. 2014; Y. Wang et al. 2018). As described above, the systematic warming of permafrost areas under climate change has the effect of turning continuous sheets of permafrost into discontinuous or fragmented ones. This allows surface water, both from precipitation and glacial melt, to sink deep into the underlying soil and bedrock, lowering local water tables and reducing the amount and quality of water reaching river headlands. Under such circumstances, the roots of grassland vegetation cannot reach available water, leading to the kind of desertification witnessed on the eastern Tibetan Plateau (Ding, Wang, and Lu 2018; Cheng and Wu 2007a). The loss of grassland and vegetation cover in turn reduces the insulation of underlying permafrost, further accelerating the process in a positive feedback loop (Wu, Yu, and Jin 2017).

The underlying deep soil, which may initially be very dry, may take time – possibly years or decades – to saturate, with the warming process makes the land a deep ‘sponge’ (Cuo et al. 2013; 2020; Y. Wang et al. 2018) to precipitation and glacial run-off. Nonetheless, that underlying dry soil does eventually reach saturation – the sponge does ‘fill up’. Recent evidence from NASA supports this picture. The GRACE (Gravity Recovery and Climate Experiment, a joint mission between NASA and the German Aerospace Center) and GRACE-Follow On satellite gravitational surveys, carried out since 2002 tracks the movement of underground freshwater concentrations across the planet. This mapping has shown that despite significant glacial retreat and a considerable loss of water concentrations in the *outlying* areas of the TPR (that is, the Himalayan and Tian Shan ranges), the *inner* areas of the Tibetan Plateau have seen progressive increases in overall freshwater mass at a rate of between 7-9.7 gigatonnes¹ per annum (Jacob et al. 2012; F. Zou, Tenzer, and Jin 2019; J. Guo et al. 2016; P. Yang and Chen 2015; G. Zhang et al. 2013).

Put simply, the desertification and river water problems that were – and effectively still are – treated as a local land-use problem by PRC policymakers, have proven to be symptoms of a deep underlying transformation of the entire Plateau region under wider warming patterns.

¹ A gigatonne being 1,000 million tonnes.



EFFECTS ON WIDER ASIAN REGION

The progressive loss of cryosphere (glaciers, permafrost and snow) across the Third Pole Region has important impacts across Asia and beyond. While the overall trend of these changes is broadly agreed on, the different computer models used in making these projections vary in specific details, and the timescales indicated below depend on unknowns such as the impact of natural feedback mechanisms and human uncertainties such as global greenhouse gas accumulations.

	2020 - 2035	2035 - 2065	2065 - 2099-
Tibetan Plateau	<ul style="list-style-type: none"> Increased temperature and precipitation. Increased infrastructure compromise: road, rail, pipelines and buildings. Significant increase in flooding, landslides and infrastructure damage. Desertification of immediate river headlands. 	<ul style="list-style-type: none"> Increased temperature and precipitation. Significant infrastructure compromise. Increased seasonality in glacially-fed rivers such as the Indus and Yarlung Tsangpo Rivers. Changes in river water chemistry from deep soil runoff. Reduction in desertification. 	<ul style="list-style-type: none"> Increased temperature and precipitation. Reduced infrastructural compromise. Widespread growth of forest and shrubland in non-headland areas. Changes in river water chemistry from deep soil runoff.
North India, Pakistan and Tarim Basin (Xinjiang)	<ul style="list-style-type: none"> Increased water flow from glaciers; flooding from glacial lake collapse. Increase in acute monsoon events. Significant increase in landslides, flooding and infrastructure damage. 	<ul style="list-style-type: none"> Increased seasonality in glacial rivers such as upper Brahmaputra, the Indus and Sutlej. Increased flooding in Brahmaputra, Indus and Sutlej. 	<ul style="list-style-type: none"> Significant desertification across north-west India. Effect on monsoon unclear.
China and South-East Asia	<ul style="list-style-type: none"> Increased flood-drought cycles. Reduced waterflow during dry season. Increased freshwater scarcity across northern China. Changes in river water chemistry from deep soil runoff. 	<ul style="list-style-type: none"> Increased seasonality of upper Yangtse River during dry season. Seasonality of Yellow River. Significantly increased desertification across north and west mainland China. 	<ul style="list-style-type: none"> Increased seasonality of upper Yangtse River during dry season. Seasonality of Yellow River. Significantly increased desertification across north and west mainland China.



Freshwater Availability – The Asian Picture

From a water availability perspective, the thawing of the TPR cryosphere presents a fundamental threat to human carrying capacity in many continental regions of Asia. By freezing freshwater at high altitude and releasing it throughout the year, the present low winter temperatures of the TPR, combined with gradual melting in the spring and summer, provide a constant supply of meltwater to Asia's rivers throughout the year. The progressive warming of the TPR, witnessed over the last few decades and projected across the next century, will compromise that regulating effect, delivering freshwater back to surrounding regions soon after it is deposited across the TPR by the summer rains. This will generate cycles of flooding during the summer and drought during the drier winter months. While coastal regions will continue to experience local rainfall to mitigate this effect, deep inland areas of the Asian continent will face increasingly seasonal extremes of freshwater supply.

The impact of these hydrological shifts will be most strongly felt in the upper sections of those rivers fed by the TPR. In the medium to long-term, this is particularly the case for rivers that are primarily glacially-fed: the Indus, Ganges, Sutlej and Yarlung Tsangpo/Brahmaputra. Urban and rural communities around the Himalayan Range (particularly in the west), that depend on prolonged meltwater seasons to feed crops and supply communities with drinking water, will face greater extremes of water run-off during a shorter and more vulnerable growing season. The Punjab – until recently one of the most fertile agricultural areas on earth and dominant supplier of rice, wheat and cotton both regionally and internationally – already suffers from considerable groundwater depletion and will face enormous challenging in maintaining its farming capacity.

In the People's Republic of China, changes in the TPR cryosphere may result in significant short to medium-term destabilisation of water supplies from all key rivers, and potentially complete loss of glacial meltwater-based rivers such as the central Tarim River and its tributaries – the basis of almost all agriculture, industry and population support in Xinjiang province. In mainland China, the Yangtse and more substantially Yellow River will lose much year-round supply in their upper reaches, significantly compromising human carrying capacity in provinces such as northern Sichuan, Gansu, Shaanxi, Ningxia and Inner Mongolia. Where meltwater presently crosses significant areas of permafrost before reaching river headlands (such as the Yangtse, Yellow, Mekong and Irrawaddy), deepening hydrological flows will introduce considerable, and presently unknown, mineral and chemical content into these rivers, compromising their already weakened capacity to provide adequate support for agriculture and human populations.

These changes in freshwater availability will directly impact Asia's significant regional population, and indirectly impact the world population as a whole. The area within and immediately surrounding the TPR constitutes a population of 240 million people. Those that depend on dry season meltwater for the majority of their dry season water supplies is nearly 1.4 billion people, including 23% of the population of China (Barnett, Adam, and Lettenmaier 2005). More than this, however, nearly half the world's population depends on foodstuffs grown within these affected areas, and industrial produce centred there.

CONCLUDING REMARKS

Several key conclusions can be drawn from this review of the scientific literature on the processes and effects of climate change across the Third Pole Region.

The first and most important of these is that the effects of global atmospheric warming on the Third Pole cryosphere are not recent events but have been well in train for at least half a century. The effects that are being witnessed now – variations in water output in TPR rivers, flooding/drought cycles, landslides and infrastructural compromise, amongst many – are the resultant effects of deep climate change processes that are now well-established. All physical, chemical and biological – and therefore environmental – processes have a variety of thresholds that are not open to negotiation. In the case of the Third Pole Cryosphere, the most important of these is the temperature threshold between ice and water – 0°C. The existence of such thresholds means that the effects of climate change are not always proportionate to the degree of warming but are instead organised as abrupt shifts in overall state. The majority of available evidence suggests that the loss of the majority of the TPR's cryosphere – with its vital slowing effect on Asia's water cycles – will occur within this century *at present global temperatures* – no further warming is required for this to occur.

In this sense, it is clear that, even if the 1.5-2.0°C limitations of the 2015 Paris Agreement are met, the Third Pole cryosphere is nonetheless undergoing a catastrophic and irreversible ecological shift (Scheffer 2001; Walker 2014). The implication of this is that, even with adherence to the Paris Agreement's targets at a global level, regional governments will be faced with massive adaptation costs and hard adaptation limits. Specifically, in those regions where freshwater supplies are significantly compromised by changes in the water cycle, the ability to maintain large urban centres, surplus agricultural production and viable industry will be dramatically downgraded and possibly eradicated.

Secondly, as we have again seen in the case of desertification, specific climate change processes – particularly in combination or as a result of feedback effects – may be *transient* (in the sense of lasting only years or decades, to be replaced by others later) as climate change processes progress through several stages. As a consequence, long-term planning for climate change requires both a deep awareness of the manner in which climate change mechanisms interact on the local to regional level, and a flexibility in policymaking approach.

Thirdly, the development of comprehensive *regional* climate-change awareness now seems vital to the effort to combat climate change more broadly. As we have seen in the case of the Third Pole Region, overall warming, pollution and urbanisation tend to impact specific ecosystems simultaneously and at multiple levels. This means that while climate change effects may be publicly *understood* in terms of individual mechanisms (such as the 'peak water' model for glaciers, or methane release for permafrost decay), they are *experienced and confronted* by human populations and policymakers as complex combinations of effect. The disjunct between these two (as in the case of headland desertification above) can lead to public confusion and ineffective or counterproductive mitigation policies.

The production of such comprehensive regional assays requires both a more systematic approach to data and a deeper level of co-operation between regional governments and scientific communities than is presently practiced. While certain climate change trends are scientifically well-established, the precise medium- to long-term consequences of these processes remain difficult to calculate with any precision in the absence of more systematic empirical data. The TPR is a good example of this, with the vast majority of empirical data for this research being drawn from extremely unevenly distributed scientific measuring stations (generally located around population centres). As a consequence, key data – particularly regarding local meteorological patterns, hydrology and permafrost depths – remains overly dependent on mathematical modelling rather than on-the-ground empirical data. This makes the local climate change

impacts more difficult to mitigate or prevent in a skilful and well-informed manner, and hampers long term, on-the-ground strategies.

Finally, the production of such regional assays requires a deep level of international co-operation. The TPR is crosscut by a large number of politically sensitive borders, and while the scientific establishments of many of involved countries have generally done an excellent job of sharing their scientific results on the world stage, it nonetheless remains clear that many studies (even large scale ones) are dominated by the particular geographical viewpoint that teams are working from. This has an uneven impact: while there is general agreement on the reality of the crisis and indeed its specific symptoms, there is often considerable, and highly politicised, disagreement over its causes. International scientific co-operation and raw data sharing remains politically problematic in this regard and should be encouraged for the mutual benefit of all involved countries.



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