The Himalayan cryosphere: past and present variability of the ‘third pole’

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The Tibetan Plateau and the Himalaya, which comprise a major portion of the region often referred to as the ‘third pole’, contain the largest surface area of the cryosphere outside the polar regions (Fig. 1). Unlike in other domains, glacier melting in this region is complex and highly variable. The glaciers in the western part of the region, dominated by the Karakoram and Western Himalaya, are either advancing or retreating relatively slowly, whereas the glaciers in the monsoon-dominated Eastern and Central Himalaya are retreating at a faster rate (Fig. 1).

The 2400 km long arcuate Himalaya–Hindu Kush mountain range bordering the Tibetan Plateau is composed of the world’s highest mountain chains and contains 18 peaks with altitudes >8000 m above mean sea-level (m a.s.l.). The mighty Himalaya, which lie under the sovereign control of Afghanistan, Bhutan, China, India, Nepal and Pakistan, are the source of ten major rivers that support a 1.3 billion people in one of the most densely populated regions of the world. The Himalaya–Hindu Kush range is composed of three major parallel zones, identified from north to south as the Great Himalaya, the Inner Himalaya (also known as the Middle or Lesser Himalaya) and the Sub-Himalaya or foothills.

Glaciers in the low latitudes have the potential to play an important part in the global radiation budget. As part of a feedback mechanism, the high albedo from surfaces covered by snow and ice in the Himalaya region has a cooling effect over the mountains and a warming effect over the Persian Gulf and Arabian Peninsula (Bush 2000). The Himalaya, which receive precipitation from both mid-latitude westerlies and the South Asian summer monsoon, and the Karakoram region, which receives little rainfall, are warming much faster on average than the rest of the world. A decreasing trend in snowfall is accompanying this temperature change over higher altitudes and both these trends have serious impacts on the dynamics and melting rate of glaciers. Most glaciers have fragmented as a consequence of ice recession over the last five decades. The rate of retreat differs between individual glaciers and depends on the climate regime and geomorphological factors, such as ice thickness, length and slope, as well as altitude, debris cover and the nature of the underlying substrate.

The presence of a vast spread of snow and ice at relatively low latitudes (26–30° N) is made possible by the extreme elevations of the Tibetan and Himalayan regions. There are conflicting opinions about the timing of tectonic uplift of this vast plateau and its bordering ranges, with estimates varying from c. 35 Ma (Rowley & Currie 2006; Copley et al. 2010) to 9–7 Ma (Zhisheng et al. 2001). The disparities in the estimates are due to differences in the techniques used to determine the timing of uplift. Rowley & Currie (2006) used oxygen and hydrogen isotopes in low-latitude hydrological systems to estimate palaeoelevations, whereas Zhisheng et al. (2001) related the evolution of the Asian monsoon to the phased uplift of the Himalaya–Tibetan Plateau using marine sedimentary and terrestrial aeolian records. In their climate model experiment, Zhisheng et al. (2001) estimated elevation changes ranging from 1700–2700 m in the early stages of uplift to 5700 m during Marine Isotope Stage 3 (MIS3) in the late Miocene.

The uplift of the Himalaya and the evolution of the South Asian Monsoon (SAM) are intrinsically linked. Recent modelling studies suggest that the role of the Himalaya as an orographic barrier is more important for SAM circulation than the elevation and extent of the Tibetan Plateau (Boos & Kuang 2010). The proto-SAM was established during the early Miocene (Betzler et al. 2016). A major intensification of the SAM took place c. 13–15 myr
ago (Gupta et al. 2015; Betzler et al. 2016), by which time the Himalaya had attained a height of >5000 m a.s.l. (Gébelin et al. 2013, 2017). This period of monsoon intensification also coincided with a period of warmth known as the Middle Miocene Climate Optimum, when global temperatures were 3°C higher than at present. The SAM subsequently weakened, possibly as a result of Late Miocene global cooling (Zachos et al. 2001). The Himalaya had attained their current elevation by 10–5 Myr (Wang et al. 2014). Several studies indicate a strengthening of the monsoon at c. 10–7 Ma (Kroon et al. 1991; Huang et al. 2007; Gupta et al. 2015). More recently, SAM intensification took place at c. 3.2–2.8 Ma (Tripathi et al. 2017), which coincided with the Mid-Pliocene Warm Period. This was a period of global warmth, with a CO₂ level (400 ppmv) similar to the present day, but a sea-level that was 25–30 m higher than at present. Thereafter the intensity of the SAM decreased over the next c. 1.8 myr, concurrent with glaciation in the northern hemisphere. A study by Tripathi et al. (2017), using samples collected during the International Ocean Discovery Program Expedition 355 in the Arabian Sea, suggests that the modern strength of the SAM was attained at c. 1.0 Ma.

It has been hypothesized that the rapid uplift of the Himalaya from 0.9 to 0.8 Ma was responsible for asynchronous Pleistocene glaciation in these mountains. At least four successive glacial advances have been identified in parts of Kashmir, Ladakh and Tibet (Valdiya 2010). The oldest of the glaciers extended as low as 1675 m a.s.l., whereas the youngest reached an elevation of 2400 m a.s.l. (Wadia 1975). Over the last two decades, ice core records have been systematically recovered from low-latitude, high-elevation ice fields across the Tibetan Plateau and each core has provided new information about the regional climate and environmental change. When viewed collectively, these ice core histories provide compelling evidence that the growth (glaciation) and decay (deglaciation) of large ice fields at lower latitudes are often asynchronous with the high-latitude glaciation and deglaciation that occur on Milankovitch timescales (Thompson et al. 2005, 2006).

Direct evidence of glacial activity by the mapping and dating of glacial landforms is extremely difficult due to ongoing surface-modifying processes. The nature and dynamics of late Quaternary glaciation in the monsoon-dominated Indian Himalaya are poorly understood because of a paucity of

Fig. 1. Map showing the distribution of the Himalayan cryosphere. Relevant publications on the various glaciated areas are depicted by colours in the bar graphs. Graphs A, C, E, and G show the reported mass balance data of the Karakoram, Western, Central and Eastern Himalaya, respectively. Graphs B, D, F and H show the reported ice volumes in the Karakoram, Western, Central and Eastern Himalaya, respectively.
INTRODUCTION

The past

Thompson et al. (2017) present palaeoclimatic records from high-elevation tropical glaciers. Comparison among three ice core records from tropical mountains on opposite sides of the Pacific Ocean show how climatic events are linked through large-scale processes such as the El Niño Southern Oscillation. Recent warming, particularly at high elevations, is posing a threat to tropical glaciers, many of which have retreated at unprecedented rates since the mid-twentieth century. The decreasing amount of ice in these alpine regions endangers water resources for populations in South Asia and South America.
Mujtaba et al. (2017) describe lake deposits formed by damming the Indus River and conclude that more than one period of lake formation occurred, with the first phase dated c. 125 ± 11 to 87 ± 8 ka within MIS5. The second damming event took place at c. 79 ka and the lake was breached after c. 46 ± 3 ka. These researchers relate the formation of the lake to cold and arid climate conditions and analyse regional v. global climate forcing during the late Quaternary period.

Swain et al. (2017) used ground-penetrating radar to estimate the thickness necessary for assessing the volume of water resources in the related basins. They computed a thickness range of 35–95 m for the Hamtah glacier and 40–140 m for the Parang glacier. The shape analyses for different parts of the glacier suggest that mathematical equations can be used to describe their sequential development.

Dutta et al. (2017) report alluvial fan progradation around the Sangla till at c. 45 ka (middle of MIS3) due to glacier retreat in the Baspa River valley. Towards the end of MIS3 (>23 ka), intensified precipitation blocked the course of the river and imposed lacustrine conditions, which recorded sedimentation until the beginning of the Holocene (c. 11.4 ka). In the upper reaches of the valley, coeval aggradation continued from c. 28 to c. 19 ka under cold and relatively arid climate conditions. This study emphasizes that the Late Quaternary geomorphic evolution of the valley is synchronous with glacial fluctuations, indicating the rapid response of glacio-fluvial systems to the dynamics of the Indian summer monsoon.

The present

Khan et al. (2017) estimate the average annual precipitation of the three Himalayan river basins, describe the east to west and north to south precipitation controls, and discuss solid v. liquid precipitation using 10-year remote sensing data. They explain the causes of variability in the existing data and comment on the relationship between the summer monsoon and precipitation from westerly winds.

Mitkari et al. (2017) accurately map snow cover from Moderate Resolution Imaging Spectroradiometer (MODIS) data at 500 m resolution. The results have been validated. The selected regression model for the Snow Cover Fraction Index, SCF = 0.25 + 0.35 × NDVI, where NDVI is the Normalized Difference Snow Index, shows that, at the pixel level, this relationship provides useful results when measured in independent tests against the actual SCF obtained from the ASTER scene.

Agrawal et al. (2017) model the mass balance over the Gangotri glacier for the time period 1985–2014 using ice flow velocity and energy balance approaches. Estimates of mass balance vary between −0.92 ± 0.36 m water equivalent per year (ice flow velocity method) and −0.98 ± 0.23 m water equivalent per year (energy balance modelling approach). The study utilizes multiple remote sensing data to estimate precipitation over the Gangotri glacier and concludes that an accurate precipitation estimate requires an improved glacier-wide determination of weather parameters.

Tiwari et al. (2017) examine the annual cycle and interannual variability of runoff in the Sutlej basin from 1982 to 2005 to assess the impact of temperature on snowmelt runoff. The multivariate regression model to predict the daily discharge of the Sutlej River with the input of precipitation and surface temperature shows that for every warm and cold phase of temperature, the impact persists for around one month.

Chiphang et al. (2017) detail the temporal variation of snow albedo at the upper elevation zone of the glaciated Mago basin of the easternmost Himalayan domain in the state of Arunachal Pradesh using MODIS data with a 500 m spatial resolution and other remote sensing products for a ten-year period (2003–13). The average monthly slopes show a decreasing trend in the percentage area of dry snow and wet snow and an increasing trend for firm and ice.

Soheb et al. (2017), working at a higher time resolution, describe a time series of meteorological parameters and surface energy balance of seasonal snow cover using an automatic weather station at 4863 m elevation on the Chhota Shigri glacier in the Himachal Himalaya. For >80% of the winter, the snow surface remains in a cooling phase and the net all-wave radiation is mostly negative. Mass loss is primarily through the process of sublimation, as the latent heat flux is always negative.

Sustainability

Owen (2017) advocates an understanding of the nature and dynamics of Earth surface processes and landscape evolution for geohazard mitigation and sustainable development. This is because the Himalaya are one of the most dynamically active tectonic domains, as well as the most glaciated terrain.

Rowan et al. (2017) conclude that glaciers are losing mass at a mean rate of between 0.18 and 0.5 m water equivalent per year. Although glaciers in the Himalaya are generally shrinking, those in the Karakoram have experienced a slight gain in mass. In the westerlies-influenced Indus catchment, glacial meltwater makes up a large proportion of the hydrological budget and a loss of glacier mass will ultimately lead to decreasing water supplies. In the monsoon-fed Ganga–Brahmaputra catchment,
the contribution is comparatively small and the decrease in the annual water supply will be dramatically less.

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