

Rapid warming in the Himalaya exacerbates geohazard cascades beyond adaptation limits

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1 Introduction

A catastrophic rock-ice avalanche that transitioned into a debris flood in the Himalaya along the Nepal-China border Lhunde River on 26 August 2026 has caused widespread destruction in Nepal and the neighbouring regions. It left thousands of people dead, injured or unaccounted for and displacing communities, tourists and rescuers.

As of the 12th September, 1,386 people have been confirmed dead. 5,130 people are reported missing while 13,728 people have been rescued. 339 injured people have been treated in hospitals, and a further 8,615 have received treatment from security-force medical teams ([NDRRMA, 2026a](#)). There are 3,434 people, including 102 orphaned children and 439 separated children, taking shelter in 36 holding centers. A total of 156 persons with disabilities are affected, of whom 7 have died, 16 are missing and 79 displaced ([NDRRMA, 2026b](#); [NDRRMA, 2026c](#); [NDRRMA, 2026e](#)). About 84,000 people require emergency WASH support, and damage to schools is estimated to affect 7,000 children ([UN Resident Coordinator's Office in Nepal, 2026a](#)). At least 43,000 women and girls, including pregnant and breastfeeding mothers, require immediate assistance, while 7,921 adolescent girls and 1,854 persons with disabilities require emergency nutritional support ([UN Women, 2026](#)). Approximately 84,270 people in 17 local levels in the six districts of Rasuwa, Nuwakot, Dhading, Gorkha, Chitwan and Tanahu are affected, and 15 local levels have been declared as disaster crisis-hit areas for three months ([UNDP, 2026a](#); [MOHA, 2026](#)).

Initial reports suggested that the event may have been triggered by a 5.2 magnitude earthquake, however, later evidence indicates that the seismic activity was associated with the rapid collapse of a large volume of glacier ice and rock ([US Geological Society Earthquake Hazards Program, August 26, 2026](#)). The collapsing material fell approximately 1400 m, from an elevation of 5150 m above sea level (asl.) to the valley floor at ~3750 m, releasing enormous amounts of energy and generating seismic waves that were initially detected as an earthquake-like signal. The rock-ice avalanche initiated a sequence of cascading processes. As ice, rock and debris travelled rapidly down the mountain slopes, the heat generated from the mechanical energy and friction may potentially have melted glacier ice, thereby producing large amounts of glacier meltwater ([Le Page, 26 August 2026 \[NewScientist\]](#)). When the rock-ice avalanche reached the valley floor it impacted buried ice, the melting of which contributed water to the debris flood. The subsequent flood was likely caused by a combination of the meltwater from the collapsed section of the glacier and the buried ice, and ice and water in the debris entrained into the flow during runout, in addition to the pressure wave displacing

river water ahead of the debris flood. This combination of ice, water rock and sediment travelled over 35 km downstream resulting in the highly destructive debris flood, sweeping away roads, bridges and other infrastructure, and isolating communities along the valley. The water travelled much further at Glachi, 88 km downstream, the water level of the river Trishuli rose by 8.5m ([Center for Land Surface Hazards, 2026](#)). As per the [CHWRR](#) (2026), the flood wave velocity averaged 188 km/h at the Rasuwagadhi border.

1.1 Impacts

The extent of this disaster has been particularly severe across the river corridor of northern and central Nepal. The rock-ice avalanche occurred in the Langtang region of Rasuwa District, close to the Nepal–China border, with the resulting debris flood entering the Lhende Khola river (Figure 1.1.1). The floodwaters then propagated downstream into the Bhoti Koshi River system before reaching the Trishuli River, one of the major river systems of central Nepal. River levels on the Trishuli reportedly rose by as much as 9 metres within approximately 30 minutes, illustrating the exceptional rate at which the flood wave propagated downstream ([Al Jazeera Staff, AFP and Reuters, 27 August 2026a](#)). And at Devghat, from where onwards the river is named Narayani, the water level reached a maximum of 6.57 meters, before it began receding. ([CHWRR, 2026](#))

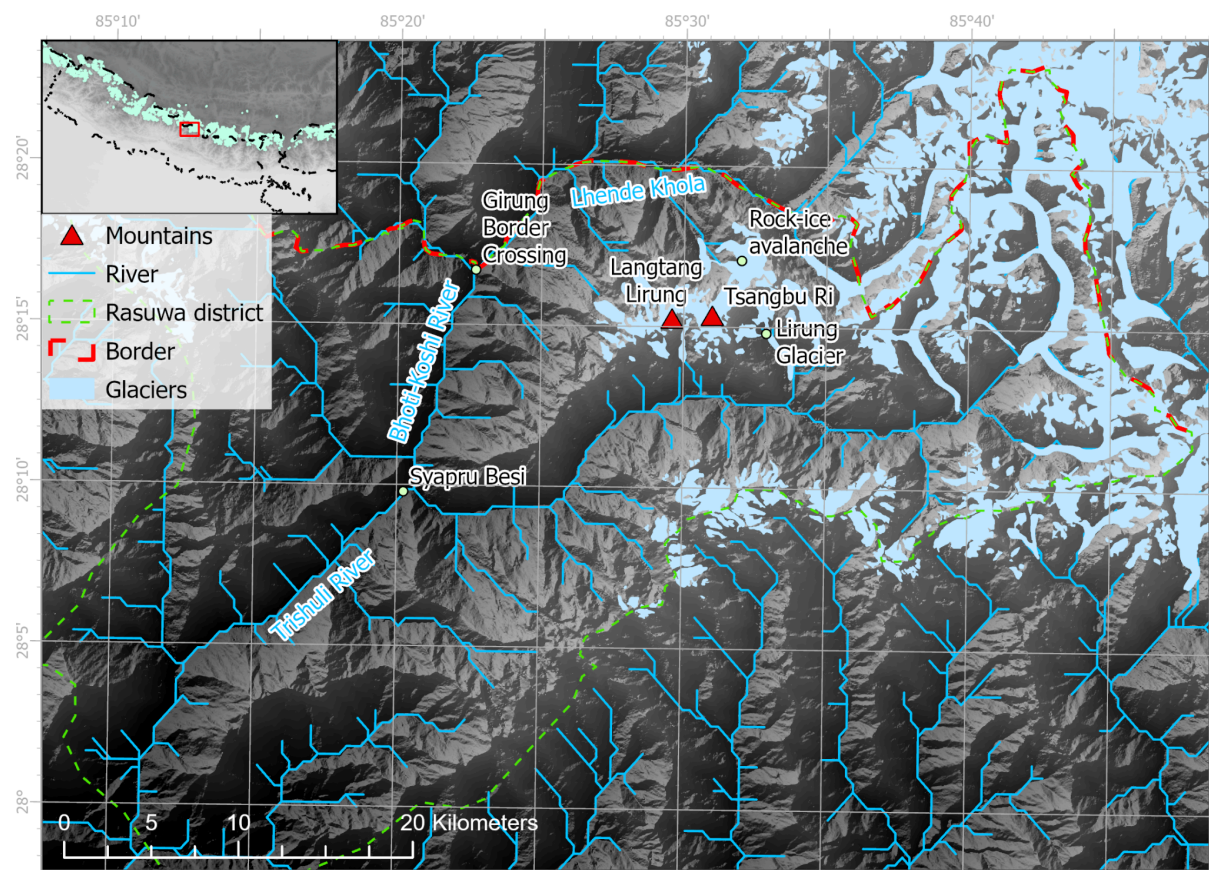


Figure 1.1.1: Map of the area, showing the site of the rock-ice avalanche on the northern side of Langtang-Lirung Mountain. Glacier area from the Randolph Glacier Inventory (RGI 7.0).

Some of the worst-affected settlements include Timure and Syabru Besi in Rasuwa District, located close to the international border and important routes connecting Nepal with China. Further downstream, the flood affected settlements in Nuwakot and Dhading districts, including Betrawati Bazaar and Bidur, where homes, roads, bridges and riverside infrastructure were inundated or swept away ([NH Digital, 27 August 2026 \[National Herald\]](#)). At Devighat, near Bidur, floodwaters reached the confluence of the Trishuli and Tadi rivers, where satellite imagery has documented extensive sediment deposition and changes to the river corridor ([Nayak, 26 August 2026, \[India TV\]](#); [Muzaffar, 27 August 2026 \[The Independent\]](#)). The impacts extend across the border into Gyirong County in China, where the debris flood reached the Gyirong Port area, an important crossing and transport route between China and Nepal ([AJLabs, 27 August 2026 \[Al Jazeera\]](#)). At this location, the debris flood was so powerful that floodwater reportedly travelled ~2 km upstream along the Bhote Koshi/Kerung river towards China ([European Space Agency, 31 August 2026; Landslide Hazards Program, 27 August 2026 \[USGS\]](#); [McDermott, 28 August 2026 \[APNews\]](#)).

Nepal's Government's Rapid Damage and Needs Assessment (RDNA) was finalized on 10 September, these numbers are rapid estimates that will be updated once the more comprehensive Post Disaster Needs Assessment (PDNA) is completed ([NDRRMA, 2026d](#)). The total economic impact of the flood is estimated at USD 2.7 billion while the cost of recovery and reconstruction at USD 4.8 billion, equivalent to 6.7% and 11.8% of national GDP respectively. Of the USD 2.7 billion, physical damage is estimated at USD 1.8 billion while the economic losses amount to USD 883 million. The losses cover one year only without projecting closure periods, reduced operating capacity etc. Additionally, the RDNA records impacts up to 3rd September only and notes that many economic and service losses remain unquantified. Recovery needs exceed damages and losses because they include reconstruction, disaster risk reduction and resilience elements. Almost all of recovery spending is long-term with only 1.2% being spent in the first six months ([NDRRMA, 2026d](#)).

The RDNA documents impacts on a number of sectors including social, productive, infrastructure, and cross-cutting sectors. Housing and social services were affected extensively with 7,570 houses, 48 public buildings (35 destroyed), 18 schools (11 destroyed), 7 health facilities (4 destroyed) and 47 cultural heritage assets (43 destroyed) were damaged. The total number of households and individuals affected within the corridor were 8,317 and 32,963 respectively. The total damage to the social sector was USD 448 million, with USD 684 million needed for recovery ([NDRRMA, 2026d](#)). The impact on livelihoods was estimated to be substantial with the corridor economy losing an estimated USD 965 million. Of this a fifth is destroyed assets and the remaining USD 765 million represents the lost annual revenue across 4,800 businesses, including shops, hotels and restaurants, and finance and insurance services ([NDRRMA, 2026d](#)). Energy infrastructure faced heavy physical destruction, with damage to 13 hydropower projects (7 operating and 6 under construction) totaling 759 MW of generation capacity, 5 solar plants totaling 24 MW capacity, and grid infrastructure. Around 12% of Nepal's operational hydroelectric generation was disrupted with the number doubling when under-construction plants are also accounted for ([NDRRMA, 2026d](#); [UNDP, 2026b](#)). The flood also impacted the corridor's connectivity severely. Around 69 km of road, 37 motorable bridges (33 washed away) and 68 trail bridges were damaged. This damage to transport and communication networks isolated several communities and made rescue and relief difficult ([NDRRMA, 2026d](#)). Water supply, telecommunications and irrigation systems serving the corridor were also disrupted, 4,990 m of riverbank protection work were destroyed, alongside damage to 1,806 hectares of standing

paddy and vegetable crops ([NDRRMA, 2026d](#)). Beyond cropland, the total land area damaged by the flood is estimated at around 11,381 hectares, with 292,000 livestock affected ([UNDP, 2026b](#)). The RDNA reports that 30.5 million cubic meters of sediment and debris was deposited along the corridor (including on settlements, agricultural land, and hydropower infrastructure) of which 1.85 million cubic meters needs to be cleared ([NDRRMA, 2026d](#); [NDRRMA, 2026c](#)).

Damage to 47 cultural heritage sites (43 destroyed), including religious sites, archeological sites, and monuments has been recorded by the RDNA. There are also reports of damage to temples, sacred cremation grounds, the Betrawati treaty stone, as well as interrupted access to pilgrimage destinations. Beyond the tangible impacts on physical assets, these also affect the continuity of cultural and religious practices. Damage and losses to these are valued at USD 1.1 million, with USD 2.4 million estimated for their restoration ([NDRRMA, 2026d](#)). The RDNA also sets aside USD 0.99 million for inclusive cross-cutting recovery measures for women, children, older persons and persons with disabilities ([NDRRMA, 2026d](#)). As a rapid assessment based on secondary records, the RDNA did not capture environmental, cultural, psychosocial and identity-related losses. The government situation reports do, however, indicate that 10,532 people have received psychosocial counselling to date ([NDRRMA, 2026b](#)). There are unidentified bodies in 21 hospitals, while families search for loved ones between hospital lists, displacement centers, and riverbanks, unable to find closure and perform funeral rites ([UN Resident Coordinator's Office, 2026b](#)). There are reports of destruction of local monasteries, and monks with highly localised knowledge are gone. One survivor described becoming "homeless with our culture and tradition" ([Associated Press, 2026](#)). Experts warn of dangers to old markets, religious sites, and historical and cultural civilization ([MyRepublica, 2026](#)). Psychosocial distress is widespread ([National Public Radio, 2026](#)). Relocation may sever communities from land and place that defines their culture, occupation and identity ([The Kathmandu Post, 2026](#)).

As of 12th September, the government-led response includes mobilization of 21,022 security personnel and 1,802 helicopter flights. Cash relief worth USD 1.06 million has been released for three districts and 15 local governments to support affected communities. 75 tonnes of food has been distributed to 2,084 households, Electricity has been restored in Dhading and Nuwakot districts and to about 80% of households in Rasuwa. Almost all cell towers have been brought back on line. 151 health personnel have been deployed to treat 7,323 people ([NDRRMA, 2026b](#); [NDRRMA, 2026f](#); [NDRRMA, 2026a](#)). This immediate relief support is complemented by grants and in-kind relief from international humanitarian organizations, bilateral partners, development banks, non-government agencies, civil society, private sector, and philanthropies ([MOFA, 2026](#); [UN Resident Coordinator's Office in Nepal, 2026b](#); [IFRC, 2026](#); [ADB, 2026](#)).

1.2 Event mechanisms

While initially thought to be a glacier collapse, analysis of satellite imagery indicates that the event actually involved a large rock avalanche from the north face of Langtang Lirung at an elevation of approximately 5,150 m. This rock avalanche occurred beneath a glacier, causing a section of the glacier to collapse simultaneously, becoming a combined rock and ice avalanche. Preliminary measurements suggest the rock and ice avalanche involved a section of the mountain approximately 2.2 km² with a depth approximately 50 m giving a total initial volume of rock and ice totalling

approximately 110 million cubic metres. Rock avalanches of this size are rare, with annual frequency estimates of approximately one event this size every 1,000-10,000 years.

The combined rock and ice avalanche fell approximately 1,400 m (from 5,150 m to the valley at 3,750 m asl.), with the impact in the valley bottom recorded on nearby seismometers releasing the same energy as a magnitude 5.2 earthquake ([Landslide Hazards Program, 27 August 2026 \[USGS\]](#)). From here, the avalanche eroded and entrained further material and buried glacier ice from the glacial deposits in the valley bottom, increasing both the total debris and water volume by up to 30 million cubic metres. By the time the debris reached the Lhende Khola, it had transitioned from a rock and ice avalanche into a highly mobile debris flood. Once the debris flood entered the narrow gorge of the Lhende Khola, it was funnelled downstream at high speed. The avalanche impact with the valley bottom was recorded at 08:37 Nepal Time (NPT) (10:52 China Standard Time, CST). The images of the debris flood reaching the Gyirong port border crossing approximately 20 km away are time stamped at 08:44 NPT (10:59 CST) giving a travel time of 7 to 8 mins at an average velocity of approximately 170 km/h (~47 m/s). The debris flood was travelling with such high speed and force that upon reaching the river confluence at the border port, it backflowed up to 2 km upstream into China. The main mass continued downstream along the Bhote Koshi/Trishuli river, being funnelled through the narrow gorge.

Initially, in the upper reaches, the debris flood may have been composed mostly of rock and debris, with water comprising only a small percentage of the material. South of Syapru Besi the flood began depositing most of the larger heavy rock debris and transitioned into a more water-laden flash flood that continued many kilometers downstream. As the valley widened, the flood began to slow and deposit finer grain material, clear in the imagery in the thick sediment and mud deposited in towns downstream.

Rock-slope failure occurs when the driving shear stress exceeds the shear resistance along a potential failure surface. [Krautblatter et al. \(2013\)](#) provide a useful conceptual framework for this balance in glacier- and permafrost-affected rock walls. Driving stresses are dominated by gravity but may be enhanced by hydrostatic or cryostatic pressure, while resistance is provided by friction along discontinuities, intact rock bridges, rock-ice contacts, and ice within fractures (Fig. 1.2.1). Importantly, several of these resisting components are temperature dependent. Warming and thaw can reduce the strength of ice-filled discontinuities and rock-ice contacts, while water entering fractures can increase hydrostatic pressure and thereby further reduce stability.

A key question for attribution is therefore not only whether meteorological conditions were unusual, but also how long-term warming and changes in precipitation could have modified the mechanical stability of the source slope before failure.

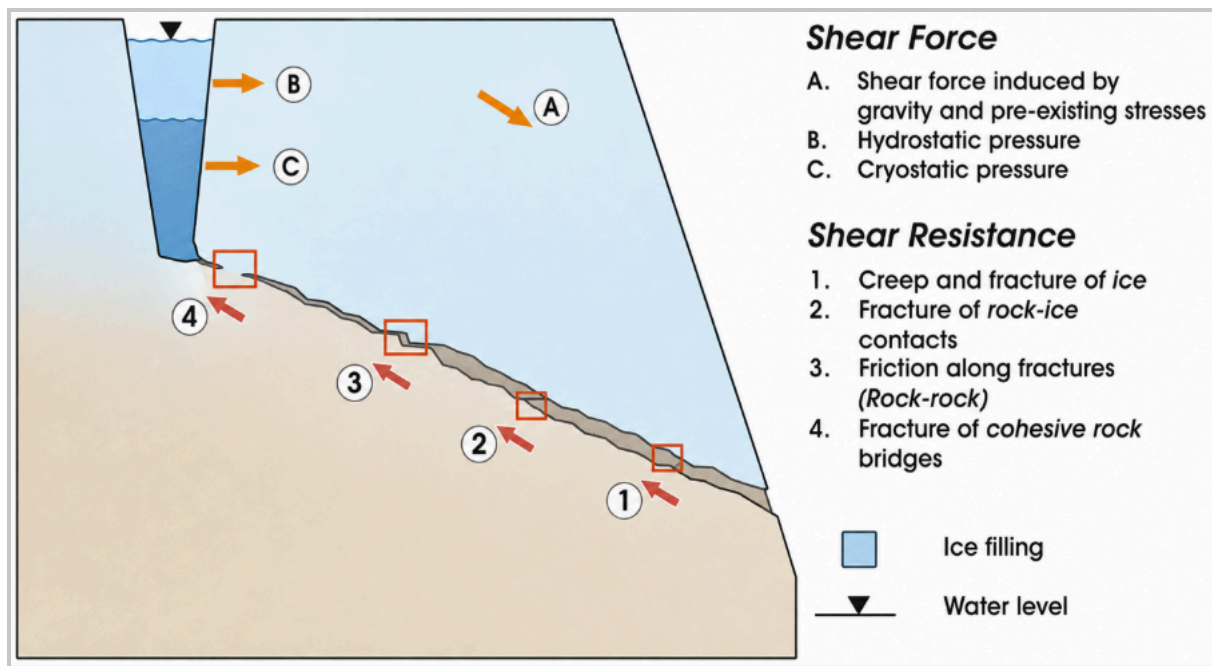


Figure 1.2.1: Conceptual mechanical framework. Conceptual representation of the forces controlling failure of glacier- and permafrost-affected bedrock, after [Krautblatter et al \(2013\)](#).

The geometry of the Rasuwa source area suggests that the failure did not occur through an otherwise homogeneous rock mass. Comparison of the pre-event topography with the mapped upper boundary of the failed mass shows that a substantial part of the failure line follows a pre-existing depression in the bedrock that may express a structural weakness. This feature is visible in the pre-event terrain independently of the mapped failure outline (Fig. 1.2.2). The geometry therefore indicates an important geological control on the location and shape of the failure.

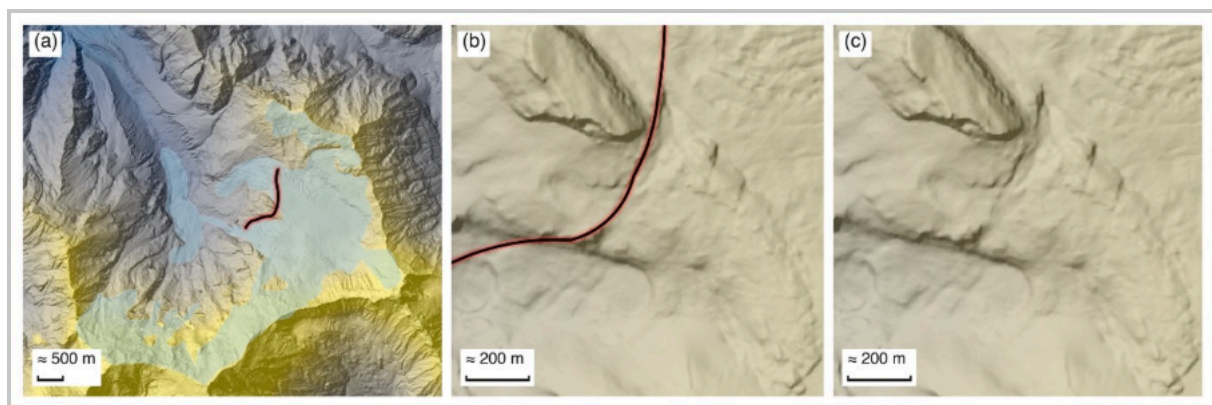


Figure 1.2.2: Structural predisposition of the Rasuwa rock wall. (a) Overview of the source area showing the mapped failure boundary. Elevation is shown from light grey to yellow. (b) Pre-event topography with the failure line superimposed. (c) The same terrain without the failure line.

This distinction is important for climate attribution. Atmospheric warming does not create the fundamental geological structure of the mountain. Instead, the existing discontinuity provides a mechanically favourable surface or zone along which progressive deformation and eventual failure

can occur. This is consistent with the general understanding of steep rock slopes: large failures commonly exploit pre-existing joints, faults, fracture zones or other discontinuities, whereas environmental forcing modifies their mechanical state. [Gruber and Haeberli \(2007\)](#) similarly emphasize that geological and geometric conditions provide the primary structural control, while permafrost and water can act as transient factors affecting stability.

2 Event drivers

Several interacting processes could have progressively reduced the stability of this preconditioned rock slope. They operate over different timescales and should therefore be regarded as potential contributing mechanisms rather than independent causes (Figure 2.1).



Figure 2.1: Climate-sensitive and other key preconditioning processes potentially contributing to failure. Conceptual representation of the main mechanisms through which climate variability and climate change may have influenced the stability of the Rasuwa rock wall in addition to earthquake preconditioning.

2.1 Earthquake preconditioning

The Langtang region was severely affected by the 25 April 2015 magnitude 7.8 Gorkha earthquake ([Thapa et al., 2026](#)). The earthquake triggered more than 25,000 landslides across central Nepal ([Thapa et al., 2026](#)), and in particular, a catastrophic rock and ice avalanche from the southern face of Langtang Lirung that completely engulfed the village of Langtang, killing up to 400 people ([Kargel et](#)

[al., 2016](#)). While this event was directly triggered by strong shaking during the earthquake, it was exacerbated by climate variability and snowfall anomalies in the region at the time ([Zhuang et al. 2024](#)). Since the earthquake, long-term bi-annual monitoring has shown that both the northern and southern slopes of Langtang Lirung have experienced increased rates of landsliding. These rates have continued to increase since the earthquake, such that by the end of 2018, landslide rates in the area were higher than they had been the day after the earthquake ([Kincey et al. 2020](#)). Across the whole earthquake affected area, whilst slopes between ~1,500 and ~4,500 m have shown generally decreasing rates of landsliding since the earthquake, slopes above ~4,500 m have shown increased rates, or landslide rates have decreased slower.

Strong ground shaking during earthquakes have been shown to trigger chronic long-term increases in landslide rates. The duration of this legacy varies with location, but in high mountain regions could be up to a quarter of a century ([Wang et al. 2024](#)). The mechanism for this longevity is multi-faceted and complex, but for coherent rock masses this may result from changes to rock strength during shaking ([Brain et al. 2021](#)). Ground shaking during earthquakes is known to be amplified by topography, with stronger shaking recorded near ridgelines compared to valleys. A greater intensity of shaking over a prolonged period may result in rock strength weakening by enlarging cracks and failure surfaces within a rock mass, leading to further landslides sometime after the shaking has stopped.

Whilst it is not possible at this stage to conclusively determine the role of the 2015 earthquake in preconditioning this particular slope for failure, numerous conditional factors suggest this may have played a role. The area experienced some of the highest recorded ground motions during the 2015 earthquake, and the failure location near the ridgeline at an altitude of 5,150 m above sea level (a.s.l.) suggests this shaking may have been even stronger due to topographic amplification. Both the northern and southern facing slopes of Langtang Lirung saw widespread landsliding during the shaking and have seen increasing rates of landsliding since the earthquake. Combined with the role of climate change (see below), this suggests that the underlying rock mass was preconditioned for failure, possibly due to increased damage within the rock mass caused by shaking during the earthquake.

2.2 Permafrost degradation

If the source rock wall contained permafrost, sustained atmospheric warming could have increased temperatures within the bedrock and deepened any seasonally thawed layer. Rock at below-freezing temperatures can be substantially stronger than the same rock at higher temperatures, while the strength of ice-filled discontinuities within the rock generally decreases as temperatures approach the melting point. [Krautblatter et al. \(2013\)](#) showed that warming and thaw affect rock bridges, rock–ice contacts, fracture friction and ice creep simultaneously. [Gruber and Haeberli \(2007\)](#) likewise describe permafrost degradation as a potentially important mechanism for destabilising steep high-mountain bedrock. The relevant attribution question is therefore whether temperatures at the failure elevation have increased sufficiently to alter the probability, depth or duration of rock-wall temperatures close to 0°C.

Fractures within permafrost rock can contain considerable quantities of ice. This ice can contribute to slope stability through bonding, mechanical interlocking and adhesion between fracture surfaces. As fracture ice warms toward 0°C, its mechanical strength decreases; once it melts, this contribution to

cohesion can be partly or completely lost. Water produced by thaw may additionally migrate deeper into the fracture network. This mechanism is especially relevant where a failure follows a pre-existing discontinuity, because the thermal and hydrological evolution of that discontinuity can determine whether an already weak geological structure becomes mechanically critical. Repeated freeze-thaw cycles can further destabilize the rock.

Measurements of permafrost are not available from this valley or from Langtang catchment. However, [Streletskiy et al. 2026](#) argue that monitoring sites in High Mountain Asia show widespread permafrost degradation. Active layer thickness has increased at more than 90% of sites in high- elevation Asia, with the largest changes found in mountain permafrost, typically bedrock, and especially with low to medium ice content.

There are only a handful of studies monitoring permafrost within Nepal. In Kanchenjunga, east of Khumbu, the permafrost lower limit was 5,300 m on south-east facing slopes and 4,800 m on north facing slopes ([Haq and Baral, 2019](#); [Ishikawa et al., 2001](#)). The lower limit of mountain permafrost, from ground temperature measurements, was measured as 5,400-5,500 m in the Khumbu Himal region ([Fukui et al., 2007](#)). In the Sikkim Himalayas, climatic conditions above 5,000 m a.s.l. are generally favourable for the presence of permafrost ([Haq and Baral, 2019](#)). The elevation of the landslide on Langtang-Lirung is therefore likely within the permafrost zone, but near the lower boundary.

Within Nepal, ERA5 and WorldClim data indicate that, over the last 60 years, the distribution of discontinuous permafrost at altitude has grown, and continuous permafrost shrank and become increasingly fragmented ([Sthapit et al., 2026](#)). The area of high-probability permafrost has retreated significantly, particularly in lower elevations, and discontinuous permafrost has expanded considerably (Sthapit et al., 2026). Following warming, ERA5 Support Vector Machine (SVM) results indicate a substantial decrease in permafrost below 5,500 m in the recent period (2010-2018) compared with the earlier period (1961-1970). The reduction of permafrost in the 4,500-5,500 elevation band is particularly pronounced. This is a critical transition zone in Nepal, where permafrost is most sensitive to climatic warming. The catastrophic landslide on Langtang-Girung occurred within this elevational zone, where permafrost degradation is most likely.

2.3 Glacier changes

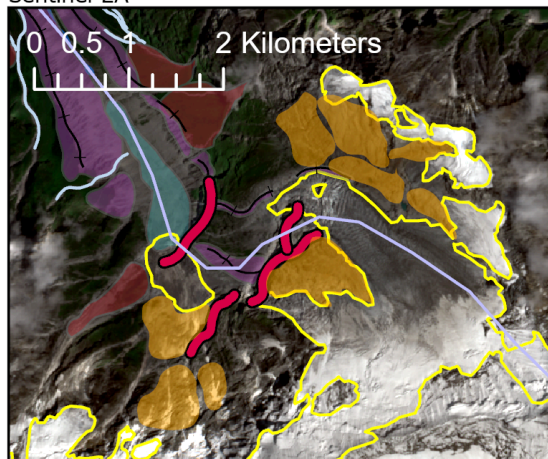
Regionally, glaciers are shrinking rapidly. Shrinking glaciers are associated with amplification of cryospheric hazards, including slope instabilities and GLOFs ([Chiarle et al., 2021](#); [Coe et al., 2018](#); [Cossart et al., 2008](#); [Huggel et al., 2012](#); [Kos et al., 2016](#)). The sustained mass loss of glaciers is driven primarily by rising temperatures ([Berdahl et al., 2026](#)).

Since the end of the “Little Ice Age” (LIA), Himalayan glaciers have undergone substantial mass loss and retreat ([Lee et al., 2021](#)). Across the Hindu Kush Himalaya, an inventory based on Landsat imagery shows that glaciers lost 12% of their starting area between 1990-2020 (Fig. 2.3.2) ([Maharjan and Sherpa, 2026](#)). The glacier recession was most pronounced from 2010-2020.

In the Langtang catchment, adjacent to the catchment including the Langtang-Lirung Glacier, there has been significant glacier retreat since the end of the “Little Ice Age”, with a loss of 78 km² of ice (41%) ([Silwal et al., 2026](#)). Glaciers are increasingly fragmented and separated. Rates of glacier area loss increased more than fourfold through the study period, from 0.11% a⁻¹ (LIA-1964) to 0.49 % a⁻¹ (1964-2023), with rates particularly rapid after 2000 CE (0.79% a⁻¹ from 2000-2016 and 0.5 % a⁻¹ from 2016-2023). Glaciers also underwent widespread thinning, reduced ice-flow velocities and rising equilibrium line altitude (ELAs), driven by pronounced warming (0.3°C dec⁻¹ above 4,000 m, compared with 0.1°C dec⁻¹ at 3,865 m). Thinning migrated up-glacier to accumulation zones, and, in heavily crevassed icefall regions, has led to glacier fragmentation (Silwal et al., 2026). The glaciers within a radius of approximately 50 km around Langtang-Lirung Glacier (in total >900 km² of glacier ice) thinned at an average rate of more than 0.5 m a⁻¹ between 2000 and 2020, with slight acceleration in thinning rate during this period ([Hugonnet et al., 2021](#)).

Consistent with these regional-scale changes, the Langtang-Lirung Glacier has also undergone substantial thinning and recession over recent decades. Our analysis (see Appendix A1 for methods) shows that in August 2026, prior to event, the glacier was 3,770 m long and covered 7.34 km² (Figure 2.3.1). It occupied a cirque on the northern face of Langtang-Lirung, with two main glacier tongues (a northern, glacier-right tongue, and a southern, glacier-left tongue) descending either side of the rocky buttress that failed on 26 August 2026. This rocky buttress is ice-scoured on its southern flank, indicating previous cover by erosive ice (Fig. 2.3.1). It terminates in a steep cliff, potentially the site of a previous rock fall at some time in the past. The Langtang-Lirung Glacier is fragmented, with buried ice remaining in the lower valley, between the “Little Ice Age” (LIA) moraines (dating from approximately 1815 CE). Glacier ice also remains at the foot of the steep slope below the glacier-left tongue. This indicates that in the past, the rocky buttress was surrounded by ice on its lower slopes on either side.

24th August 2026.
Sentinel-2A



28th August 2026
Planet image

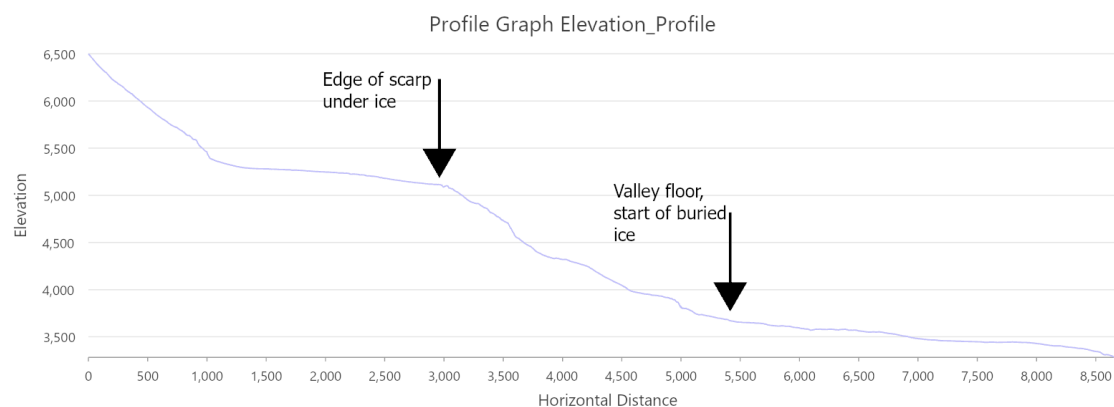
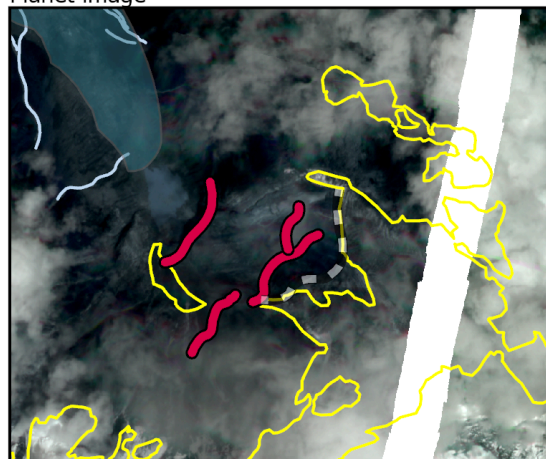


Figure 2.3.1: The Langtang-Lirung Glacier before and after the rock-ice landslide.

On the northern side of the Langtang-Lirung mountain, the Langtang-Lirung Glacier has been undergoing significant retreat and thinning in the decades prior to collapse (Appendix A3, Figs. 2.3.2 & 2.3.3). Glacier area reduced from a neoglacial LIA maximum (estimated at 1815 CE) of 18.9 km² to a pre-event minimum of 7.34 km² (24 August 2026). After the event, the glacier area was reduced to 6.88 km² (9 September 2026). Glacier shrinkage of the Langtang-Lirung Glacier occurred slowly from 1815-2010 (rates of ~ -0.1 to -0.5 % a⁻¹) with a significant acceleration in area loss after 2010 (Table A3.2). From 2010-2015, the glacier changed at a rate of -2.28 % a⁻¹, then at -2.07 % a⁻¹ (2015-2020). From 2020-2026, the rate was -1.15 % a⁻¹. This is faster than the catchment-wide average noted in Langtang. This recession left the Langtang-Lirung Glacier hanging at the head of a steep rock wall, with fragments of ice disconnected and decaying close to the valley floor. Buried ice was left behind in the valley floor which continued to thin until the event on 26 August 2026.

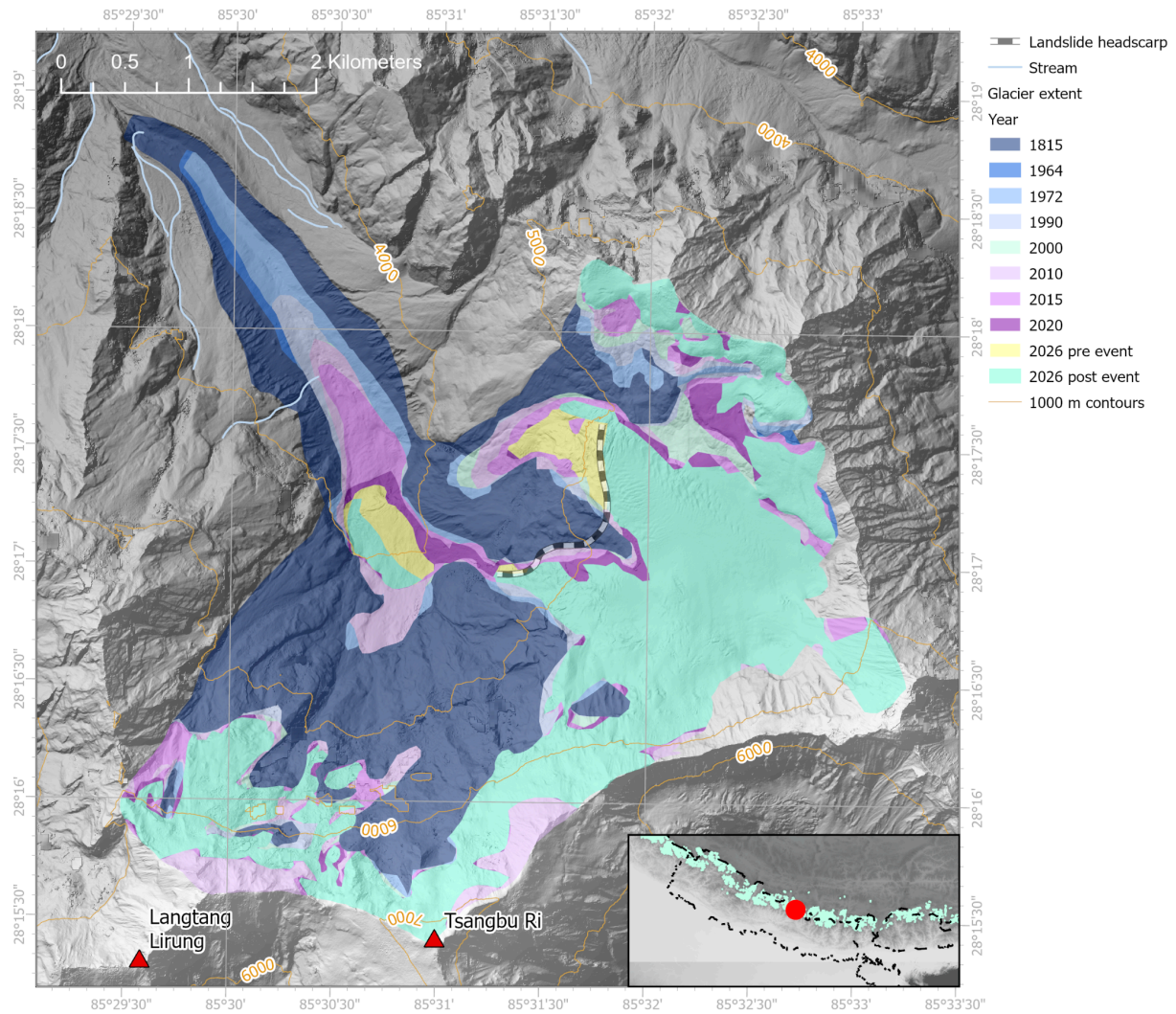


Figure 2.3.2: Glacier extents of the Langtang-Lirung Glacier, northern Langtang-Lirung mountain, 1815 - 2026, mapped from Sentinel, Landsat and declassified Corona and Hexagon imagery (see Appendices A1 and A3). Glacier extent in 1990 modified from Maharjan and Sherpa (2026). Glacier extent in 1815 (Little Ice Age) modified from Lee et al. (2021) using geomorphology observed in the Sentinel satellite imagery. 2 m Pleiades DEM from Berthier (2026). Inset shows location of the site (red dot) within Nepal, with glacier area (marked in cyan) from RGI v.7.0.

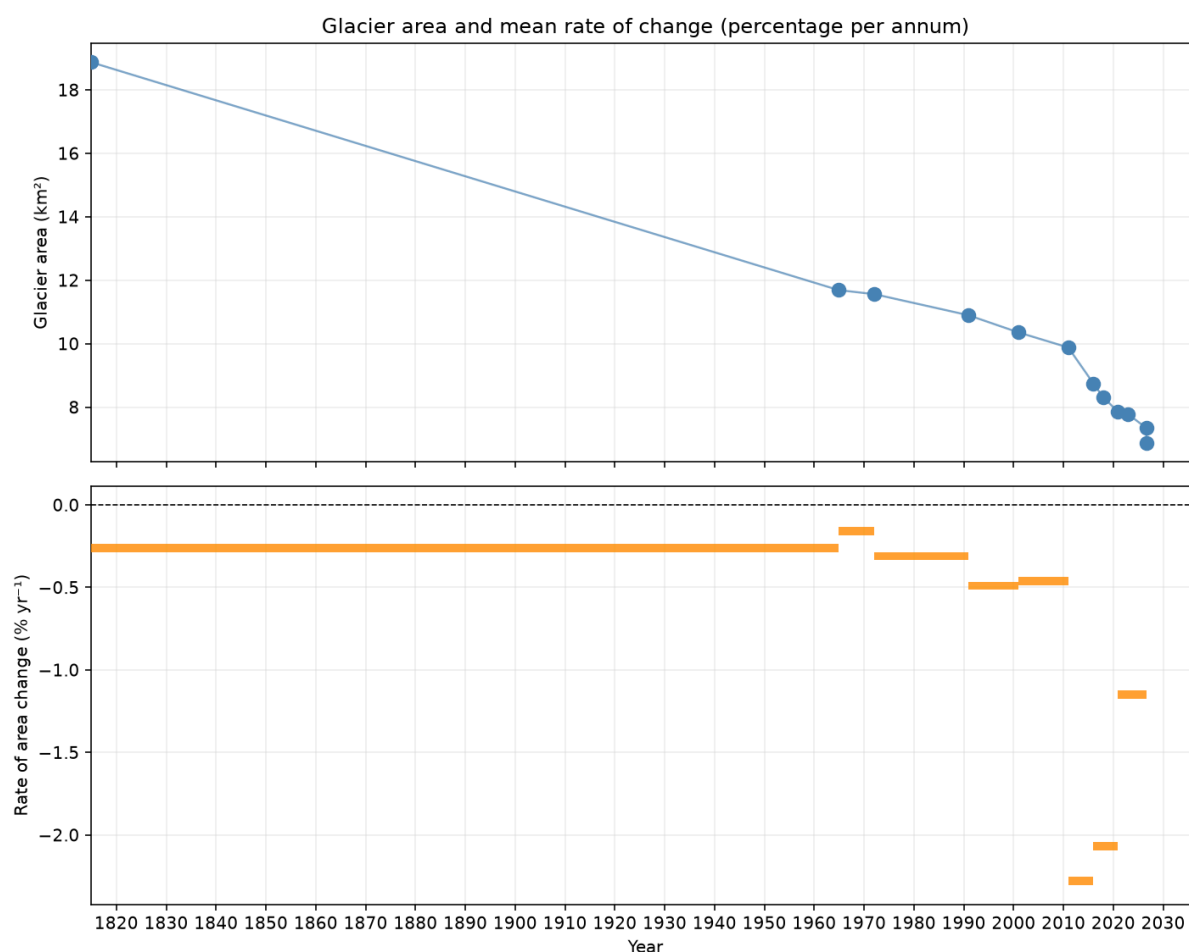


Figure 2.3.3: Mapped glacier area from 1815 to 2026 (upper panel) and rates of area change over periods between successive observations for Langtang-Lirung Glacier (lower panel).

Our analysis of satellite imagery shows that around the rocky buttress specifically, prior to failure, the glacier has thinned and retreated since the 1960s. In 1964, the glacier-right tongue had separated from the glacier-left tongue and had also separated from the valley floor. The ice descending over the scarp reached a minimum elevation of 4,133 m a.s.l.. The recession of this tongue was slow; by 2000, this tongue had receded only a further 75 m to an elevation of 4,198 m. Between 2010 and 2026, this glacier tongue receded rapidly upslope, retreating a distance of 373 m and rising from a minimum elevation of 4,237 to 4,466 m a.s.l.. This left the rocky buttress exposed following the removal of ice over the preceding decades, and in particular, the removal of stabilising glacier ice at the lower slopes of the mountain side. Further, the significant retreat and thinning in recent years has provided a substantial increase in the availability of meltwater at the elevation of the failure site.

Overall, the Langtang-Lirung Glacier has undergone significant recession in recent decades, with recession accelerating significantly in the last 15 years (Fig. 2.3.3). The steep rock slope below and on either side of the rocky buttress has become progressively ice free. This could have contributed to the failure by debuttreassing the lower slopes, with ice loading remaining at the top of a high, steep and potentially vulnerable slope.

Hillslope steepening due to glacial erosion, combined with glacial debuttreasing and resultant stress release, can provide conditioning and triggers for slope failure ([Kos et al., 2016](#)). This is because glacier mass loss adjacent to a rock wall modifies the mechanical boundary conditions of the slope. As ice thins, the rock wall experiences unloading and changes in normal and shear stresses along existing fractures. This is often referred to as glacier debuttreasing, although direct mechanical buttressing by glacier ice can be limited because glacier ice deforms viscously. More recent mechanical studies therefore emphasize the broader effects of glacier thinning, unloading, erosion and stress redistribution rather than simple removal of a rigid buttress. [Grämiger et al. \(2017\)](#), for example, showed that glacier fluctuations can bring existing fractures closer to failure and enhance progressive rock-mass damage. Further, [Chiarle et al. \(2021\)](#) note that a high incidence of landslides are attributable to progressive deglaciation and debuttreasing of steep slopes, and perhaps permafrost thaw. Where failures occur in hot summer weather, one trigger can include the penetration of snow and ice melt into sediments and fractured rock. For Rasuwa, changes in glacier surface elevation and geometry adjacent to the failed slope, alongside slowly degrading permafrost, could therefore provide an important independent line of evidence for long-term destabilisation. Failure was strongly conditioned by geological conditions at the site, with highly fractured bedrock, and with changes in the cryosphere (snow, glacier ice and permafrost) acting upon this to prime the site for failure.

2.4 Increased melt water infiltration

Warming can increase snow and ice melt and therefore the availability of liquid water. Meltwater entering bedrock fractures can influence rock stability in several ways. It can advect heat into the rock mass and accelerate thaw, particularly along deep fractures; it can replace fracture ice with water; and it can increase hydrostatic pressure. Higher water pressure reduces the effective normal stress acting across a discontinuity and therefore reduces frictional resistance to sliding. [Gruber and Haeberli \(2007\)](#) specifically note that water circulation can produce deep thaw corridors much more rapidly than conductive warming alone. This process provides a direct physical connection between warming, glacier/snow melt and the mechanical state of the failure rock surface. Increased meltwater can also reduce effective stress at the glacier bed, promoting ice–bed decoupling, enhanced basal sliding and glacier instability.

2.5 Shift from snow to rainfall

Precipitation can provide an additional short-timescale forcing. As temperatures rise, the rain–snow transition moves upward and a larger fraction of high-elevation precipitation can fall directly as rain rather than snow. Rain produces an immediate liquid-water input to the slope, whereas snowfall temporarily stores water at the surface. Intense or prolonged rainfall can therefore rapidly increase water supply to fractures and potentially increase fracture-water pressure. This mechanism could operate as the final trigger on a slope whose resistance had already been reduced over years to decades by warming, fracture-ice degradation and changes in glacier geometry. However, whether this occurred at Rasuwa needs to be established from the meteorological conditions immediately preceding the failure.

2.6 Observed conditions preceding the failure

Observations from Langtang, with temperatures adjusted to the failure elevation of 5,150 m using locally observed lapse rates, indicate sustained warmth during August 2026. Daily mean temperatures exceeded the corresponding 2016–2025 averages on most days preceding the failure (Fig. 2.6.1). The departure was particularly pronounced on 24–25 August, when daily means reached approximately 5.3–5.4°C, compared with reference values of approximately 2.7–2.8°C, giving positive anomalies of around 2.5–2.7°C. Daily maximum temperatures were also markedly elevated immediately before the failure (Fig. 2.6.1). On 23–25 August, the maxima reached approximately 11.3–12.6°C, compared with corresponding 2016–2025 mean daily maxima of approximately 5.5–6.0°C. The largest departure occurred on 25 August, when the maximum was approximately 7°C above the reference mean. The hourly series further shows that all plotted temperatures during 12–26 August remained above freezing (Fig. 2.6.2).

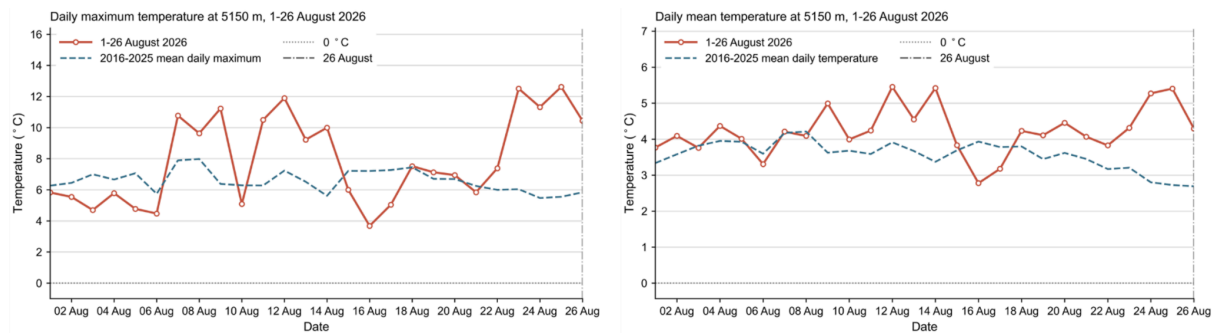


Figure 2.6.1: Daily maximum (left) and mean (right) temperature from 1st - 26th August leading to the slope failure based on in-situ measurements from the Langtang catchment (see section A2.1 for details). Daily statistics are calculated from hourly in-situ station measurements and estimated for 5,150 m a.s.l using locally-observed lapse rates.

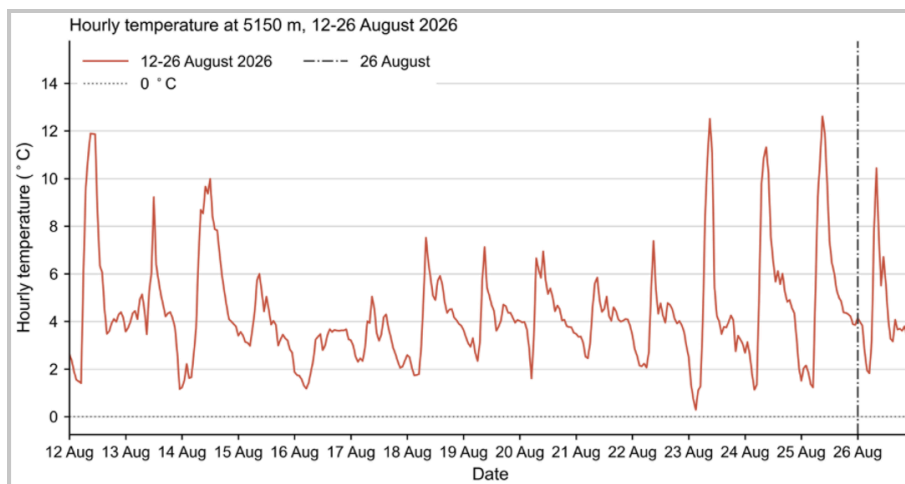


Figure 2.6.2: Hourly temperature from 12th - 26th August leading to the slope failure based on in-situ measurements from the Langtang catchment (see section A2.1 for details). Values are estimated for 5150 m a.s.l using locally-observed lapse rates.

Figure 2.6.3 illustrates using the height of the 0°C isotherm near the slope failure (explored further in section 3.1.2) for a 15-day moving average each year in the past decade, using in-situ station data, and the decadal mean each decade since the 1980s below based on MSWX data. The 2025/26 year was consistently towards the upper end of isotherm height across most of the year, with a notable spike in March, sustained periods averaging above 0°C as early as June, and consistently elevated conditions in the monsoon period, especially from the start of July. It is further notable that the isotherm only dipped below the base of the slope for a short duration in the current glaciological year. This is also clear from the monthly mean temperatures at the nearest grid cell to the event occurrence in two gridded reanalysis products (Fig. 2.6.4), with temperatures above the climatological average and most other years in the record in both datasets for all months except June (and slightly cooler conditions in April and May in ERA5-Land). This excess warmth was experienced across most of the wider Himalayan region (Fig. A3.1). Together, the elevated daily means and maxima and sustained positive air temperatures leading up to the event indicate conditions favourable for continued snow and ice melt in the days and months preceding the failure.

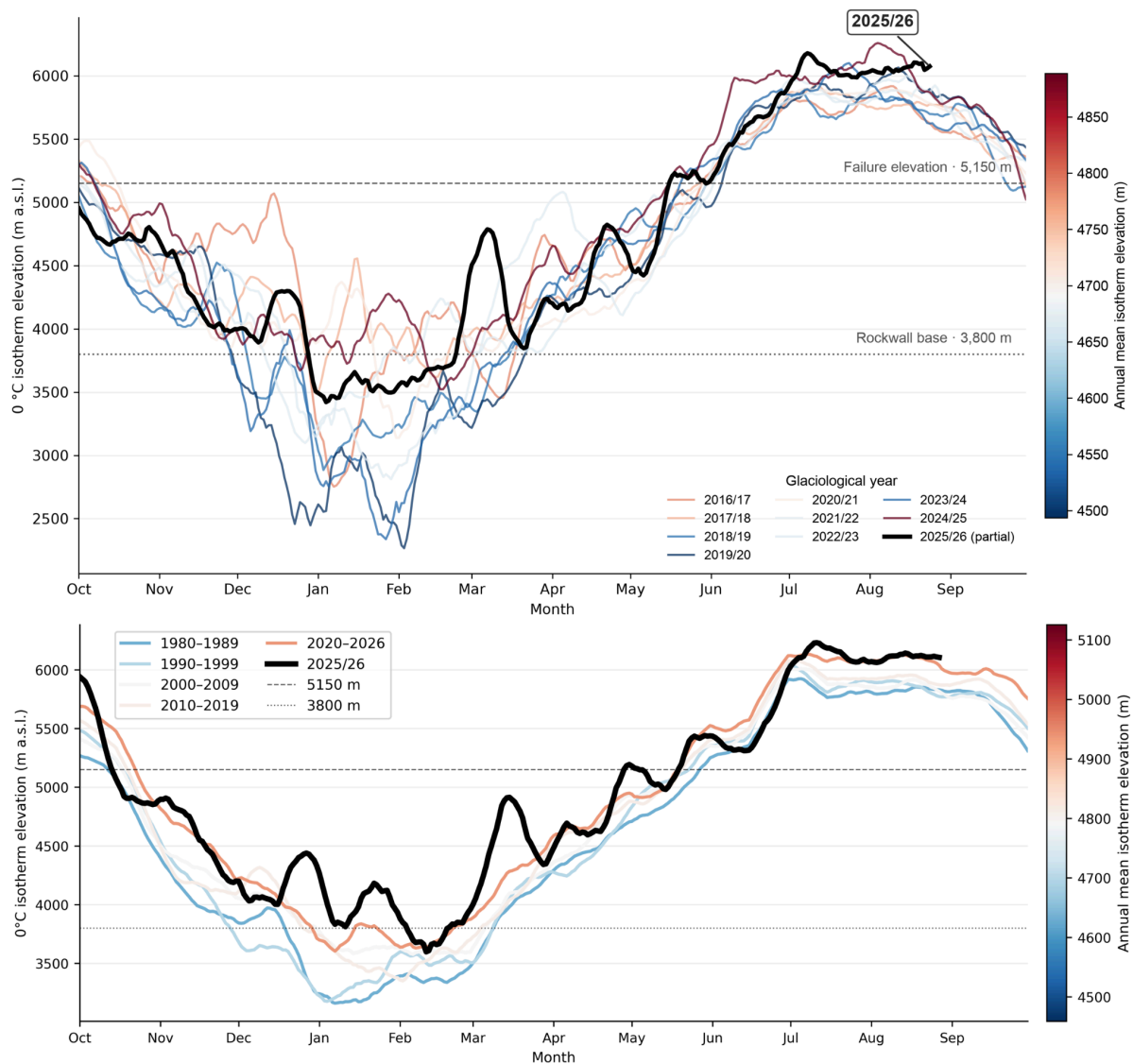


Figure 2.6.3: Top: Daily height of 0°C isotherm at the approximate location of slope failure for the past 10 glaciological years (October-September) using a 15-day moving average, based on in-situ

station data (see section A2.1 for details). Dotted and dashed lines show the height of the rockwall base and failure elevation, respectively. The black line shows the data for the 2025/26 year, and the colour of the other lines indicates the mean isotherm elevation (see colourbar). Bottom: The same index as in the top figure but for decadal mean of the 15-day moving isotherm height for each decade since 1980, based on MSWX data (see sections A2.1 and A2.4 for details). The year 2025/26 is shown as a bold black line for comparison.

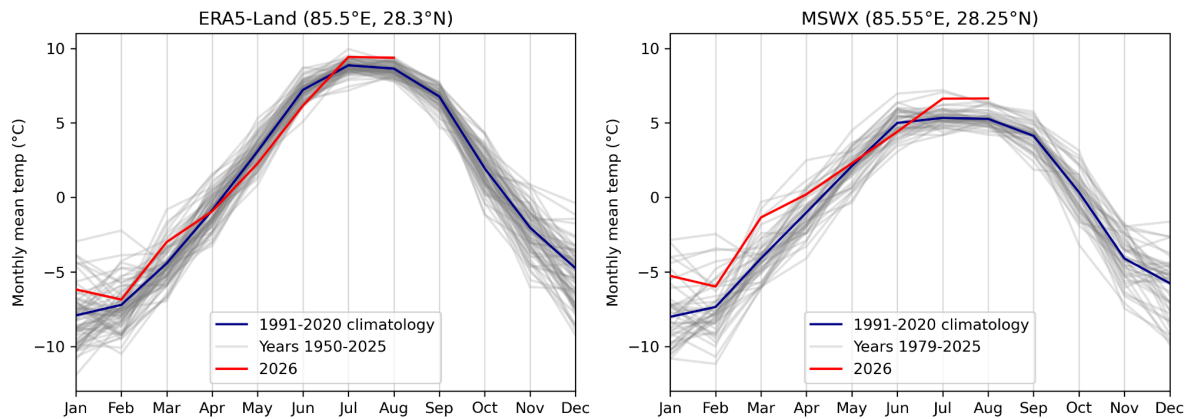


Figure 2.6.4: Monthly mean temperature for the nearest grid cell to the event in the ERA5-Land and MSWX datasets. The central point of the nearest grid cell in each dataset is shown in brackets. All years in each record are shown in grey, with the climatological mean for 1991-2020 shown in blue and 2026 in red.

Figure 2.6.5 shows the annual time series for three precipitation indices- seasonal precipitation and the 10-day extreme precipitation spell ($Rx10day$) in the monsoon season which is from June to September (JJAS), and winter seasonal precipitation from October to December (OND) from one reanalysis product (ERA5-Land), two satellite products (CHIRPS and IMERG), two high-resolution downscaled products (CHELSA and WRF) and stations. Out of these, only ERA5-Land contains data covering the rock-ice-avalanche event (1979-Aug 28 2026), The CHIRPS dataset is also 45 years long, beginning in 1981 but ending in July 2026. The other products CHELSA (1980-2019), WRF (2000-2025) and the stations (2016-2025) are all short and do not go up to 2026. All values are shown in mm/day, considering that the 2026 JJAS season is not over at the time of writing this report.

Gridded data products of precipitation at the nearest gridpoint to the event as well as the larger Himalayan region show approximately average precipitation in the JJAS season directly preceding the rock-ice avalanche as well as in the winter (OND) before. Station data directly preceding the event is not available. However, in the years for which it is available the station data does not match any of the gridded data products very well in the monsoon season, though IMERG, CHIRPS, ERA5-Land and WRF appear to track closely with each other in terms of the absolute magnitude of rainfall, but with slight differences in the year-to year variability (Fig. 2.6.5). CHELSA on the other hand, seems to be overestimating the precipitation by a factor of ~ 2 in the JJAS season with a high degree of year-to-year variability. The same level of disagreement is observed for the case of the 10-day extreme precipitation spell in JJAS as well. In the winter (OND) season, when it does not precipitate as much it is the reanalyses and the high-resolution downscaled products that all agree in terms of the variability and the magnitude with the stations, while the satellite products seem to grossly

underestimate the precipitation. A likely reason could be that at these high altitudes, during the winter, the precipitation may also fall as snow, which may not be recorded properly by the satellite products on account of the algorithms not being able to or underestimating snow (CHIRPS; Tang et al., 2020). From evaluating the different datasets for their fidelity in representing rainfall in this complex, high-altitude region, ERA5-Land seems to be a good candidate dataset. From this dataset, we see that neither the 2026 monsoon nor the preceding winter was exceptional in terms of precipitation, with all of the precipitation indices considered staying well within the variability.

An important observation from analysing these time series is the exceptionally high precipitation recorded by the stations during the 2025 OND season. This anomaly is particularly notable, given that a great part of this precipitation that fell in October 2025 was recorded as snow (Fig. 2.6.6), which may have contributed to meltwater to the catchments in the subsequent 2026 spring and monsoon. This also suggests that even at broader spatial scales, winter precipitation could be relevant as an antecedent hydrological condition for the subsequent monsoon season, potentially influencing snow accumulation, soil moisture and catchment water storage. However, because the available data do not allow us to establish such a mechanism, without further analysis.

In the wider region the variability in the different data products is much more similar with the exception of the last year, which shows average or below average precipitation in all datasets except IMERG. We therefore conclude that anomalous precipitation is not likely a major causal factor behind the rock-ice avalanche. This does not, however, preclude the possibility that there was greater rainfall, which is important for rock destabilisation, as the increase in temperature may have resulted in a larger proportion of winter precipitation falling as rain rather than snow (see section 2.5).

Annual precipitation indices at the rock-ice-avalanche site (left) and the surrounding Himalayan region (right)

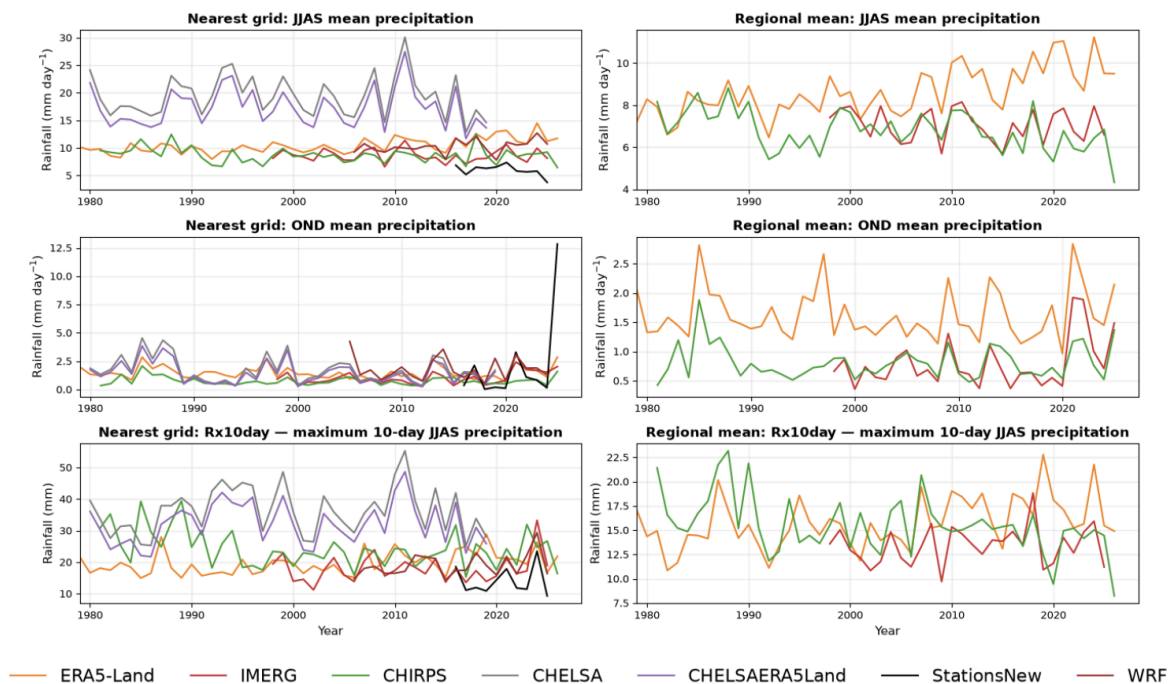


Figure 2.6.5: Annual time series of mean daily precipitation in the JJAS season (top row), OND season (middle row) at the rock-ice-avalanche origin (left) and wider Himalayan region at similar elevation (right). The bottom row shows these plots for the heaviest 10 day spell in the JJAS season expressed as mean daily average.

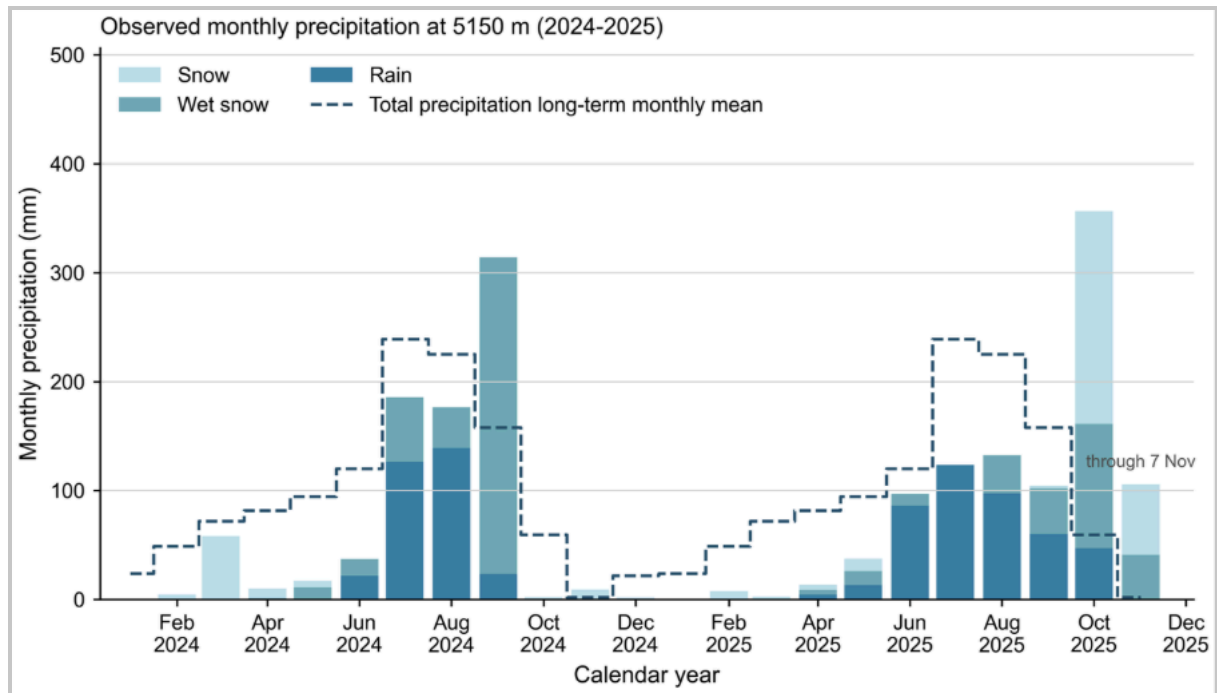


Figure 2.6.6: Observed precipitation and estimated phase during 2024–2025. Monthly precipitation from Langtang observations, partitioned using temperatures adjusted to 5,150 m: dry snow below -2°C , wet snow between -2 and $+2^{\circ}\text{C}$, and rain above $+2^{\circ}\text{C}$.

3 Temperature changes

In this section we analyse changes in temperature in the region of this event. In section 3.1 we study changes in a range of temperature indices throughout the historical record to characterize the changing environment around high mountain slopes, including: trends with GMST at different spatiotemporal scales, height of the 0°C isotherm, positive degree days, change in mean temperature per calendar month, and the elevation-dependency of temperature changes. In section 3.2, we use high resolution regional and global climate models to analyse changes in temperatures at the grid and regional scale, using the same event definition indices as in section 3.1.1. We assess how well the climate models perform at various scales in this high mountain and topographically- and climatologically-complex region, and synthesise the observation-based and model-based results to assess the degree to which human induced climate change influenced long-term temperature changes in the region.

3.1 Observed changes

3.1.1 Trends in temperature in gridded data and station data

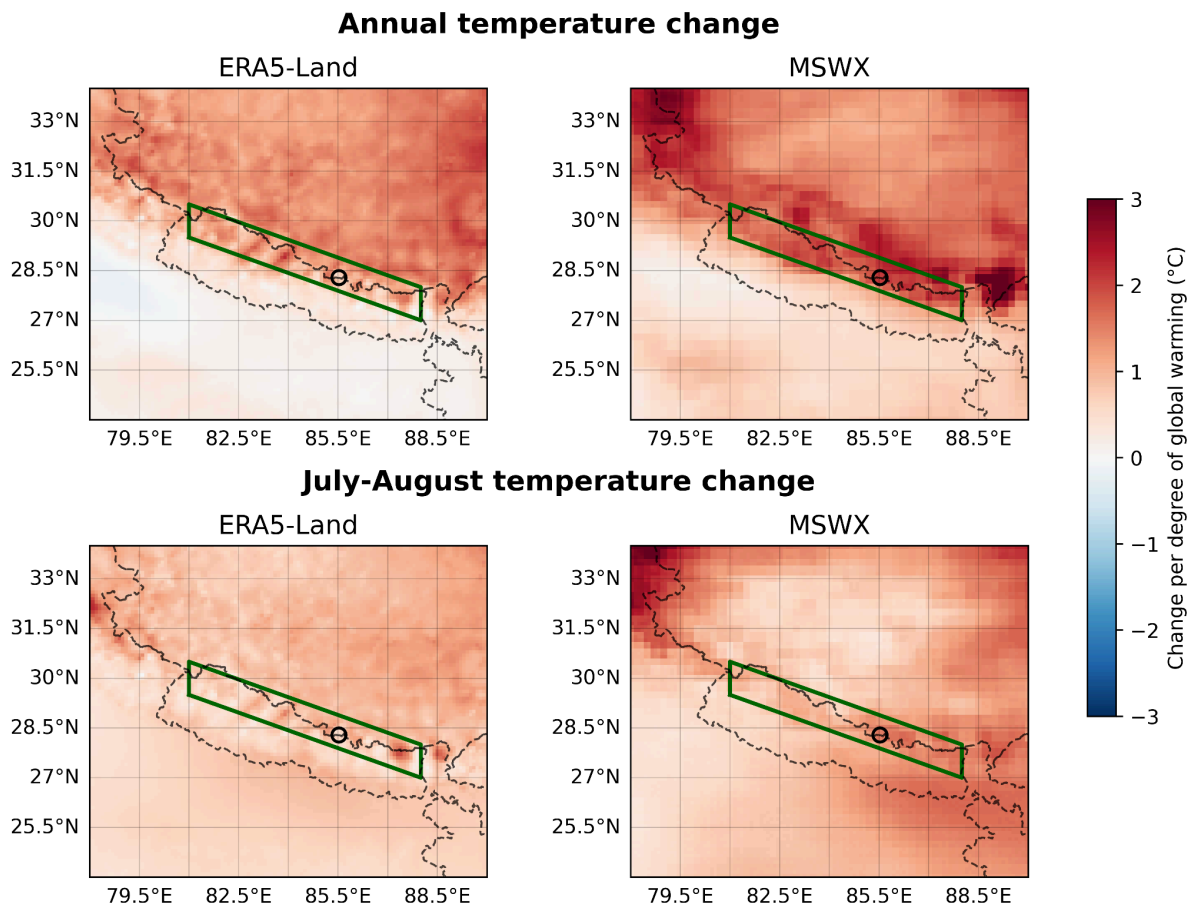


Figure 3.1.1: Change per degree of global warming in annual (top) and July-August (bottom) average of daily mean temperature over Nepal and surrounding regions for each grid cell in two reanalyses (ERA5-Land, from 1950, and MSWX, from 1979). The wider Himalayan region is shown with the dark green box and the approximate location of the slope failure is shown by the black dot.

Event definitions

The slope failure on August 26th occurred against the backdrop of a warm 12-month period from September 2025-August 2026, with the warmest two months of the year (July and August) directly preceding the event also substantially warmer than the climatological average (Fig. 3.1.1). These conditions were anomalous at the location of the slope failure itself and across the wider Himalayan region. To capture the long-term changes in both the vicinity of the failure itself and the wider Himalayan region, we study changes in daily mean temperatures averaged across four spatiotemporal domains:

- **July-August** average of daily mean temperature at the location of the **nearest grid cell** to the slope failure (at 28.288708°N, 85.528159°E) and averaged across the **Himalayan region** (Fig. 3.1)
- **Annual (September - August)** average of daily mean temperature at the location of the **nearest grid cell** to the slope failure (at 28.288708°N, 85.528159°E) and averaged across the **Himalayan region** (Fig. 3.1)

The glaciological year in the Himalayas is generally considered to run from 1st October to 30th September. However, at the time of analysis data was only available up to the event at the end of August 2026. We therefore use the slightly adjusted definition of September-August. We do not expect this to affect long-term trends, which are the main focus of this analysis.

1. In this section, we study the influence of anthropogenic climate change by comparing the expected intensity of temperatures over these domains at present with those in a 1.4°C cooler climate without human-caused warming (based on [Forster et al., 2026](#)). In section 3.2, we conduct a full attribution of these trends incorporating climate model analyses. We also extend this analysis into the future by assessing the influence of a further 1.4°C of global warming from present. This is in line with the latest Emissions Gap Report from the United Nations Environment Programme, which shows that the world is on track for at least 2.8°C temperature rise given currently implemented policies ([UNEP, 2025](#)).

Nearest grid cell

Figure 3.1.2 shows mean annual and July-August temperatures at the nearest grid cell to the slope failure (see section A2.1 Observational data for details). The values from each dataset are offset due to differences in the domain covered by the nearest grid cell. For instance, MSWX is selected from the cell 28.2-28.3°N and 85.5-85.6°E, ERA5-Land is 28.25-28.35°N and 85.45-85.55°E, and CHELSA and WRF are at higher resolutions of 1km and 4km, respectively. This means that there are differences in the mean elevation of the topography covered. Using GEBCO bathymetry data at 15 arc-second resolution (see section A2.1 for details), we estimate that the mean elevation of the ERA5-Land grid cell is 4,520m and MSWX is 4,866m. There are also differences in the mean elevation used in the land-surface scheme of each dataset. For instance, using the geopotential field from ERA5-Land, selecting the same grid cell and dividing the geopotential by acceleration due to gravity (9.80665 m/s^2), we find that the effective model height for this grid cell is approximately 4,167 m, lower than suggested by the GEBCO data. The WRF grid cell has a given surface height of 4,971 m. The in-situ station record is adjusted to 5,150 m using daily measured lapse rates.

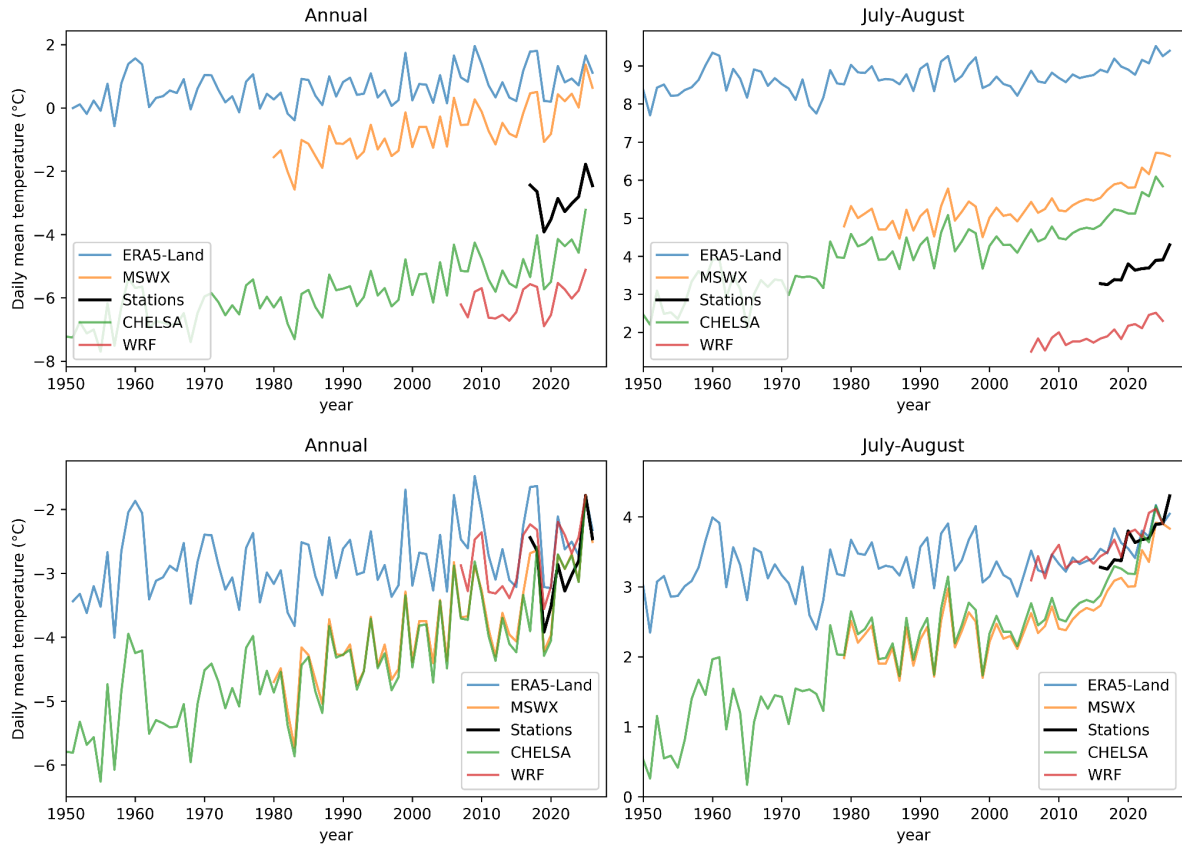


Figure 3.1.2: Time series of annual (left) and July-August (right) average of daily mean temperature at the location of the ice-rock avalanche for several gridded observation-based datasets and in-situ measurements. Top row: all time series without any adjustment. Bottom row: all time series adjusted to match the station-based 2025 value to facilitate visual comparison of trends. For time series adjusted for elevation, see appendix A3 (Fig. A3.1). For gridded datasets, we select the nearest grid cell to the coordinates of the slope failure (28.288708°N, 85.528159°E).

In order to account for this difference and estimate the temperature at the approximate height of slope failure (5,150m), we applied catchment specific lapse rates (see section A1.4 Elevation correction for full details; Fig. A3.2 for adjusted time series). Given the challenge of obtaining exact elevation data for each dataset and the challenge of modelling high mountain environments, the datasets remain offset (Fig. A3.2). However, this correction does not substantially affect the long-term trends, which are the focus of this analysis.

For visual clarity here, the time series are also matched to the 2025 value (the most recent data covered by all datasets) of the in-situ station data (Fig. 3.1.2). This highlights consistency in the measured variability across datasets in recent years as well as consistent qualitatively increasing trend over time. It also highlights a divergence in the rate of change between datasets, with ERA5-Land and WRF showing generally weaker trends than MSWX and CHELSA.

The influence of GMST upon these temperature indices was estimated by fitting a nonstationary normal distribution to each dataset using GMST as a covariate (see section A1.3 Statistical methods

for details). Table 3.1.1 shows the results of this trend analysis, giving the change in local temperatures associated with the global temperature rise of 1.4°C. ERA5-Land gives a weaker trend than other datasets, with local temperatures warming at approximately half the rate of the global mean. The other datasets all show stronger increases at rates of approximately 1.5-2 times the global average, with estimates of the mean change from 2.1-2.9°C annually and 1.7-3.0°C in July-August. Despite the difference in magnitude of the trend with ERA5-Land, all datasets show a consistent rise in temperatures that is statistically significant at the 95% confidence level. It is also notable that the annual temperature increase is larger than the July-August change in all datasets apart from CHELSA, which is comparable, suggesting that other parts of the year are warming at least as fast as the monsoon season. This is also shown for the wider region and especially other parts of the Himalayas in Fig. 3.1.1. Section 3.1.4 explores the changes per calendar month over the wider region and for each spatial event definition studied here.

Finally, because the datasets each have different horizontal resolution as described at the beginning of this subsection, we tested the effect of dataset resolution on these results. Aggregating the CHELSA data at 1km to approximately align with the ERA5-Land grid cell dimensions, and using the 3x3 array of WRF grid cells around the closest one used in the analysis, we find that the results are effectively unchanged (Table A3.2).

Table 3.1.1: Change in temperature for the annual and July-August average of daily mean temperatures at the location of the slope failure (left) and the wider Himalayas region (right), associated with a 1.4°C increase in GMST. All changes are statistically significant at the 95% level.

Dataset	Change in temperature due to 1.4°C global warming (95% C.I.)			
	Nearest grid cell		Himalayan region	
	Annual	July-August	Annual	July-August
ERA5-Land	0.784 (0.331, 1.21)	0.700 (0.394, 0.901)	1.53 (0.934, 2.04)	1.10 (0.846, 1.32)
MSWX	2.90 (2.15, 3.58)	2.08 (1.56, 2.47)	2.56 (1.70, 3.31)	1.57 (1.09, 1.91)
CHELSA	2.86 (2.37, 3.35)	3.04 (2.73, 3.34)		
WRF	2.09 (0.45, 3.40)	1.74 (1.08, 2.33)		

Himalayan region

Figure 3.1.3 shows mean annual and July-August temperatures over the wider Himalayan region for ERA5-Land and MSWX. Despite the common region, an offset remains between these datasets likely due to the application of an explicit land-surface scheme in ERA5-Land. However, when this offset is removed it is clear that the long-term trends between the datasets are similar, suggesting a consistent link to warming. Table 3.1 shows that over this wider region there is a consistent warming associated

with global temperature rise that is significant at the 95% confidence level in both datasets. A discrepancy remains in the magnitude of this change, with a rate of warming substantially above the global average in MSWX and at or slightly below the global average from ERA5-Land. Over this wider region there is an even stronger difference between the annual warming rate and in July and August, in the middle of the monsoon season, which again aligns with Fig. 3.1.1.

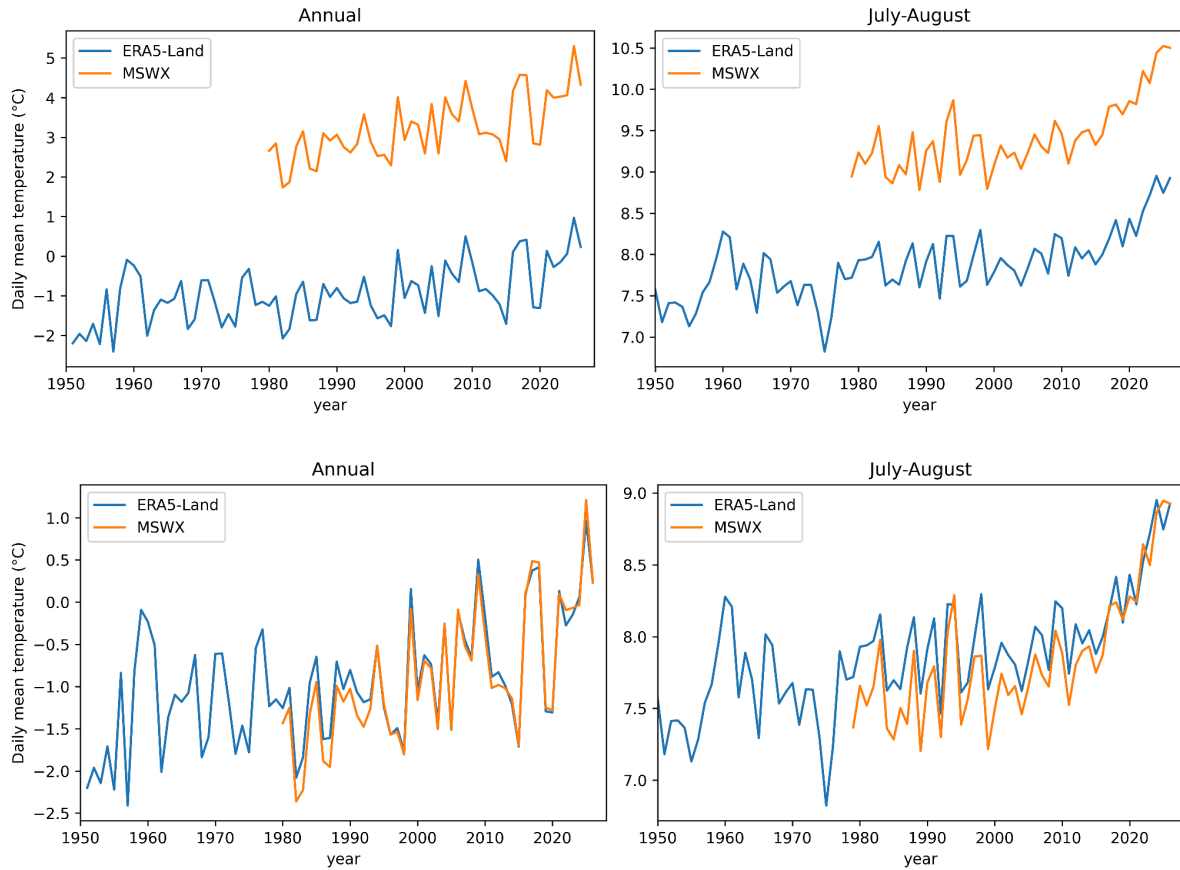


Figure 3.1.3: Time series of annual (left) and July-August (right) average of daily mean temperature over a region covering the Himalayas and wider region (green box, Fig. 3.1.1) for two gridded observation-based datasets, ERA5-Land and MSWX. Top row: both time series without any adjustment. Bottom row: MSWX time series adjusted to match the ERA5-Land 2026 value to facilitate visual comparison of trends.

3.1.2 0°C Isotherm height

The 0°C isotherm in the atmosphere generally describes the level below which ice melts. If the isotherm is consistently above the height of a glacier, the result is net melting leading to thinning and retreat. The height of the 0°C isotherm varies significantly throughout the year and is typically at its highest during the monsoon season and the warmest months of July and August, and at its lowest during the winter months of January and February (Fig. 2.6.3). Preliminary analysis suggests both an elevated isotherm during large parts of the 2025/26 glacial year and a robust long-term increase in height of the isotherm. We extend this analysis here by studying seasonal means separately. While a seasonal mean above the glacier elevation does not imply conditions entirely above the freezing level, a higher isotherm indicates conditions more conducive to melting. For each dataset, we estimate the

seasonal mean height of the 0°C isotherm using the elevation data described in section 3.1.1 and catchment specific lapse rates (see Appendix A2.4).

Figure 3.1.4 shows time series of the 0°C isotherm for the in-situ station, ERA5-Land, MSWX and WRF datasets, as well as linear trends in all but the in-situ station data, giving mean rates of change over different time periods. It is worthy of note that restricting ERA5-Land to 1979 results in stronger trends in all seasons. As with other indices, a significant offset between datasets persists but the variability in the index is broadly captured by all datasets with respect to the in-situ station data. The height of the 0°C isotherm is rising or remaining unchanged in seasons with the highest year-to-year variability. The strongest changes are occurring during the Monsoon (mid-June - September) and Postmonsoon (October-December) seasons, with all datasets giving significant increases, and best estimates around 100m/decade in MSWX (slightly lower during the Monsoon) and WRF and 14m/decade and 31m/decade in the more steadily warming ERA5-Land data in the two seasons, respectively. MSWX also indicates strong significant increases in winter (January and February) and the Premonsoon (March - mid-June), but trends are weaker and less certain in the WRF dataset in both seasons. It is worthy of note that the WRF dataset is only ~20 years in length and that the isotherm height is highly variable in some seasons, particularly winter. The longest dataset, ERA5-Land, also indicates a significant ($p=0.031$) rise in the winter. Clearly, while the specific height of the 0°C isotherm remains challenging to estimate, the long-term trends are that it is increasing in most if not all seasons. In the warmest seasons and recent decades, this has occurred at a rate of around 50-100m/decade.

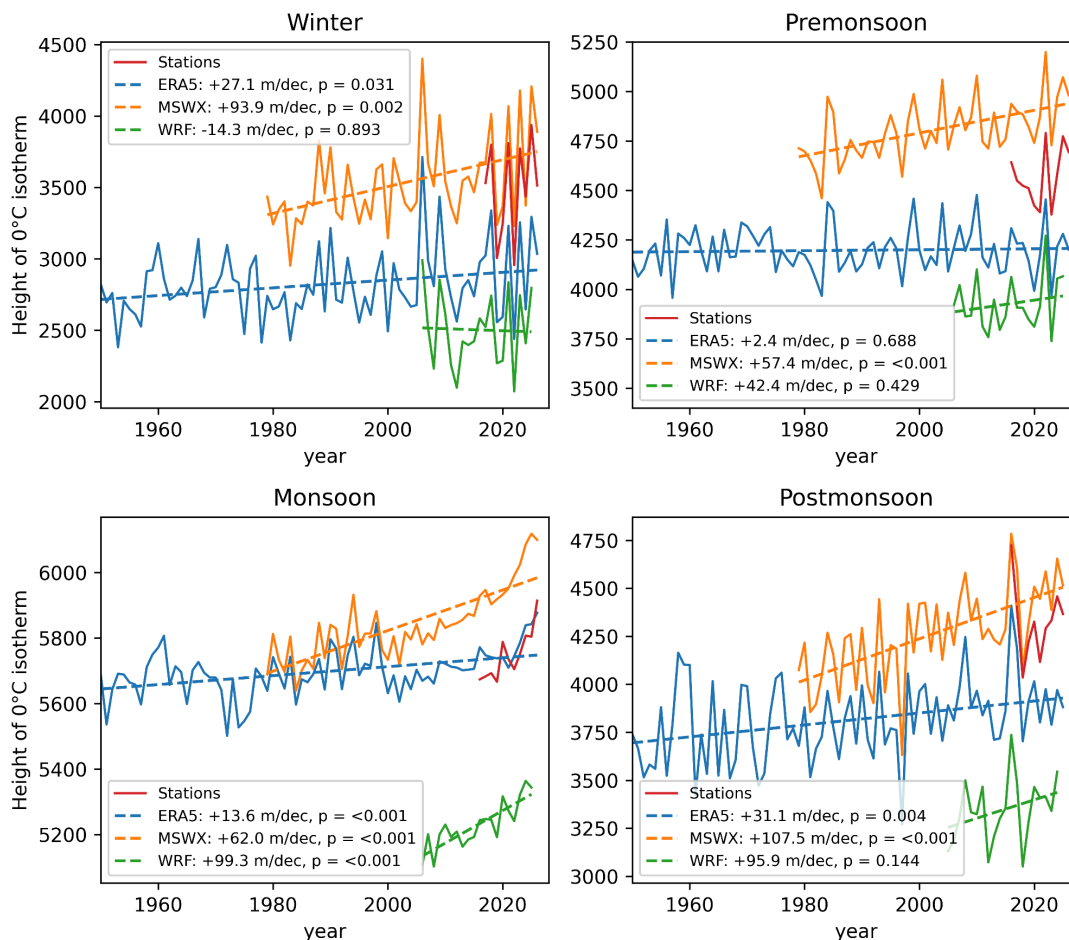


Figure 3.1.4: Time series (solid lines) and linear trends (dashed lines) in the estimated height of the 0°C isotherm for several gridded observation-based datasets and in-situ measurements, for each season of the year. For gridded datasets, we compute the height of the isotherm over the nearest grid cell to the coordinates of the slope failure (28.288708°N, 85.528159°E).

3.1.3 Positive Degree Days

Positive degree days (PDD) account for the overall exposure of a location to temperatures above freezing, measuring the cumulative temperature in excess of 0°C over a given period. Figure 3.1.5 shows the PDD for the 12-month period from September-August each year, with temperature at 5,150m approximated for each dataset as described in section 3.1.1.

All datasets give significant increases in PDD in the historical record. The WRF dataset is substantially offset from other datasets due to its overall cold bias, as also observed in the lower isotherm height (section 3.1.2). Nevertheless, the long-term trends in PDD are consistent with other datasets, with an estimated increase of +34.1°C-days/decade in line with the much longer CHELSA dataset (+35.9°C-days/decade). The smallest increase is observed again from ERA5-Land at +7.1°C-days/decade (restricting this dataset to 1979 onwards increases this slightly to +7.8), and the largest for the in-situ station data, which show that in the past decade the rate has accelerated to +135.4°C-days/decade. Finally, MSWX suggests an increase of 49.5°C-days/decade since around 1980. Overall, it is clear that there has been a significant rise in the cumulative PDD experienced by the glacier each year, at a rate of approximately 35-50°C-days/decade since the 1980s and at an accelerating rate in the recent decade. This increase in positive degree days is driving the negative mass balance seen in the Langtang catchment ([Silwal et al. 2026](#)) and in the glacier recession observed both for Langtang-Lirung Glacier (section 2.3) and in Langtang, as well as across the broader Hindu Kush Himalaya ([Maharjan and Sherpa, 2026](#)).

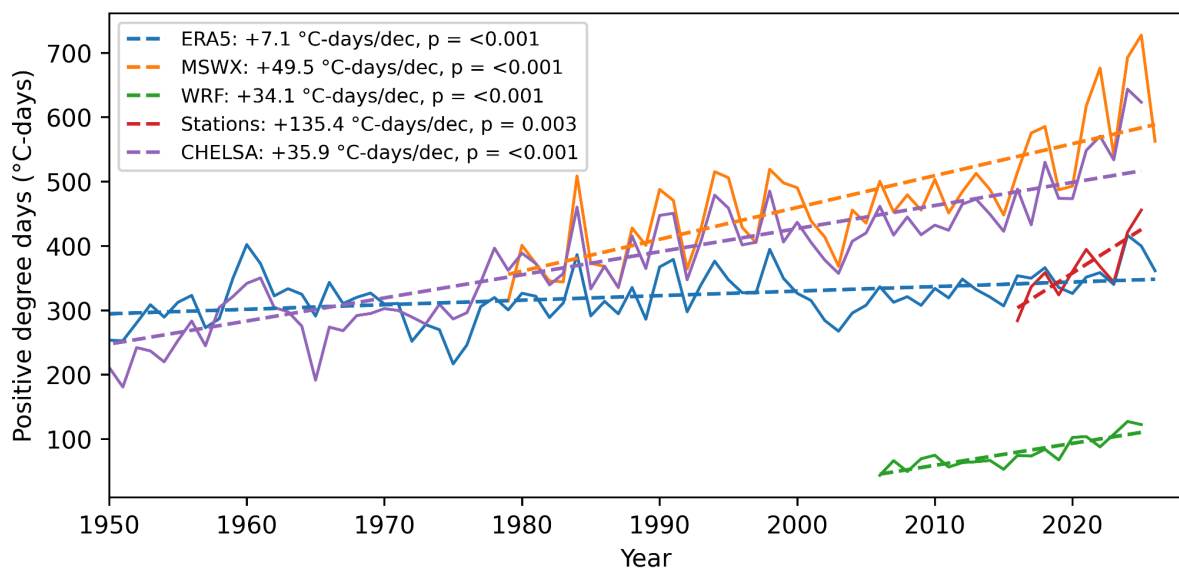


Figure 3.1.5: Time series (solid lines) and linear trends (dashed lines) in positive degree days for several gridded observation-based datasets and in-situ measurements. For gridded datasets, we select the nearest grid cell to the coordinates of the slope failure (28.288708°N, 85.528159°E).

3.1.4 Change per calendar month

Analyses of trends in temperature indices at different spatiotemporal scales (section 3.1.1) and isotherm height in different seasons (section 3.1.2) showed that the warmest period around the monsoon is warming more slowly than the annual average, but with lower year-to-year variability. To further explore changes across the year, we analyse changes by calendar month, both across the region as a whole and for the indices assessed elsewhere in the report. The mean temperature per month is shown in Fig.A3.4.

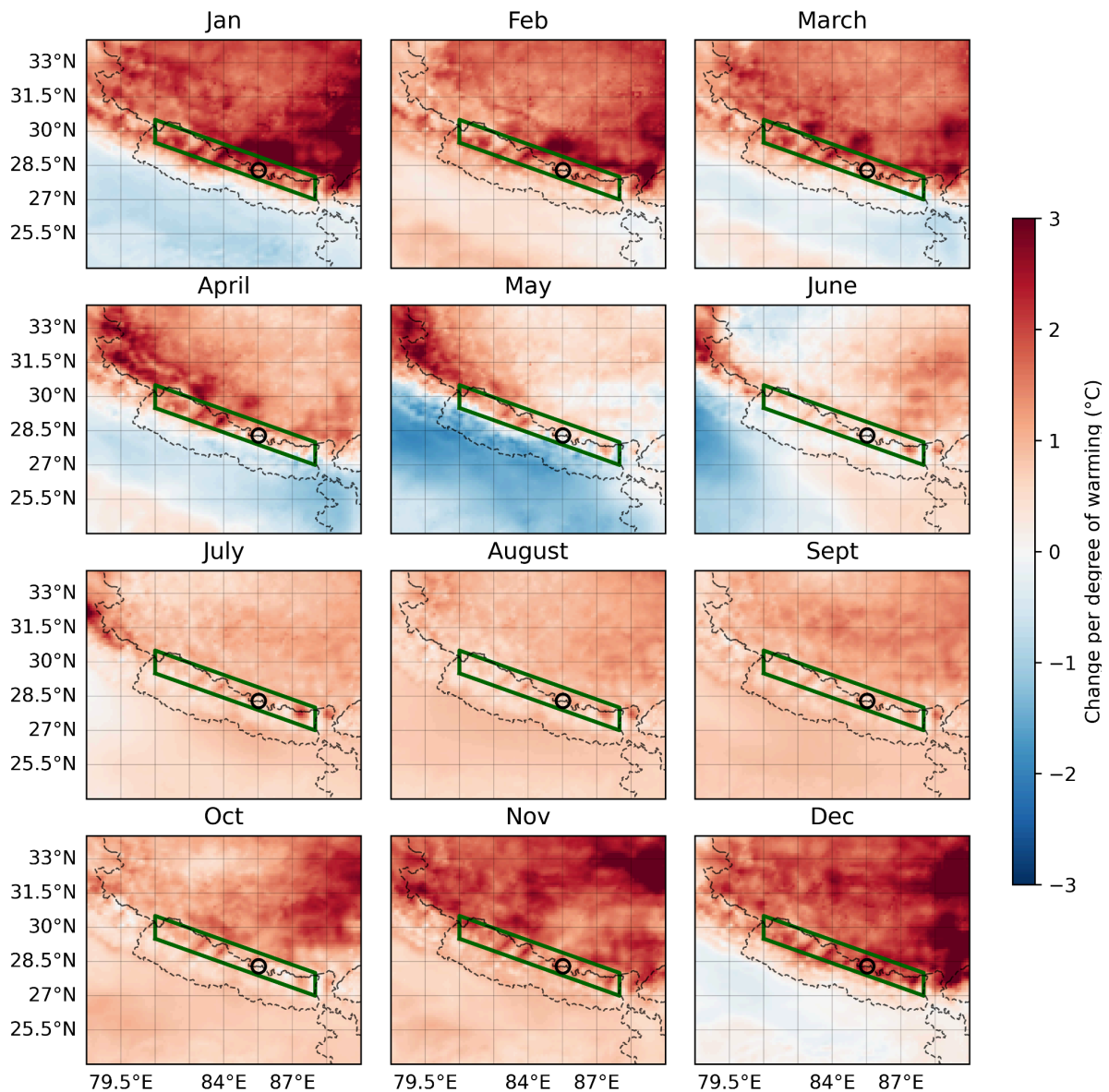


Figure 3.1.6: Change per degree of global warming in the monthly average of daily mean temperature over Nepal and surrounding regions for each grid cell in ERA5-Land reanalysis. The wider Himalayan region is shown with the dark green box and the approximate location of the slope failure is shown by the black dot.

Figure 3.1.6 shows the change in monthly mean temperature in each grid cell associated with each degree of global warming surrounding the study region, from northern India through Nepal and into the Tibetan Plateau, based on the ERA5-Land dataset. It is worthy of note that this dataset was generally warming at the slowest rate of those assessed in other sections. The maps show a pronounced seasonality and spatial pattern to rates of warming. The high altitude regions of the Himalayas, including the study regions, and Tibetan Plateau are warming most rapidly, especially in the December-February period. Meanwhile, in the premonsoon and early monsoon seasons there is an apparent cooling south of the mountainous regions. The core of the monsoon season is most stable, with a consistent but relatively mild warming. This effect has been documented in other studies, with ERA5-derived products generally cooling more than local in-situ measurements and gridded observational data would indicate.

Figure 3.1.7 shows the change per calendar month since 1979 for all datasets in the two study domains: the Himalayan region and the nearest grid cell to the August slope failure event. Here, ERA5-Land shows consistently lower changes in temperature compared to the two other datasets that also go back to 1979, MSWX and CHELSA. With only 20 years of data, the WRF time series has larger uncertainty in the fitted trend than the other datasets, but remains consistent with MSWX and CHELSA in the monsoon period in which variability is lowest. The findings here confirm and build on the trend analyses: in both the wider Himalayan region and the approximate location of the slope failure event, the warm monsoon period is becoming consistently warmer at approximately the rate of global temperature rise, while other parts of the year are warming more rapidly on average, at a factor of 2-3 times the global mean for the coldest months, but with higher year-to-year variability in absolute temperatures.

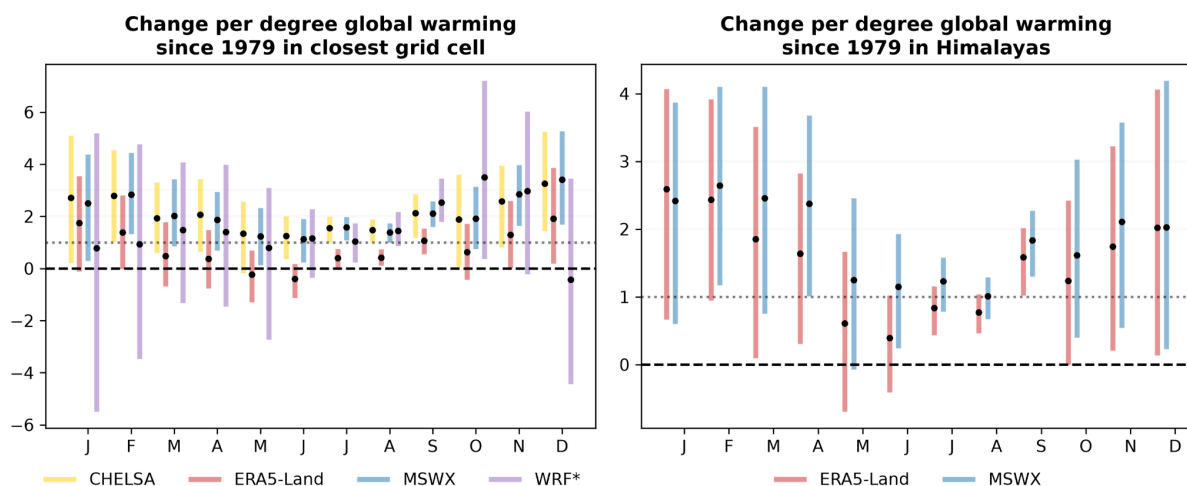


Figure 3.1.7: Change per degree of global warming for each calendar month for the nearest grid cell to the slope failure (left) and the wider Himalayan region (right) based on data since 1979, in several observation-based datasets CHELSA, ERA5-Land, MSWX and WRF. * indicates that WRF only has 20 years of data, starting in 2006 rather than 1979.

3.1.5 Elevation-dependency of warming

The long-term warming rates in high-elevation regions such as Langtang in Rasuwa District are higher than those at lower elevations, a pattern in which higher elevations warm faster than lower elevations under the same greenhouse-gas forcing, known as elevation-dependent warming ([Pepin et al., \(2015\)](#), [Byrne et al., \(2024\)](#)). Elevation-dependent warming accelerates change in mountain glaciers and hydrological regimes, driven by mechanisms such as snow-albedo feedbacks, water vapour and latent heat changes, surface radiative flux shifts, altered surface heat loss, and aerosol effects ([Pepin et al., \(2015\)](#)).

Figure 3.1.8 shows the elevation-dependent warming pattern for the annual mean and for July–August across the domain (20°N–40°N), encompassing the Himalayas for the period 1979–2024. The warming trend for different elevations over 20°N–40°N shows clear amplified warming with elevation in the CESM2 Large Ensemble (LENS2) annual mean, with some spread among individual ensemble members. As a single-forcing large ensemble, the LENS2 mean essentially isolates the forced response to greenhouse-gas and other prescribed forcings, following the CMIP6 historical and SSP370 radiative forcing scenarios (1979–2014 and 2015–2024, respectively).

The Langtang region is represented at a lower mean surface elevation in CESM2-LENS2 (3.986 km) than in ERA5 (4.254 km), reflecting differences in terrain representation over the 85–86°E, 28–29°N grid box. The corresponding annual trends are 0.417 and 0.362°C/decade, respectively; July–August trends are 0.242 and 0.211°C/decade. This signal is less evident in ERA5, whose annual and JA trend profiles do not show a comparably systematic increase in warming with elevation over 1979–2024. Differences may reflect observational/reanalysis uncertainty, internal variability, and contrasts between ERA5 and CESM2-LENS2 spatial resolution and representation of complex Himalayan terrain.

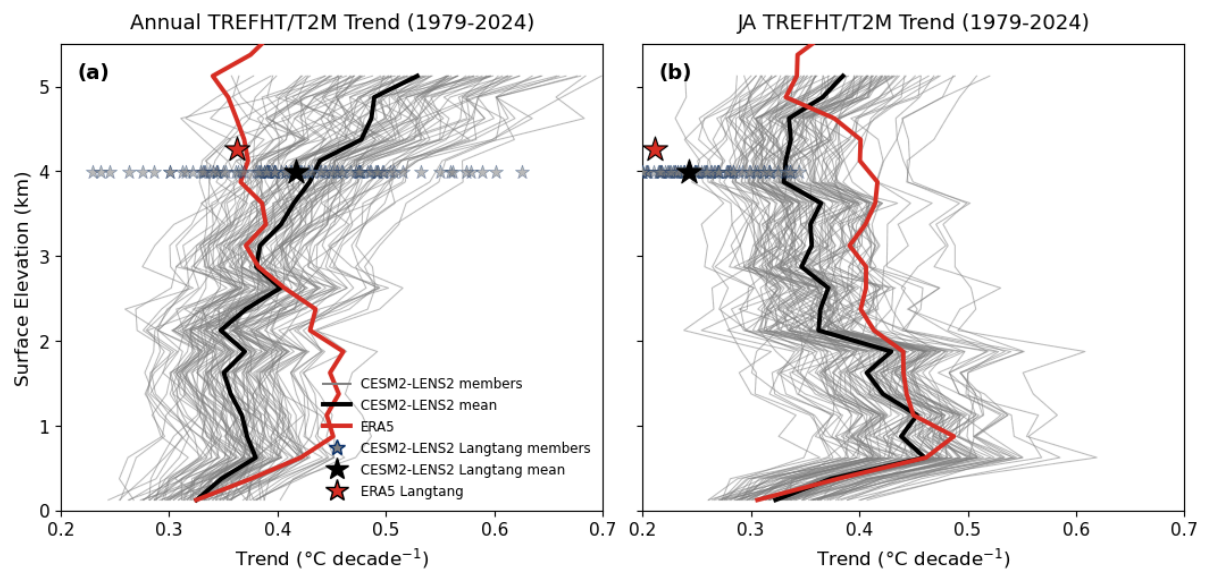


Figure 3.1.8: Elevation-dependent near-surface air temperature trends over 1979–2024 for (a) Annual (b) July–August. Grid-cell trends in CESM2-LENS2 reference-height air temperature (TREFHT) and ERA5 2-m air temperature (T2M) are grouped into geometric surface-elevation bins across the

20–40°N domain. Thin grey solid lines show individual 100 CESM2-LENS2 members, the black solid line shows the ensemble mean, and the red solid line shows ERA5. Stars indicate trends for the Langtang region (blue box) (85–86°E, 28–29°N): grey stars show individual CESM2-LENS2 members, the black star shows the CESM2-LENS2 ensemble mean, and the red star shows ERA5.

3.2 Attribution of trends in temperature

3.2.1 Evaluation of climate models

In the subsection below we show the results of the model evaluation for each location. The climate models temperatures are evaluated against the observations in their ability to capture:

1. Seasonal cycles: For this, we qualitatively compare the temperature seasonal cycles based on model outputs against observations-based cycles. We discard the models that exhibit ill-defined peaks in their seasonal cycles.
2. Spatial patterns: Models that do not match the observations in terms of the large-scale temperature patterns are excluded.
3. Parameters of the fitted statistical models. We discard the model if the model and observation parameters ranges do not overlap.

The models are labelled as ‘good’, ‘reasonable’, or ‘bad’ based on their performances in terms of the three criteria discussed above. A model is given an overall rating of ‘good’ if it is rated ‘good’ for all three characteristics. If there is at least one ‘reasonable’, then its overall rating will be ‘reasonable’ and ‘bad’ if there is at least one ‘bad’. For each framing or model setup we also use models that only just pass the evaluation tests if we only have five models or less for that framing that perform well. Tables of the model evaluation results can be found in Appendix A3.

3.2.2 Synthesis of results

For the spatiotemporal indices described in section 3.1.1 we evaluate the influence of anthropogenic climate change on the change in temperature using observations and climate models. Models which do not pass the evaluation described above are excluded from the analysis. The aim is to synthesise results from models that pass the evaluation along with the observations-based products, to give an overarching attribution statement. Tables of the results of this model fitting are in Appendix A4.

Figures 3.2.1 & 3.2.2 show the changes in intensity for the observations (blue) and models (red). Before combining them into a synthesised assessment, first, a representation error is added (in quadrature) to the observations, to account for the difference between observations-based datasets that cannot be explained by natural variability. This is shown in these figures as white boxes around the light blue bars. The dark blue bar shows the average over the observation-based products. Next, a term to account for intermodel spread is added (in quadrature) to the natural variability of the models. This is shown in the figures as white boxes around the light red bars. The dark red bar shows the

model average, consisting of a weighted mean using the (uncorrelated) uncertainties due to natural variability plus the term representing intermodel spread (i.e., the inverse square of the white bars).

Observation-based products and models are combined into a single result in two ways. Firstly, we neglect common model uncertainties beyond the intermodel spread that is depicted by the model average, and compute the weighted average of models (dark red bar) and observations (dark blue bar): this is indicated by the magenta bar. As, due to common model uncertainties, model uncertainty can be larger than the intermodel spread, secondly, we also show the more conservative estimate of an unweighted, direct average of observations (dark blue bar) and models (dark red bar) contributing 50% each, indicated by the white box around the magenta bar in the synthesis figures.

*Table 3.2: Attributable change in temperature for the annual and July-August average of daily mean temperatures at the location of the slope failure (left) and the wider Himalayas region (right), due to a 1.4°C increase in GMST. Statistically significant changes at the 95% confidence level are shown in **bold text**.*

Data		Change in temperature due to 1.4°C global warming (95% C.I.)			
		Nearest grid cell		Nepal Himalayas	
		Annual	July-August	Annual	July-August
Observations	Past - present	2.16 (0.0469, 4.23)	1.88 (-0.0861, 3.84)	2.05 (0.445, 3.61)	1.34 (0.588, 2.04)
Models		1.89 (1.07, 2.70)	1.43 (0.419, 2.44)	1.95 (1.20, 2.71)	1.66 (1.02, 2.28)
Synthesis		1.92 (0.846, 2.99)	1.53 (0.252, 2.80)	1.97 (1.01, 2.93)	1.52 (0.831, 2.18)
Models only	Present - future	1.89 (1.41, 2.36)	1.37 (0.443, 2.29)	2.07 (1.39, 2.75)	1.71 (1.09, 2.32)

Across both regions and time periods, all datasets show increasing trends with rising global temperature, most of which are statistically significant at the 95% confidence level. Climate models also show comparable changes in magnitude to the observed trends across all indices.

Several clear findings emerge from this analysis. First, changes in annual temperatures are larger than in the warmest months of the year, in line with analysis in section 3.1.4. In the wider Himalayan region covering parts of northern Nepal and the Tibetan plateau, the warmest months of July and August have become approximately 1.5°C (0.83 to 2.2°C) warmer, while the mean annual temperature has risen by about 2.0°C (1.0 to 2.9°C) warmer, due to human influence on the climate. In the vicinity of the slope failure in August 2026, the warmest months of July and August have become approximately 1.5°C (0.25 to 2.8°C) warmer, while the mean annual temperature has risen by about 1.9°C (0.85 to 3.0°C) warmer, due to human influence on the climate.

Projected future changes are directly in line with these findings. Climate models suggest that with another 1.4°C of global warming compared to present, in the wider Himalayan region, the warmest months of July and August are projected to become approximately 1.7°C (1.1 to 2.3°C) warmer, while

the mean annual temperature is projected to rise by a further 2.1°C (1.4 to 2.8°C). Similarly, in the vicinity of the slope failure in August 2026, the warmest months of July and August are projected to become approximately 1.4°C (0.44 to 2.3°C) warmer, while the mean annual temperature is projected to rise by a further 1.8°C (1.4 to 2.4°C). This would lead to even greater changes across high mountain environments.

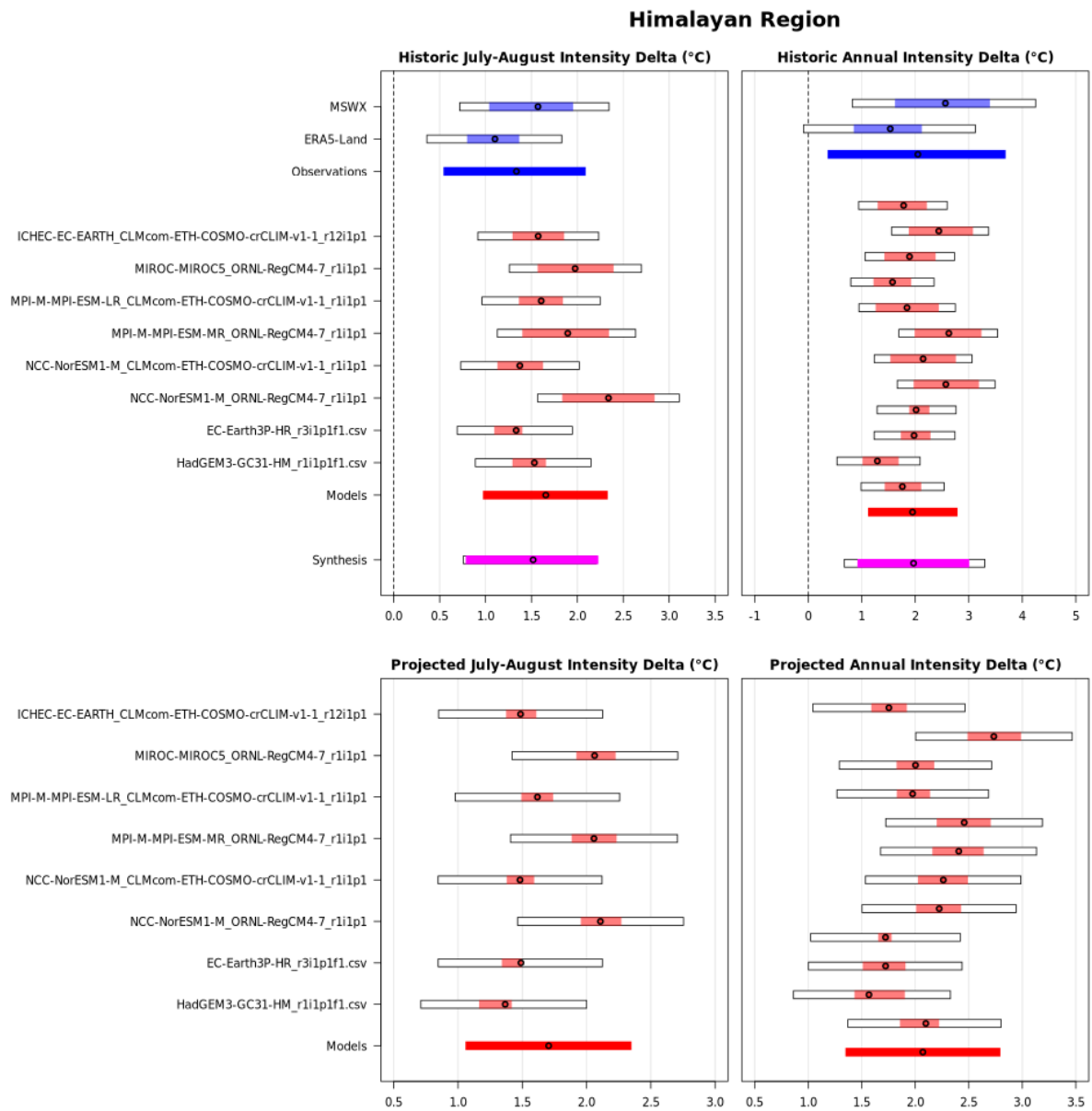


Figure 3.2.1: Synthesis of changes in July-August (left) and Annual (right) temperatures in the Himalayan study region. Changes are shown for a historical period comparing the past 1.4°C cooler climate with the present (top) and for a future period comparing a 1.4°C warmer climate with the present. Observations are shown in blue, climate models in red, and the synthesis in magenta.

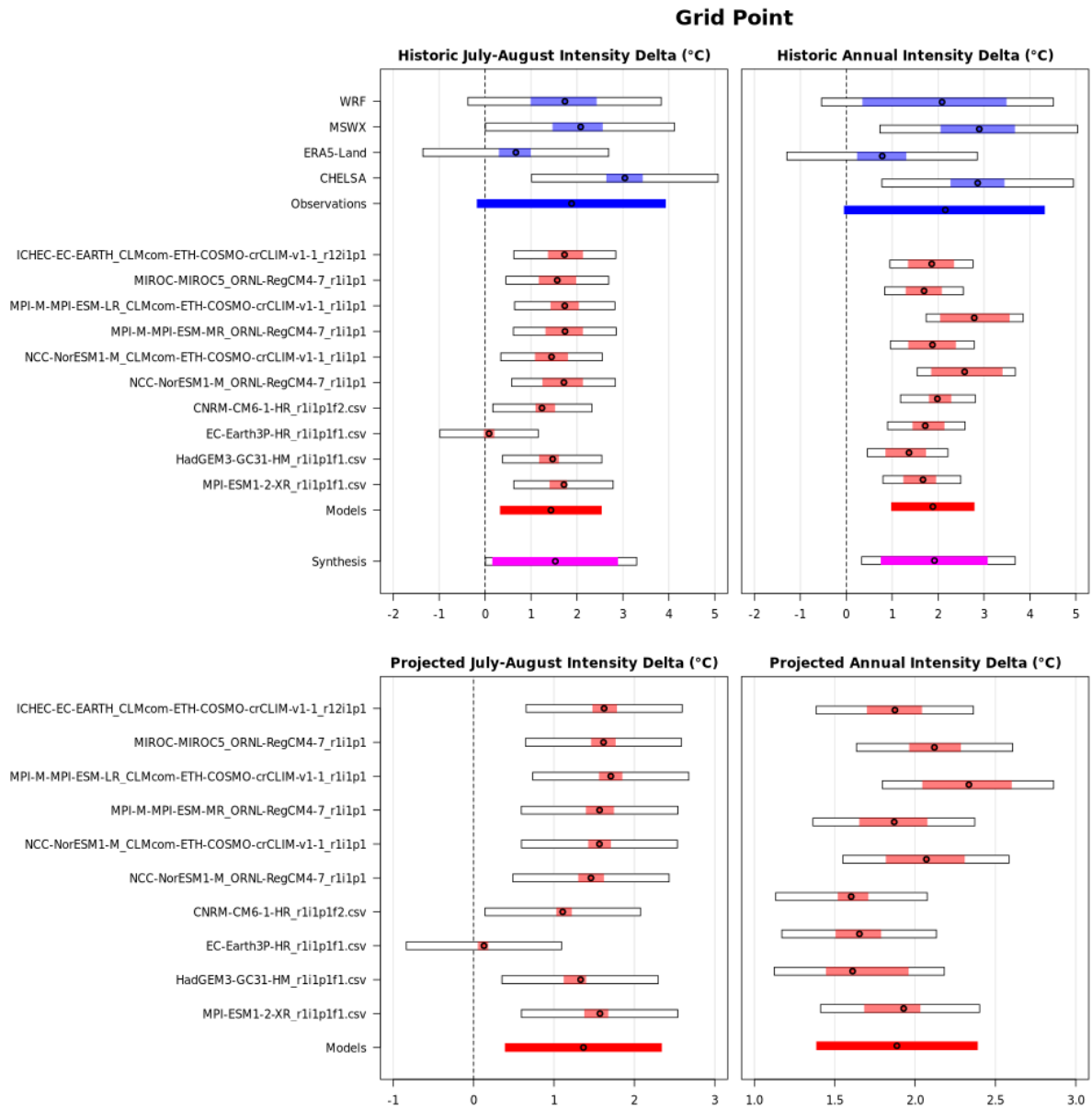


Figure 3.2.2: Synthesis of changes in July-August (left) and Annual (right) temperatures in the nearest grid cell to the slope failure. Changes are shown for a historical period comparing the past 1.4°C cooler climate with the present (top) and for a future period comparing a 1.4°C warmer climate with the present. Observations are shown in blue, climate models in red, and the synthesis in magenta.

3.3 Summary of temperature changes

All lines of evidence show robustly increasing temperatures in the wider Himalayan region and in the proximity of the August 2026 slope failure event as a result of human-induced climate change. All observational and reanalysis datasets and climate models give consistent and statistically significant temperature rises across both of these regions for annual temperatures and July-August mean

temperatures, with increases at approximately 1-1.5 times the global mean temperature rise. These changes are projected to continue at the same rate if the world continues to warm.

This warming can be characterized in multiple ways. At the approximate location of this slope failure event, the 0°C isotherm is rising in all seasons. At longer timescales and using data prior to the satellite era the changes are smaller in the cooler seasons, also partly related to high year-to-year variability. However, in the Monsoon and Postmonsoon seasons and recent decades, the 0°C isotherm has risen at a rate of approximately 50-100 m/decade. The cumulative PDD, an index that relates to the total energy available for melting, has increased at a rate of approximately 35-50 °C-days/decade since 1980 and has likely accelerated in the past decade. Evidence from model analysis and the wider literature suggests that higher elevation regions are warming more rapidly than lower elevations, though this feature is not observed in ERA5 data or when analysing only the Monsoon months of July and August. Finally, we find that across the year, warming rates are variable. The cooler winter months are warming most rapidly at a rate of 2-3 times the global mean. Meanwhile, the monsoon season is warming most slowly but with the lowest variability, and at a rate still slightly above the global mean.

4 Precipitation changes

4.1 Observed changes

The response of JJAS precipitation to 1.4°C of global warming is heterogeneous across the Nepal Himalayas. At this scale, the reanalysis-based product, ERA5-Land suggests a strong wetting tendency, with a best estimate of approximately 48%, and statistically significant. In contrast, the satellite-based products CHIRPS and IMERG suggest overall drying, with best estimates of approximately 22% (statistically significant at 5% s.l) and 11% (but with large uncertainties), respectively. It is important, however, not to interpret the satellite products as necessarily being more accurate than reanalyses: each product has different strengths and limitations, particularly over complex Himalayan terrain, and the divergence between them provides an indication of physical factors contributing to uncertainty rather than reliability of the dataset itself.

A similar heterogeneity is evident at the rock-ice-avalanche location. ERA5-Land once again shows a statistically significant increase in JJAS precipitation of approximately 45%, alongside WRF which gives similar estimates. In contrast, CHIRPS and IMERG indicate more modest drying, of approximately 8% and 7%, although the confidence intervals are wide and encompass zero. Further, when considering only the satellite-based products, the estimated drying is weaker at the rock-ice-avalanche location than across the wider Nepal Himalayas: CHIRPS and IMERG indicate approximately 7–8% drying locally, compared with 11–22% drying across the wider region, highlighting uncertainties due to the high degree of variability likely on account of the complex terrain and high altitudes, challenging data quality.

We additionally consider station observations at the rock-ice-avalanche location. The station-based estimates, based on only ten years of observations (2016–2025), show a strong drying tendency of ~83% for JJAS precipitation. The high-resolution CHELSA and WRF dataset estimates also span both positive and negative changes in best estimates, with wide uncertainties encompassing zeros. These short records and substantial spatial variability in precipitation over complex Himalayan terrain limit our ability to detect a robust climate-related trend at the collapse location. The absence of a statistically detectable trend and/or strong increases (and decreases) in short observed records should however not be interpreted as evidence that climate change has no effect on precipitation; rather, it reflects the limitations in the length and density of the station network, and strong geographical variability.

Changes in the maximum 10-day JJAS precipitation (*JJAS Rx10day*) were also analysed in an effort to gather evidence about changes in extreme precipitation characteristics that may be relevant to the collapse. At the glacier-collapse location, ERA5-Land, IMERG, MSWX, CHELSA and WRF all have positive best estimates for changes in *JJAS Rx10day*, although the associated confidence intervals are generally wide, except for the stations where it is statistically significant in ten years of data. Combined with the physical expectation that a warmer atmosphere will precipitate more, this suggests a possible tendency toward more intense extreme precipitation events under the current warming levels, even where changes in seasonal-mean precipitation are difficult to resolve.

Table 4.1.1: Percentage change in intensity of seasonal rainfall during June to September (JJAS) and the maximum 10-day rainfall in the season (JJAS Rx10day) over the rock-ice-avalanche location

(nearest-grid cell) and the wider region (Nepal Himalayas) between the climate of 2026 and a 1.4°C cooler world. Statistically significant changes are highlighted in **bold**.

Dataset	Percentage change in precipitation intensity due to 1.4°C global warming (95% C.I.)			
	Nearest grid cell		Nepal Himalayas	
	JJAS	JJAS Rx10day	JJAS	JJAS Rx10day
CHIRPS	-7.9 (-28.0 to 17.9)	-21.9 (-47.2 to 16.9)	-21.5 (-34.5 to -5.3)	-27.8 (-46.9 to 3.7)
ERA5-Land	45.4 (27.3 to 66.1)	33.5 (4.9 to 74.7)	48.4 (31.9 to 70.8)	34.9 (9.8 to 70.7)
IMERG	-7.1 (-33.0 to 23.4)	27.4 (-39.7 to 145.3)	-11.3 (-30.2 to 13.4)	15.5 (-20.9 to 90.8)
CHELSA-near est	-9.3 (-42.0 to 50.2)	-2.2 (-34.0 to 63.4)	n.a	n.a
CHELSA-box	-4.4 (-40.0 to 62.1)	5.8 (-30.7 to 70.9)	n.a	n.a
Stations	-83.4 (-94.0 to -35.6)	-55.0 (-84.2 to -31.2)	n.a	n.a
WRF	46.1 (6.4 to 93.2)	16.5 (-22.9 to 191.8)	n.a	n.a

Figure 4.1.1. shows the rainfall and snowfall contributions during JJAS from WRF from 2006-2025, at the rock-ice avalanche location. A linear trend fit to the two datasets shows a decreasing trend in snowfall alongside increases in rainfall, suggesting a shift towards liquid precipitation. As described in section 2.5, this can lead to direct input to the slope rather than acting as water storage, which in turn can increase water supply to fractures and potentially increase fracture-water pressure. This shift could therefore imply that there can be an increase in the amount of water present in the bedrock in the land under the avalanche site, even in the absence of anomalously high total precipitation. However, this analysis is based on only a single dataset with 20 years of data and is not long enough to assess long-term trends without additional evidence.

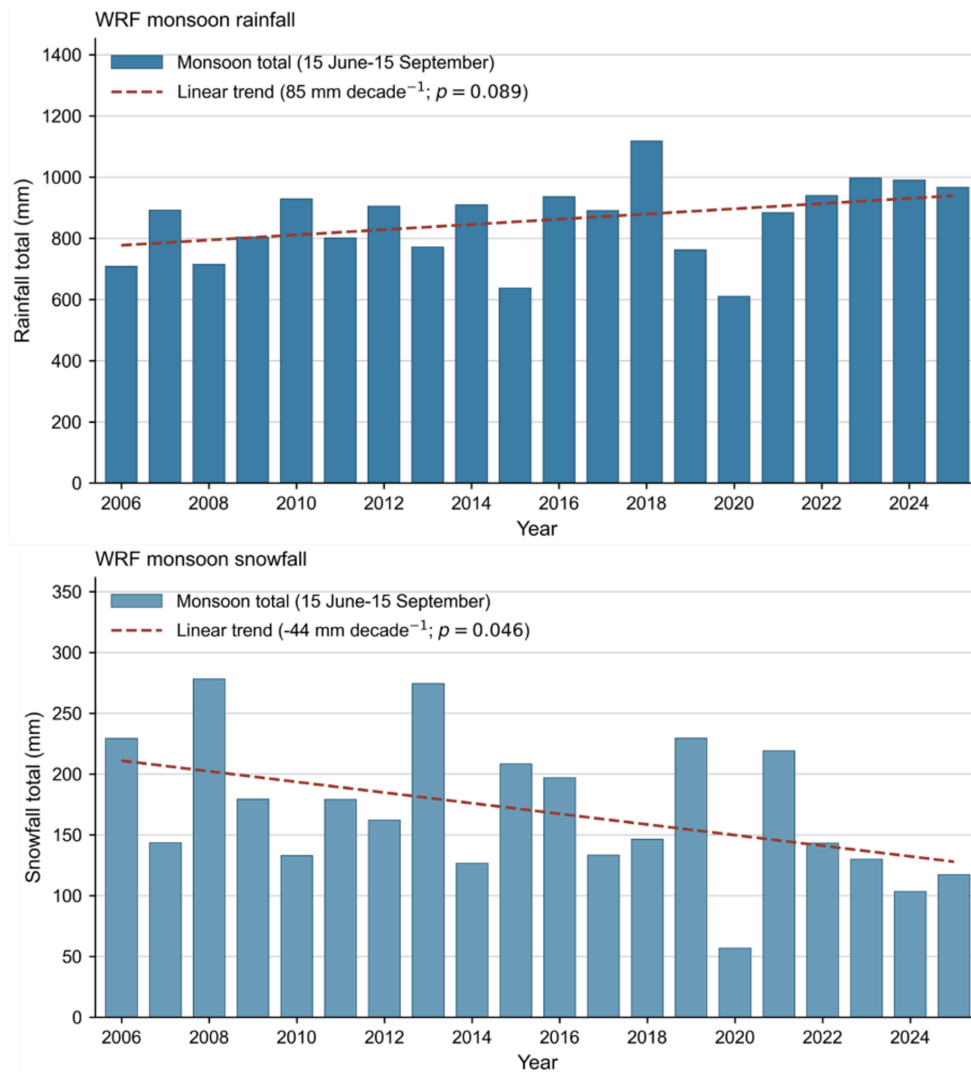


Figure 4.1.1: Total monsoon season (15th June - 15th September) rainfall (top) and snowfall (bottom) from 2006-2025 using the WRF model. Linear trends are shown with red dashed lines.

4.2 Summary of precipitation changes

1. The annual time series of the seasonal precipitation during the monsoon and the winter over the wider Himalayas do not highlight anomalously high precipitation in the preceding monsoon (JJAS) or winter (DJF), that could be used for understanding pre-conditioning factors that led to this catastrophic event. However, exceptionally high precipitation was recorded in the stations during OND 2025, much of which fell as snow, providing a potentially large store of water that, coupled with subsequent warmth, may have increased meltwater in the following year.
2. There is no robust evidence of a detectable change in monsoon season precipitation either at the avalanche location or the wider region, with disagreement in the datasets in both the direction as well as the magnitude of change. This disagreement, with wide uncertainty ranges encompassing no change, is likely an artefact of the strong spatial variability and challenges

of both observing and modelling precipitation across the complex Himalayan terrain, which limits our ability to detect a climate change-related signal (if any).

3. Analysis of the rain and snow contributions from the total precipitation using high-resolution WRF data during the JJAS season show a shift from snow to rainfall in recent years, with more moisture entering fractures in the bedrock rather than being stored at the surface as snow. Further analysis is required to assess long-term trends in this transition.
4. Additionally, this absence of trends in the seasonal precipitation does not preclude changes in extreme precipitation. Most datasets show positive best estimates for the maximum 10-day precipitation in the JJAs season at the rock-ice-avalanche site, consistent with the physical expectation of more intense precipitation in a warmer atmosphere, but with wide uncertainties.
5. Lastly, this also highlights the broader issue of sparse station networks, short observational records, complex terrain and difficulties in measuring snow that limits our ability to confidently characterise precipitation variability and change in high mountain regions such as the Himalaya.

5 Vulnerability and exposure

The Rasuwa Bhotekoshi flood was a catastrophic, high-intensity disaster triggered by a large rock-ice avalanche initiated on the north side of the Langtang range, within Nepal but near to the Nepal-China border, which flowed downslope into the Lhende River in China generating a sudden, debris-laden flash flood that swept down past the Nepal-China border at Rasuwagadhi and down the Bhotekoshi/Trishuli river valley in Nepal. This extreme flow event generated towering water waves that ranged from 10 meters to almost 100m in the upstream regions, tearing through the communities of Rasuwagadhi, Timure, and Syaphrubesi in northern Rasuwa district before rushing down the Trishuli River basin. The surge swept across multiple downstream districts, causing intense loss and damage in Rasuwa and Nuwakot, and flood impacts in Dhading, Gorkha, Chitwan, and Nawalparasi (figure 5.1).



Figure 5.1: Municipalities affected (in orange) and the flow path and extent of the extreme flow event (in red). Source: UNDP (2026).

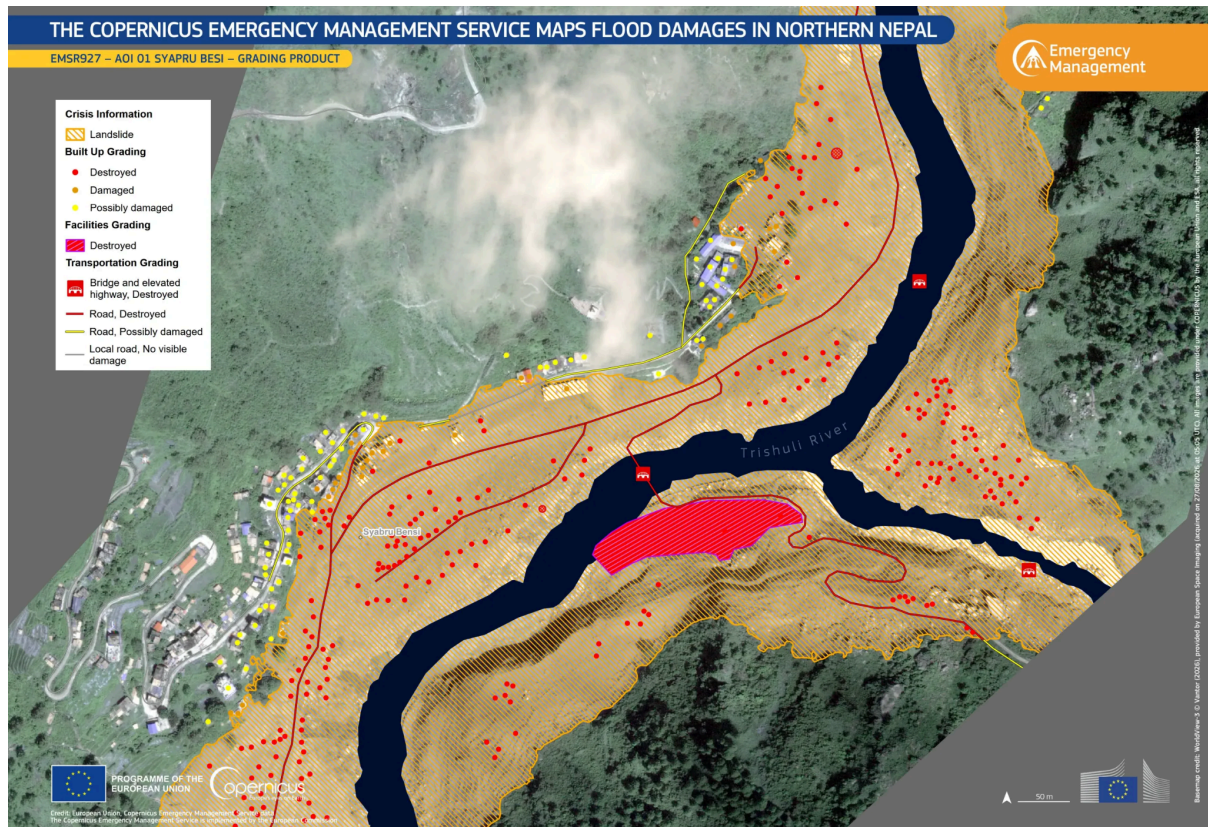


Figure 5.2: Flood extent and footprints of impacted structures in Syaprubesi, Rasuwa District.
 Source: European Union, Copernicus Emergency Management Service data (2026).

About 35 km downstream of the source, in Nuwakot, the second-most severely affected district (NDRRMA, 2026), the valley widens and market towns occupy the riverbanks. The first town impacted in Nuwakot was Betrawati - located at the junction for both major roads that access Rasuwa and home to Uttar Gaya, temple that attracts religious pilgrims.. The timing of this disaster coincided with the Gosaikunda monsoon pilgrimage season, Janai Purnima, which brings tens of thousands of Hindus passing through to the sacred lakes of Gosainkunda in the mountains of Nepal's Langtang National Park (Poudel, 2026). In Betrawati bazaar, a large share of homes were inundated and covered in mud debris (The Kathmandu Post, 2026c; The Rising Nepal, 2026) (figure 5.3). Debris-laden floodwaters also caused widespread damage and deposited mud and debris several meters thick in the larger market towns of Trishuli and Battar, further downstream in Nuwakot. Further down the Trishuli River corridor, in the wider valleys of Dhading, Gorkha and Tanahun, impacts fell mostly on bridges and riverside markets (Peoples' Review, 2026).



Figure 5.3: Flood extent in the Betrawati area, Nuwakot District on the Bhote Koshi-Trishuli river system before and after the flash floods, on 12 and 27 August, respectively. Source: European Union, Copernicus Sentinel-2 imagery ([2026](#)).

While this was unique in its magnitude and the intensity of loss and damage, a range of other extreme flow events generated by cascading mountain hazards have occurred in recent years. Other similar events include the the 2021 Chamoli rock-ice avalanche in India's Uttarakhand state, and 2021 Melamchi debris flood in Nepal's Sindhupalchowk district which ([Maharjan et al., 2021](#); [Shugar et al., 2021](#)) both generated fast-moving debris flows in steep Himalayan valleys, destroying villages and critical infrastructure like hydropower, water supply projects, and bridges.

In July 2025, the same Bhote Koshi-Trishuli corridor hit in 2026, a July 2025 glacial lake outburst flood (GLOF) originating from a supraglacial lake on the Purepu Glacier in China's Gyirong County killed 19 people, destroyed the China-Nepal Friendship Bridge (Miteri Bridge), and damaged multiple hydropower plants along this same river corridor ([Lord, 2025](#); [Pokhrel, 2025](#)). While this supraglacial flood occurred due to a very different set of processes, and the August 26, 2026 disaster under study was not linked to a GLOF, both events indicate the presence of significant multi-hazard risks in this specific basin - both GLOF risks already identified and other emergent risks not yet understood ([Khadka et al 2024](#); [Khatri et al 2026](#)). In the months preceding this massive disaster, infrastructure damaged by the 2025 flood had only just been restored and local economies centered on Nepal-China trade has only recently regained strength. People living in Rasuwa, and others living in similar trans-Himalayan river corridors like the Bhotekoshi-Tatopani corridor through Sindhupalchowk just to the east, face both recurring hazards and compounding patterns of exposure and economic vulnerability.

As the hazard analysis section of this report shows, this catastrophic event occurred in a high-elevation mountain environment that is changing rapidly - where climatic volatility and continued warming are thawing permafrost and altering the stability of glaciers, slopes and bedrock. Rather than focusing primarily on explaining the drivers of vulnerability within this event, we will therefore largely focus on exploring post-disaster recovery, adaptation and development in a future where continued warming seems likely and mountain hazards will continue to evolve. This includes asking where and how communities and critical infrastructure can be safely rebuilt, what this event suggests about risk in other Himalayan river corridors, and how development planning will need to adjust to changes in the risk landscape, while acknowledging both soft and hard limits to adaptation.

5.1 Limits to adaptation

The unprecedented magnitude of this extreme flow event and the scale of impacts within the affected areas highlight a new reality of unprecedented risk, raising questions about the limits of adaptation and the future of risk reduction and management in the region. The IPCC defines hard limits as the point at which ‘no adaptive actions are possible to avoid intolerable risks’, and soft limits are when ‘options may exist but are currently not available to avoid intolerable risks through adaptive action.’ ([IPCC AR6](#)) Soft limits to adaptation can include financial, technological, institutional, knowledge or social barriers ([Thomas et al 2021](#)). As climate change intensifies hazards, constraints that were once considered manageable may become thresholds beyond which adaptation is no longer viable over time. Evidence available at the time of writing indicates a variety of adaptation limits were reached in the context of the Rasuwa Bhotekoshi flood.

There are topographic limits. In the Himalayan context, glacial risk assessment is particularly challenging, as high-altitude environments make field monitoring costly and technically demanding. Due to the inherent geographic constraints of Himalayan terrain that make consistent access difficult, large parts of the Himalayan cryosphere¹ remain inadequately monitored ([Zhang et al., 2026](#), [Azam 2026](#), [ICIMOD 2026](#), [Thakuri 2026](#) [Ahmed 2025](#), [Vishwakarma et al 2022](#), [Borah et al 2022](#)) while undergoing a variety of changes due to climate change ([IPCC 2019](#)). Geographic constraints or topographic-related limits inherent to the terrain also shape and force difficult adaptation and development choices in the disaster-impacted area along the river corridor, where people must choose between developing in flood plains or on steep mountainous slopes. These same constraints are likely to shape difficult questions about reconstruction or relocation and hazard zoning in the wake of this disaster. These are elaborated in 5.2 on topography, 5.4.2 on trade and 5.4.1 on livelihoods.

There is also evidence of technological limitations. Nepal has developed risk assessments and early warning systems for hazards such as floods and GLOFs, but these systems are not designed to detect or capture all mountain hazards, including complex cryosphere hazards such as rock-ice avalanches

¹ The IPCC defines the cryosphere as: “The components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground.” ([IPCC 2019](#))

like this event ([Ahmed et al 2026](#), [Shah & Ishtiaque, 2025](#)). Rock-ice avalanches are comparatively complex and understudied, with hazard assessment methods and monitoring indicators for early warning system usage still under exploration for the Himalayan setting ([Ahmed et al 2026](#), [Wang 2026](#), [Tiwari et al 2024](#), [Zhong 2024](#), [Yang et al 2023](#)). Even if the warning system had been able to detect the initial slope failure and an immediate alert had been issued, estimates show that those furthest upstream at Rasuwgadhi and Timure would have only received a 7-8 minute lead time to evacuate. ([CHWRR, 2026](#)) While this would have been valuable life-saving time in some cases, by and large, it would not have been enough time for the scale of evacuation needed to prevent devastating loss of life, as illustrated in evacuation simulations of other disasters ([Grajadura et al 2022](#), [Chang et al 2024](#), [Suwanno et al 2023](#), [Lv et al 2025](#), [Liu 2025](#)). Additional information on Nepal's early warning system and response efforts are in 5.3.

There are also financial and institutional limits evident in this event. The scale of adaptation needs substantially exceeds the financial resources available in Nepal. According to ICIMOD's Climate Finance Synthesis Report 2025 ([Ali et al 2025](#)), annual global climate finance figures reached approximately USD 1.3 trillion in 2021-2022, predominantly towards mitigation activities in larger economies, however, the Hindu Kush Himalaya region received disproportionately low shares especially for adaptation, agriculture, water management and disaster risk reduction purposes. The glaring financing gap is further evident in ICIMOD's estimate that Nepal will require approximate USD 47.4 billion for climate adaptation between 2021 and 2050, while 88.3% of the climate finance instruments identified in its synthesis were loans rather than grants, and only USD 0.79 billion has been delivered between 2018 and 2021 ([ibid](#)). The scale of destruction also illustrates the limits of incremental adaptation measures and the need for transformational adaptation to protect against present and future risk ([Mishra et al 2019](#)). This is elaborated further in 5.5 on recovery and reconstruction and 5.6 on international cooperation and climate finance.

Socio-cultural and political factors can also shape the limits of adaptation in Nepal's mountain regions. Within the broader watershed and the Langtang region, livelihoods and social systems have historically been closely interconnected with the surrounding mountain and cryospheric environment, while socioeconomic change, changing livelihood patterns and potential weakening transmission of local knowledge are reshaping this relationship and potentially influencing adaptive capacity ([Tuladhar et.al., 2021](#)). Adaptation can also be constrained by fragmented responsibilities, uneven distribution of resources and technical capacity across levels of government, or weak coordination between national, provincial and local governments. ([Gentle et al., 2026](#); [Shrestha et al., 2024](#)). These governance constraints can be particularly important in mountain environments, where risks often cross administrative boundaries and effective risk reduction and adaptation measures require coordination across settlements, watersheds and different levels of governments. Indigenous Knowledge and local knowledge remains an important source of resilience and a long-term resource that can inform situated adaptation strategies in Nepal's mountain communities ([Gentle & Maraseni, 2012](#); [Tuladhar et.al, 2021](#)). Critically, the effectiveness of localized knowledge and strategies can be also challenged when the magnitude, speed or cascading nature of hazards exceeds the range of events experienced within living memory. All these social and political conditions can shape who can access, implement and benefit from adaptation, and can leave some groups exposed to residual risk when hazards exceed existing capacities.

The Rasuwa Bhotekoshi floods are a stark reminder that limits to adaptation are already being reached, with devastating consequences. Transformative actions are needed at local and global levels, across mitigation and adaptation, to avert, minimize and address losses and damages.

5.2 Topography and exposure

In the Hindu Kush Himalaya (HKH), where people settle is dictated by the availability of habitable land, and access to work, infrastructure, education and healthcare. Constrained by topography, growth in the HKH follows a ribbon-like sprawl along the river corridors, so that settlements are disproportionately concentrated in areas of high multi-hazard risk ([Rusk et al., 2022](#)). The Bhotekoshi corridor of Rasuwa is a stark example: it is a glacier-fed, narrow V-shaped gorge with slopes exceeding 35° ([Tsou et al., 2018](#)), where settlements, roads, run-of-river hydropower plants, and Nepal-China border and trade infrastructure are concentrated on the narrow flatlands of the valley floor "where rugged terrain leaves limited space for safe expansion" ([OCHA, 2026](#)). In the 1960s when the Araniko Highway was constructed, many people moved from hillside settlements to the roadside to benefit from economic opportunities ([Basyal, 2021](#); [Oven, 2009](#)). Local land needs, and national development priorities including energy security, trade, tourism, clean and low-emissions growth, have together concentrated settlements and high value assets on the hazard prone flatlands of this gorge, along the Bhotekoshi river ([Rusk et al., 2022](#); [Basyal, 2021](#); [NDRRMA, 2026d](#); [GoN, 2025](#))

This concentration of people and assets in hazardous locations makes risk sensitive development and land use planning particularly important, yet disaster and climate risk are not consistently integrated into land use decisions and development processes in Nepal ([Government of Nepal, 2021](#); [MOLCPA, 2019](#); [MoHA, 2018](#)). Nepal's Land Use Policy identifies rapid and unmanaged urbanisation, internal migration, land fragmentation, and encroachment on forests and other land resources as challenges that complicate safe settlement and disaster risk management ([MOLCPA, 2019](#)). Nepal's policy framework does nevertheless provide a clear mandate for addressing these risks. The National Policy for Disaster Risk Reduction, endorsed in 2018, calls for multi-hazard risk assessment to inform settlement and infrastructure decisions, risk sensitive land use plans at local level, and relocation from unsafe settlements ([MoHA, 2018](#)). The National Adaptation Plan (NAP) 2021-2050 similarly identifies climate risk sensitive land use planning, resilient settlements and infrastructure, and appropriate relocation or retrofitting as core adaptation priorities, including in mountain areas ([Government of Nepal, 2021](#)). Together, these policies and plans point to the need to identify and map multi-hazard risk, use this information to develop and enforce risk sensitive land use plans, restrict new development in unsafe areas, and relocate or upgrade settlements and infrastructure where risks cannot be adequately reduced.

Yet a flood surge of this magnitude, "at a flow an order of magnitude above anything the monsoon normally brings" ([OCHA, 2026](#)) lies beyond what risk-informed land management is designed to do. While land use planning could help reduce risks from regular monsoon floods, it would be difficult to imagine moving entire cities and towns that are built around hundreds of similar valleys downstream of the Himalayas. It points instead to the limits of adaptation in the rapidly warming Himalayas, where damages from floods and landslides are projected to increase considerably, and limits to adaptation will result in inevitable losses and damages ([IPCC, 2022](#)).

5.3 Preparedness, early warning and response

Systems for anticipating, warning of and responding to disasters are essential to reducing loss of life and supporting affected communities. For rapidly evolving mountain hazards, these challenges are compounded by limited predictability, short lead times for rapid onset events, complex multi-hazard interactions which can increase the scale of extreme flow events, and the potential for cascading impacts to disrupt access and critical infrastructure.

5.3.1 Preparedness and early warning

Mountain cryosphere hazards are extremely difficult to monitor at scale, due in part to the sheer number of potentially dangerous landforms in the Himalayas and the complexity of climatic and geologic or geomorphologic factors (often intertwined) that affect instability (Section 5.1). In recent years, a range of technical experts and scientists from across the globe have been developing and testing new systems for monitoring these complex hazards -in Nepal, throughout the Himalayan region, and in other high mountain environments around the globe - with the aim of detecting significant changes and instabilities or deformations early enough to be able to generate alerts or early warnings (ibid). The core challenge is developing systems that can detect and generate alerts for different kinds of hazards, some of them known and some of them unknown, that manifest in different forms and evolve at different timescales.

Generally, the systems built to monitor cryosphere hazards in Nepal to date have focused largely on glacial lakes and GLOF risks. This includes the development of dedicated early warning systems and risk reduction measures at sites such as Tsho Rolpa and Imja Glacial lake ([Kayastha et al., 2024](#); [Gurung et al., 2021](#)). This focus remains evident in the new seven year Green Climate Fund funded project led by the Department of Hydrology and Meteorology (DHM) with UNDP, which was approved in July 2025 ([UNDP, 2025](#)). Critically, the cryosphere hazard landscape is evolving beyond conventional GLOFs. Further, the 2024 Thame GLOF indicates that even small and previously overlooked lakes are dangerous, which prompts a reconsideration of GLOF monitoring approaches as hazard regimes shift across the cryosphere ([Lord, 2024](#)). The July 2025 supraglacial lake outburst flood along the same Lhende-Bhotekoshi river corridor last year highlighted increasing risk from supraglacial lakes, a less familiar and largely unmonitored hazard pathway ([The Kathmandu Post, 2025](#); [Lord 2025](#)). While monitoring of upstream lakes in this transboundary watershed had improved in recent years, monitoring for the kind of rock-glacier failure that triggered this disaster was not included in this program. Himalayan countries like Nepal remain largely unprepared for this kind of catastrophic failure which is not within the scope of existing monitoring systems. ([Ahmed et al., 2026](#)).

The majority of Nepal's operational early warning systems on real-time rainfall and river level monitoring ([Budimir et al., 2020](#)). A live version of this network is visible via the Nepal Meteorological Department's [Rainfall Watch](#) website. Such systems can work well for rainfall-driven riverine flooding, flash floods, or GLOFs where the majority of material is water, and even detect a rapid reduction in river levels when a landslide damming the river is creating a risk of breach floods. The 26 August catastrophe, however, was a sudden and catastrophic event fueled by a hazard chain from an unknown location that overwhelmed these traditional monitoring systems. In short, this rapidly cascading extreme flow propagated faster than the warning chain could operate and destroyed

in-stream monitoring gauges. It also destroyed private sector gauges and seismic stations which had been installed along the river course.

Existing systems could not detect, interpret and communicate the cascading hazard because it fell outside of the hazards it was designed to detect. Several upstream gauges were destroyed and ceased transmitting before warning thresholds could be reached and alerts sent ([CHWRR, 2026](#)). It is estimated that the first mass SMS warning from Nepal's flood forecasting division and subsequent evacuation alerts from district authorities came roughly 38 minutes after the initial failure of rock-ice ([CHWRR, 2026](#)). In contrast, the wave of debris reached the Rasuwagadhi-Gyirong border area around 08:44 NPT, approximately 7 minutes after the seismic signal associated with failure ([CHWRR, 2026](#)). This means, lead time of formal warning issued was effectively negative in the upper settlements of Rasuwagadi, Timure and Syabrubesi of Rasuwa and merely a few minutes for Betrawati/Bidur and Trishuli Bazaar of Nuwakot. Lead time was higher for less affected regions farther downstream, such as Dhading and Chitwan.

Nepal's National Anticipatory Action Framework provides an important foundation for forecast-based action ([NDRRMA, 2026](#)), but these systems are meant to operate in the context of hazards for which sufficiently reliable forecast information with lead times and triggers can be established, rather than rapidly evolving, cascading mountain hazards. This limitation is consistent with a recent report looking back at a decade of anticipatory action ([Stephens et al., 2026](#)), which highlights the need for anticipatory action systems to evolve beyond historically derived and understood hazards to address emerging, compound and difficult to forecast risks and cascading impacts.

The content of the initial mass SMS from the flood forecasting division may also have limited its protective value. The alert described a “large flood” and urged residents along the Trishuli to remain in a “safe location with high alert”, but failed to communicate the exceptional scale, expected timing of the flood, nor clear evacuation instructions. One post-event news report described the wording as similar to routine monsoon advisories, with limited information to act on ([Mongbay, 2026](#)) - signalling an area for potential improvement in localized risk communication. This communication challenge amid the ongoing mobile network disturbance may have been compounded by recent experiences of flooding in the same corridor, including the destructive July 2025 Bhotekoshi flood, which occurred just 14 months earlier ([NIMJN, 2026](#)).

The event also demonstrated the critical value of trusted informal communication like personal phone calls from relatives and friends upstream which in some cases conveyed the immediacy and seriousness of the threat more effectively than the generic mass SMS ([Mongbay, 2026](#); [Reuters, 2026](#)). At the same time, reliance on the informal networks only can also introduce risks of misinformation, delays, and unequal access, particularly for people without connections to those upstream ([Zhai et al., 2023](#); [Shrestha et al., 2021](#)). The fact that phone calls within social networks did, in fact, save lives during this event points to the value of cultivating these networks and alerting practices, as a system that adds valuable redundancy and may complement other more technologically advanced methods of alerting and risk communication.

5.3.2 Immediate response, rescue and relief

The Government of Nepal mobilised search and rescue operations through security forces, immediately after the flood, with first army helicopter dispatched for rescue at 9:45 am, and by the end of the day 69 helicopters flights had rescued 351 people by air with more than 13,000 security personnels mobilised ([Radio Nepal, 2026](#)). The response subsequently scaled up to around 19,000 security personnel and 16 helicopters by 30 August and by September 12, 13,728 had been rescued, 8,615 treated and 3,434 accommodated in holding centres across Rasuwa and Nuwakot, ([NDRRMA, 2026a](#) [MoFA, 2026](#)). The exceptional scale and complexity of the event challenged the ability of existing disaster response systems, even when rapidly mobilised, to reach and assist all the affected communities in a timely manner.

The destruction of multiple hydropower facilities along the Bhotekoshi/Trishuli river corridor subsequently required specialised tunnel rescue operations to reach people trapped in underground hydropower tunnels and powerhouses, prompting the Government to draw on international technical assistance and rescue teams from India, China, the Republic of Korea, Australia, UAE and Malaysia ([MoFA, 2026](#)). The Government also established a Rescue Request Portal to bring information on rescue, relief, missing and found persons, emergency contacts and financial assistance together on a single platform ([TechPana, 2026](#); [Government of Nepal, 2026](#))

The overall disaster response remained government led, with humanitarian agencies supporting national and local authorities through established coordination mechanisms. Nepal Red Cross Society (NRCS) simultaneously activated its Emergency Operations Centre and emergency response capacity, supported by the wider Red Cross and Red Crescent Partners. IFRC released nearly CHF 1 million through its Disaster Response Emergency Fund immediately after the disaster and subsequently launched a CHF 25 million Emergency Appeal to support the NRCS response and early recovery efforts ([IFRC, 2026](#)). The United Nations and humanitarian partners also launched a US\$49.6 million Flash Appeal to support NDRRMA for a fourth month response plans, targeting more than 84,000 people and aiming to complement the government-led response across critical humanitarian sectors. ([UN in Nepal, 2026](#)). Nepal has also received relief supplies and humanitarian assistance from several countries and international partners ([MoFA, 2026](#)). Additional humanitarian organizations supporting response efforts include CARE, Save the Children and Oxfam, among others ([Oxfam 2026](#), [CARE, 2026](#); [Save the Children, 2026](#)) Destruction of roads and bridges is a key barrier in relief efforts, hindering humanitarian access and delivery of emergency supplies. ([Kathmandu Post, 2026](#))

5.3.3 Transboundary collaboration

Nepal and China have an established bilateral framework for cooperation on disaster risk reduction and emergency response, strengthened during Chinese President Xi Jinping's state visit to Nepal in October 2019. During the visit, Nepal's Ministry of Home Affairs and China's Ministry of Emergency Management signed a Memorandum of Understanding (MoU) on Cooperation in Disaster Risk Reduction and Emergency Response, while the Joint Statement issued by the two governments reaffirmed their commitment for this cooperation ([Government of Nepal & Government of China, 2019](#); [MoFA of Nepal, 2020](#)). During the August 2026 event and its aftermath, cooperation between the two countries did take place, including the immediate contact between China Meteorological Administration (CMA) and China's Ministry of Water Resources with Department of Hydrology and Meteorology (DHM) of Nepal for exchange of hydrological and meteorological information ([MoFA of China, 2026](#)). At the same time, the event also highlighted the value of having more systematic and institutionalised arrangements for transboundary earth observation, research, and risk information

sharing as an opportunity to enhance routine, timely and operational exchange of early warnings on rapidly evolving mountain hazards upstream of the border.

5.4 Economy and livelihoods

5.4.1 Communities and livelihoods

The population of the disaster-affected area includes a variety of different communities. Within this region, the largest number of people identify as Tamang, an indigenous ethnic group, that represents the majority of the population in Rasuwa district (69%) and a near majority in Nuwakot district (43%). Rasuwa's remaining population includes Hill Brahman, Ghale, Gurung, Chhetri and Newar communities, while Nuwakot also has substantial Hill Brahman (17%), Chhetri (12%) and Newar (8%) populations ([NSO, 2021](#)).

Historically marginalized, Tamang people continue to face gaps in political representation, education, and income ([Lama, 2022](#)). Traditionally the Tamang were hill-slope farmers and herders ([Kunwar & Pandey, 2014](#); [Rai et al., 2025](#)) yet their agropastoral livelihoods are coming under growing climate pressure. Studies in Nepal indicate that snow and rain no longer arrive when expected, dry spells last longer, hailstorms are more frequent, high pastures are shrinking, crop yields are falling and snowmelt is accelerating ([Merrey et al., 2018](#); [Rai et al., 2025](#); [Rayamajhi & Manandhar, 2020](#); [Rai et al., 2025](#)). Springs are also drying as a result of road and infrastructure construction, earthquakes, and climate change ([Thapa et al., 2023](#); [ICIMOD, 2015](#)). These pressures are further compounded by youth outmigration ([ICIMOD, 2015](#); [ICIMOD, 2026](#)). In the impacted areas of Rasuwa and Nuwakot, as elsewhere across Nepal, declining water and pasture in the high villages, together with displacement after the 2015 earthquake ([Rieger, 2021](#)), have made lives in the hill slopes risky and harder to sustain. At the same time, roads access, infrastructure development and the prospect of trans-Himalayan trade have pulled people towards the valley floor, concentrating settlements along the river corridor ([Cambell & Smadja, 2014](#); [Murton et al., 2016](#), [McAdoo et al., 2018](#)).

Vulnerability was already high. Before the floods, in the 17 municipalities, 76% of residents lived in areas more vulnerable than the national average; 67.4% of their population was employed in agriculture (57% nationally) and 15.9% were aged 60 or over (12.5% nationally) ([UNDP, 2026](#)). Disability prevalence in Rasuwa and Nuwakot exceeded the national rate at 2.6-2.8% (against 2.2% nationally), women's literacy was behind men's by 13.4 percentage points, and only 23.8% of households had land or housing registered to a woman. While exposure to the floods was the determinant of who was impacted in this disaster, how quickly and fully people are able to recover is likely to be dependent on social and economic factors. For example, in the aftermath of the floods, Tamang women in Rasuwa could face documentation, language and mobility barriers ([OCHA, 2026](#)). These pre-existing vulnerabilities now will shape recovery for the affected population.

The RDNA reports that an estimated 7,570 private buildings, 83,17 households and 32,963 people are affected across 15 local levels. Over half of the buildings are concentrated in Nuwakot (52%), followed by Rasuwa (24%) and Dhadhing (19%). The Gosaikunda rural municipality in Rasuwa, which contains the settlements of Timure and Rasuwagadhi, alone accounts for 1,043 buildings. The

total cost of damage to homes and households assets is estimated to be USD 422 million, whereas the total cost of recovery is estimated at USD 633 million ([NDRRMA, 2026d](#)).

The RDNA's crop inventory records 1,806 hectares of land damaged, of which 1,669 hectares is rice paddy. This is estimated to result in a production loss of 7,687 tonnes. Agricultural damage is estimated at USD 7.2 million and recovery needs at USD 9.4 million, covering restoration of cultivable land, drainage and supplying seeds, fertilizers and tools etc. Longer-term recovery plans include soil rehabilitation, and restoration of productive capacity where immediate cultivation is not possible. Resumed cultivation will depend on sediment depth, drainage, soil conditions, irrigation functionality and access to seeds, fertilizers and other inputs. Livestock and poultry damage is estimated at USD 9.6 million, with recovery needs of USD 11.5 million, with the RDNA models that 252,445 animals and birds were affected, but not verified dead ([NDRRMA, 2026d](#)). Among those hit were Bidur farmers who had spent two years adopting climate-resilient practices ([The Kathmandu Post, 2026](#)).

5.4.2 Trade infrastructure

Flood risk in the Rasuwa corridor is closely tied to the concentration of infrastructure within a narrow, steep-sided river valley that has long served as a trans-Himalayan trade route. The Rasuwagadhi corridor is a centuries-old caravan route to China that was converted to a motorable crossing in 2014 and has been significantly upgraded in the years since ([Murton et al., 2016](#)). When the 2015 earthquake closed the main trade route at Tatopani border, its traffic shifted to this crossing, which was then formalised as an international border in 2017 ([Nepal Economic Forum, 2025](#)). In the years prior to the disaster, this corridor became Nepal's primary and busiest route for trade with China ([Nepal Economic Forum, 2025](#)). It is also at a lower elevation compared to alternate high pass trade routes, and is the preferred route around-the-year.

Customs buildings on both sides of the Nepal-China at Rasuwagadhi were completely destroyed by the disaster. The Government of Nepal estimates that total damages to its customs facilities at USD 6.2 million ([NDRRMA, 2026d](#)). Out of the 82 kilometers Galchhi–Trishuli–Mailung–Syabrubesi–Rasuwigadhi road, considered a strategic trade route by the government, 69 kilometers of road was damaged by the flood. The 55 kilometers Betrawati–Rasuwigadhi section was completely damaged and alone accounts for 84% of the corridor's road damage of USD 146 million. 13 motorable bridges in Rasuwa and 14 in Nuwakot were completely washed out by the floodwater. Road recovery needs are put at USD 364 million and bridges at USD 120 million ([NDRRMA, 2026d](#)). At the time of the first situation report it was reported that disruption was expected to continue for a prolonged period, and that all main highways in Rasuwa were closed ([NDRRMA, 2026a](#)). The RDNA stresses that road access, bridges, customs, freight and utilities are interdependent and restoring only an individual asset may be insufficient to restore trade. The RDNA does not cost the loss of trade or customs revenue, while noting that trade diverted to other routes is not lost ([NDRRMA, 2026d](#)). With limited alternative routes, damage to a bridge or road section in this area can interrupt cross-border trade, isolate communities, and disrupt access to critical services until repairs are complete ([Khatri et al 2025](#)).

5.4.3 Hydropower Development

Hydroelectric power plants are a critical aspect of Nepal's overall economy and account for 90-100% of Nepal's total domestic power generation capacity, which currently stands at around 4,300 MW. To ensure energy security, reduce dependence on petroleum imports from India, and meet its 2045 net-zero carbon emissions commitment, the country has rapidly expanded its hydropower capacity over the last decade ([Nepal Economic Forum, 2022](#); [Aryal et al., 2024](#)).

Damage to Nepal's energy infrastructure was the most pronounced during this disaster. The RDNA reports damage to 13 hydropower projects (7 operating and 6 under-construction plants) with a combined capacity of 759 MW ([NDRRMA, 2026d](#)). Around 12% of Nepal's operational hydroelectric generation was estimated to be disrupted, and damage to projects still under-construction will affect Nepal's future power supply ([UNDP, 2026b](#)). Some of the largest projects that were severely impacted were located along the main channel - including the Rasuwagadhi HPP (111MW, complete), the Upper Trishuli 1 HPP (216MW, under construction), the Rasuwa-Bhotekoshi HPP (120 MW, under construction), and the Upper Trishuli 3A HPP (60MW, complete). Transmission infrastructure, such as substations and towers were also heavily damaged by the erosive force of the flood; and a 25 MW solar plant in Nuwakot was also destroyed. ([MEWRI 2026](#))

Official estimates from the RDNA, dated September 11 2026, put the damage to hydropower and transmission assets at approximately USD 889.21 million. Further economic losses related to hydropower are estimated at USD 108 million based on an estimated 2,520 GWh of lost annual generation revenue, and an additional USD 2 million loss has been calculated, accounting for foregone energy royalties. The overall recovery needs for the energy sector, including hydropower and related infrastructure, are estimated at USD 2.58 billion ([NDRRMA, 2026d](#)). Less than 1% of this is for early recovery in the first six months - representing the need to prioritize repair of transmission assets, substations, and distribution. The remainder is allocated to longer-term recovery that includes the restoration of damaged generation and grid assets, and completion of on-going construction-stage projects. The RDNA notes that recovery needs exceed damages and losses because they include disaster risk reduction and resilience measures. It also notes that this gap is largest for the energy and DRR estimates, which remain subject to detailed engineering, financing and implementation review ([NDRRMA, 2026d](#)). This disaster also highlights broader issues about insurance and insurability of hydropower and other critical infrastructure. While some of these projects were partially insured, others were not. Preliminary commercial claims filed with the Nepal Insurance Authority stand at NPR 25.87B. ([Nepal News 2026](#))

Hydropower projects built along rivers in the Upper Trishuli (Bhotekoshi) watershed in Rasuwa and Nuwakot's have become an important source of electricity generation for Nepal. The original Trishuli Hydropower Station in Nepal in Nuwakot was one of Nepal's first, completed and opened in 1967 - and the projects that have since been built along the main river channel and its tributaries over the past 20 years is the result of decades of planning and construction ([Lord 2016](#)). The steep gradient and perennial river flow from the glaciers makes the Bhotekoshi/Trishuli corridor ideal for run-of-river hydropower ([Climate Technology Centre and Network, 2016](#); [Aryal et al., 2024](#)). Multiple hydropower projects are located along the Rasuwa river system, including both operating and planned facilities, with intakes, weirs, powerhouses, tunnels and associated worker camps are often located close to the valley floor, where they are exposed to high-energy floods and debris flow. This extreme flow event overwhelmed and swept away the main diversion dams in the river corridor, along with above ground powerhouses and infrastructure like desanding basins. Project offices, workers'

residences, and other hydropower project facilities were also swept away, and the entrances to powerhouse and access tunnels were buried in thick debris, leading to significant casualties within the hydropower workforce. Hydropower projects are required to have protocols for disaster preparedness, yet the scale and speed of this event exceeded all expectations and most risk mitigation measures ([ICIMOD 2018](#)).

Hydropower development in Nepal and the broader Himalayan region requires reckoning with a range of different potential hazards and operational risks. Some of these risks are more comprehensively assessed than others, and risk management is often built into project designs - yet chronic risks like seismicity and new risks like climate change add significant layers of uncertainty (cf. [Schwanghart et al 2017](#); [Lord 2018](#); [Huber 2019](#); [Lord et al 2020](#)). Recently, some scientists have explicitly pointed out the growing risk of rock and ice avalanches to hydropower systems in the Himalayas and other mountain regions of Asia ([Zhong et al 2025](#)). Unfortunately the majority of hydropower projects now built were designed and approved before the scale of these risks was fully appreciated.

Generally speaking, hydropower projects are designed to withstand a specific level of flood, or the “design flood” - for example the size of a flood with an estimated return period of 100 years, or “a 100 year flood”. Low-probability extreme events like this disaster far exceed these scenarios, overwhelming any plans or physical mitigation structures put in place. Again, climatic volatility and the uncertain impacts of climate change are also changing the risk landscapes - and several extreme events have damaged hydropower projects in recent years. Similarly, analyzing the reasons why the in-stream infrastructure for the Melamchi Drinking Water Supply Project was not prepared for an event like the 2021 Melamchi debris flood, scientists argued that conventional hydrological design standards—which calculate flood risk primarily based on historical water discharge volumes—drastically underestimate extreme sediment loads, debris bulking, and massive riverbeds rising or dropping due to scouring or aggradation ([Chen et al 2024](#)). Extreme flow events from areas where risks have long been appreciated, such as the Teesta basin where the 2023 South Lhonak GLOF devastated hydropower projects ([Sattar et al 2025](#)) represent one kind of risk. Extreme flow events from unforeseen locations, caused by cascading hazards rather than lakes which can be more easily mapped, represent a kind of risk assessment and monitoring problem. In this vein, the 2021 Chamoli disaster - which was also triggered by a rock-ice avalanche and also destroyed hydropower projects - represents another relevant example and another precedent event ([Shugar et al 2021](#)). In short, as the intensity and frequency of cascading disasters like this grows, the hydropower sector needs to carefully assess expanding multi-hazard risks.

To manage some of these risks, many hydropower projects in the Himalayas build powerhouses and other facilities underground inside the mountains, in part to protect them from flood risks. But again, hydropower projects have not been designed with a catastrophic event of this scale in mind - and the high debris content of this extreme flow event effectively buried the access points to these tunnels under thick debris deposits. During this event, hundreds of workers in the hydropower sector were tragically trapped in subterranean tunnels in the mountainside. Joint search and rescue operations were conducted by the Nepal Army and other security forces, international experts, specialized engineers, and volunteers for over two weeks. As of September 7th, 900 hydroelectric workers were missing with 121 suspected to be trapped in hydropower tunnels. ([Reuters 2026](#)) The Upper Trushuli-1 project appears particularly impacted, with around 576 workers missing ([ABC News, 2026](#)).

In this case, it is also important to note that the 2025 glacial flood along the Lhende-Trishuli corridor also highlighted a preview of these potential risks - impacting several of the same hydropower projects (at a lesser scale) and demonstrating that these and others could be exposed to a large transboundary flow event ([Khatri et al 2025](#)). Research on transboundary flow scenarios also highlighted the vulnerability of critical infrastructure within this watershed and others in central Nepal ([Khadka et al 2024](#)).

At a broader scale, this disaster highlights systemic risks to hydropower development that exist in basins across Nepal, highlighting the need for rigorous multi-hazard impact assessment that includes upstream cryosphere hazards and other emergent risks, conducted at the cumulative or watershed scale. This disaster may catalyze a broader rethinking of hydropower development plans across Nepal, with greater attention to risk-sensitive planning and the development of early warning systems to protect people and assets at hydropower sites.

5.4.4 Tourism

Tourism is a pillar of Nepal's national economy and made up 6.4% of Nepal's GDP in 2024 ([World Bank, 2025](#)). Tourism is even more important within local economies in areas where tourists, international and domestic, spend money across accommodation, food, transportation, gear, and technical expertise. In some regions, the trekking and mountaineering sector employs climbing specialists, guides, sherpas, and porters making tourism a key livelihood for mountain dwellers that employs about 15% of the workforce ([World Bank, 2025](#)).

Syabrubesi, one of the most impacted settlements in this river corridor, is the road-end entry point to the Langtang Valley, which is consistently one of the top 5 trekking destinations in Nepal - and where tourist numbers exceed the local population during peak trekking season. This crossing is also the shortest overland road route accessible by road to Kailash Manasarover, a major pilgrimage site for both Hindus and Buddhists. For example, 53,742 people crossed this area in 2025/26 fiscal year - up almost 21% since the previous year, despite the border opening for only a seven-month period due to the July 2025 glacier lake outburst flood ([Artha Sarokar, 2026](#)).

While the RDNA does not assess tourism as a sector, it looks into the scale of the impact on the hospitality economy. An estimated 1,259 hotel and restaurant establishments were affected, with damage of roughly USD 62 million and reported annual losses of about USD 193 million. Langtang National Park facilities at Timure, Syabrubesi, Mailung and Bandare were damaged, although the PDNA does not account for the impact on the biodiversity and ecosystem services in the National Park. Access to pilgrimage destinations, including Gosaikunda, was interrupted ([NDRRMA, 2026d](#)).

Climate change intensifies inequities. Rapid permafrost thaw and glacier melt and erratic weather increase hazards, rendering traditional environmental knowledge less reliable. About 150 km east of the Trishuli valley, a 2014 disaster in the Everest region's Khumbu Icefall illustrates the disproportionate risks faced by mountain workers, when a serac (large ice tower) collapse killed 16 Sherpas in one day ([Thapa, 2026](#)).

5.5 Climate-smart recovery and reconstruction

The floods swept through communities still recovering from social and economic consequences of the 2015 earthquake, the 2020 COVID pandemic, and the 2025 supraglacial outburst flood, bringing another disaster to people who had already endured economic losses, and displacement. In some places like Rasuwa and Nuwakot, large percentages of the population and settlements were washed away by the disaster with thousands of people still unaccounted for, instantly changing the composition of these districts with unknown consequences for what happens next.

The choices people face around “what’s next” are complex, especially given Nepal’s multi-hazard context. Where exposure to catastrophic or repeated hazards cannot realistically be reduced to an acceptable level, voluntary relocation may need to be considered. Such decisions should be community-led and adequately supported, taking into account not only physical safety but also access to livelihoods, services, social networks, and cultural ties. For example, there may be an urge to relocate people to areas that are not exposed to flood-related hazards, but relocating to steep mountainsides may increase their exposure to other risks such as landslides and reduce earnings leaving people more vulnerable ([Rieger, 2021](#)). The safest land is not necessarily where people can farm, work, access services or sustain the tourism economies on which many communities depend ([Shneiderman et al., 2026](#)). Risk reduction therefore has to be balanced against livelihoods, cultural ties, land availability, and economic realities. Relocation and resettlement does not constitute an end to risk, it can redistribute risks, create new forms of risk ([Goswami et al. 2025](#)).

The Rapid Disaster Needs Assessment report notes that technical assessments and consultations for relocation will be carried out with households when safe rebuilding is not an option. As of 10 September, 3,685 people were in 37 holding centres ([NDRRMA, 2026d](#)). This does not include those living with host families. The rapid assessment did not establish the extent of disruption related to "customary land use, sacred places, seasonal livelihoods or access to forests, rivers and pasture," and that relocation decisions should document existing resource use and community preferences regarding them ([NDRRMA, 2026d](#)).

Theoretically, relocating to other places in each district or even to cities like Kathmandu may be an option, but that still leaves other risks such as earthquakes and monsoon floods, and extreme pressures on urban centres to rapidly expand and accommodate newcomers. Most people do not want to leave their homes for cities like Kathmandu where they have no community ties, face pollution-related issues and face higher costs of housing, goods and services ([Abbing, 2026](#)). Relocating to areas like the Terai plans could mean changing livelihoods, leaving cultural ties and facing new risks such as extreme heat. The experience of communities relocated after the 2015 earthquake illustrates the challenge. Some resettlement sites along the Trishuli River were selected following assessments focused primarily on geohazards such as earthquakes and landslides, while other dimensions of risk, including seasonal monsoon flooding, were not fully considered ([Rieger, 2021](#)).

When there are no great choices, for individuals the key questions may be, *which locations offer the most manageable hazard risk profile and also allows for short-to-medium term livelihood sustainability?* and *How economically, culturally and socially feasible is it to move to those locations?* It may also include wider societal questions like, *where can soft limits to adaptation be overcome?* Such as, *Where is it possible to upgrade early warning systems to capture fast-onset cascading hazards of this magnitude?* This question critically requires the international community to provide climate finance which is highly inadequate at current levels (Section 5.6).

Understanding the return period of such a catastrophic hazard, and other cryospheric hazards, and especially the likelihood of repeating in a person's lifespan, are also critical to decisions about recovery. For example, if this type of event is likely to reoccur, rebuilding in the same areas seems increasingly likely to result in repeated exposure and could lead to chronic disasters. It's also critical to understand the likelihood of similar magnitude events in other parts of Nepal, the Himalayas and high-mountain regions in general to recalibrate our understanding of risk.

The Government of Nepal's Shock Responsive and Social Protection Relief Standards provide benchmark amounts, including a cash grant of NPR 500,000 (approximately CHF 2,700) to rebuild a house in mountainous areas. While this provides an important basis for humanitarian agencies to provide cash grants for permanent shelter, a recent assessment also found that Nepal's social protection system is still evolving to better include future climate risks ([Monyei, 2025](#)). This indicates the benchmark may not reflect the full cost of rebuilding a safe and resilient home, particularly in Nepal's evolving climate-related risks and rising construction costs. For example, in some remote villages the cost to transport materials to build a home is 4-500,000 NPR alone ([Kathmandu Post, 2026](#)), and following the 2015 earthquake in Nepal only 8.4% of people were able to reconstruct a house for less than USD 3,000 ([Rawal, 2021](#)). The assistance should therefore be viewed as a minimum benchmark rather than a ceiling, as the cost of rebuilding to be resilient to the present or future climate is likely higher.

There is also no blueprint for where or how people should rebuild. Typical flood adaptation advice such as rebuilding with improved drainage, and with more resilient materials and design will not necessarily prevent a similar outcome in the future. While planners may seek to develop standardized regulations and hazard zoning, questions of resettlement and relocation will also likely play out differently in each locality - since exposure and vulnerability may differ in each context, and since residents may have specific preferences and ideas about safety. Establishing a thoughtful process that recognizes the agency of displaced and affected populations and involves them as stakeholders will be a challenge. Any decisions will need to navigate these competing priorities while ensuring that development and economic interests do not lock people into escalating future risk.

5.6 Implications for international cooperation and climate finance

The financing needs for this event span from immediate relief, through various phases of recovery, rehabilitation and reconstruction. Nationally, the Prime Minister's Disaster Relief Fund had collected approximately USD 86 million in donations by 11 September ([Ministry of Finance, 2026](#)). This immediate relief support is complemented by grants and in-kind relief from international humanitarian organizations, bilateral partners, development banks, non-government agencies, civil society, private sector, and philanthropies ([MOFA, 2026](#); [UN Resident Coordinator's Office in Nepal, 2026b](#); [IFRC, 2026](#); [ADB, 2026](#)).

Reconstruction is on a far greater scale. The RDNA puts total disaster effects at USD 2.7 billion and recovery and reconstruction needs at USD 4.8 billion, at 6.7% and 11.8% of GDP respectively ([NDRRMA, 2026d](#)). Nepal's ministers of foreign affairs and finance have said the country prefers grants as the loan burden is already ballooning relative to GDP, but acknowledge that grants alone

cannot meet the need ([The Kathmandu Post, 2026c](#)). The World Bank is reported to have committed USD 137 million as concessional financing in response to this disaster ([myRepublica, 2026](#)).

As climate change warms the region, reconstruction must account for new levels of hazards through a multi-hazard approach and risk-informed decision making ([UNDRR, 2015](#); [Rieger, 2021](#)). The RDNA identifies “safer siting, strengthened early-warning systems ... and risk-informed reconstruction” supported by site-specific risk assessment as the basis for recovery ([NDRRMA, 2026d](#)). Building back better saves lives and livelihoods and is an economically sound investment over the long term. Rebuilding stronger, faster and more inclusively could avoid nearly a third of the well-being losses disasters cause ([Hallegatte et al., 2018](#)), and resilient infrastructure returns USD 4 for every USD 1 invested ([World Bank, 2019](#)). But this cost falls upfront, and often during periods of national disaster emergencies when nations are already struggling in a constrained fiscal space. Low-income countries are systematically less protected against climate extremes, because they lack the institutional, financial and technological capacity to adapt effectively ([Fankhauser & McDermott, 2014](#)). The IPCC identifies financial constraints as an important determinant of soft limits to adaptation and finds current adaptation finance insufficient ([IPCC, 2022](#)). The constraint then, does not lie in will, but in the national capacity to carry the cost alone.

Nepal has framed the response to this event as a question of climate justice rather than aid. The country accounts for about 0.1% of global greenhouse gas emissions ([Climate Change Tracker, 2026](#)) and yet, as put by the Foreign Minister, pays “the ultimate price for a global crisis [it] did not create” ([Al Jazeera, 2026](#)). The UN Resident Coordinator has described the devastation as “an extraordinary, stark illustration of the losses and damages that climate-vulnerable countries are increasingly facing,” noting that such countries “need adequate and accessible support to respond to loss and damages they did little to cause” ([UN News, 2026](#)). On 31st of August, the Minister of Finance and Minister of Agriculture, Forest and Environment jointly submitted a request to the Fund for Responding to Loss and Damage (FRLD). The Fund’s Governing Instrument mandates it to support recovery, rehabilitation and reconstruction for economic and non-economic loss and damage from extreme and slow-onset events, but states that the Fund is “based on cooperation and facilitation and does not involve liability or compensation” ([UNFCCC, 2023](#)). In the FRLD’s early phase, individual requests are capped at USD 20 million against total pledges of around USD 822 million made to the Fund ([FRLD, 2025](#); [FRLD, 2026](#)). The request, if approved, will contribute to a small fraction of Nepal’s need; but the significance will lie in a climate fund’s rapid approval in response to an extreme event.

Ex-ante and ex-post climate finance are meant to work together on the ground. The Green Climate Fund, Adaptation Fund, Least Developed Countries Fund, and Special Climate Change Fund finance risk reduction before an event, while the FRLD addresses losses after it. A response to this event will require loss and damage financing to recover what has been lost, and complementary adaptation financing for early warning and protective measures that will minimize future loss. Nepal’s NAP estimates adaptation needs of USD 47.4 billion to 2050, of which USD 45.9 billion is expected from international sources ([GON, 2021](#)). Meeting adaptation and loss and damage needs depends on financing channels operating together, and mobilizing solidarity financing internationally at a scale and speed that meets the needs of vulnerable countries.

6 Conclusions

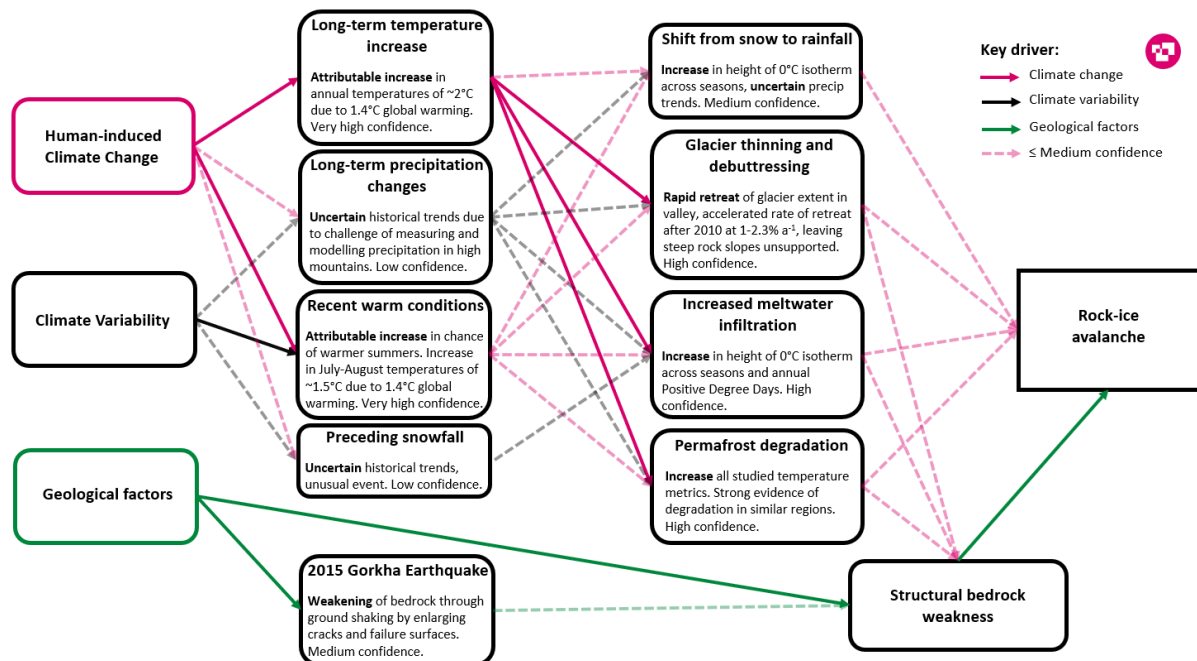


Figure 6.1: Causal network illustrating potential factors influencing the 26 August 2026 rock-ice avalanche based on the analysis in sections 2-4 of this report. Arrows indicate links to climate change (pink), climate variability (black), or geological factors (green). Solid arrows indicate at least high confidence of this link, while dashed arrows indicate medium or lower confidence in the link. A short description of key evidence is given within each box.

In this report we have assessed a range of drivers leading to the 26 August Rasuwa floods disaster, triggered by a rock-ice avalanche on the northern face of the Langtang-Lirung mountain, highlighting the potential role and mechanisms behind key events and trends. Where applicable, we assess the role of human-induced climate change in these trends (Fig. 6.1).

Leading up to the event itself, several changes in the high mountain environment are evident. In 2015, the Langtang region was affected by the magnitude 7.8 Gorkha earthquake, potentially weakening the slopes. As a result of rising temperatures, permafrost in High Mountain Asia is becoming degraded, particularly around the elevation of this slope failure, as well as weakening of ice-filled fractures and rock-ice contacts. The Langtang-Lirung glacier has undergone significant thinning and recession in recent decades, with a pronounced acceleration after 2010, leading to a loss of buttressing of the lower slopes and additional meltwater that could infiltrate bedrock fractures. Both processes are directly related to rising temperatures in the region. In addition, weather conditions directly prior to the event, may also have been conducive to slop failure. Large snowfall inputs in October and early November 2025 provided a substantial potential store of water. Where this snow persisted into 2026, its melting during the pre-monsoon and warm monsoon season could have generated large meltwater inputs. Finally, the region was affected by elevated temperatures over multiple timescales: the year from September 2025 - August 2026, the monsoon months of July and August 2026, and the 3 days prior to the collapse itself were all anomalously warm.

Due to the robust connection between temperatures and many of these potential drivers, we analysed changes in temperature around this slope and the wider region using several indices. We found that, as a direct result of human-induced climate change, annual temperatures and July-August mean temperatures have risen significantly around this slope and the wider Himalayas, with increases at approximately 1-1.5 times the global mean temperature rise. These changes are projected to continue at the same rate if the world continues to warm. This finding was similar across other indices: the height of the 0°C isotherm has risen in all seasons, especially in the Monsoon and Postmonsoon seasons at a rate of around 50-100m/decade; the cumulative PDD, an index that relates to the total energy available for melting, has increased at a rate of approximately 35-50 °C-days/decade since 1980 and has likely accelerated in the past decade; temperatures have risen in all calendar months, with the most pronounced changes in the coldest seasons.

Analysis of precipitation in the Monsoon season suggests no clear role of climate change in winter or monsoonal precipitation in the region. This is due at least in part to strong spatial variability and challenges of both observing and modelling precipitation across the complex Himalayan terrain. However, using a high resolution dynamical downscaling of ERA5 land using the WRF model, we do see evidence of increasing rainfall and decreasing snowfall in the monsoon season in the past two decades, potentially leading to greater volumes of water in bedrock fractures. This also aligns with our expectations from rapidly warming temperatures in the region, though further analysis of long-term trends is required to confirm this link for precipitation, which has high seasonal and spatiotemporal variability in the region.

Together, the results identify thermal weakening and water supply as key processes to consider alongside the pre-existing structural and topographic controls on the failure. They support a physically plausible contribution of climatic conditions to progressive destabilisation, but do not establish the magnitude of that contribution or identify a unique trigger. Direct attribution requires additional evidence linking atmospheric conditions to subsurface temperatures, fracture-water pressures and the mechanical evolution of the slope.

Regardless of the complexities of direct attribution for a specific event, it is clear that human-induced climate change is driving rapid and warming-driven transformation of high mountain environments in the Himalaya, which in turn contributing to the risk of potentially catastrophic geohazards, especially in regions such as Nepal with substantial seismic activity. Until emissions from fossil fuels are brought to net zero globally, this risk will continue to grow.

The immediate impacts of this cascading hazard were almost entirely dependent on exposure to hazard, whereas longer-term impacts (e.g. related to recovery, long-term health effects) are likely to vary based on socioeconomic vulnerability characteristics of the populations affected.

Exposure to the Rasuwa Bhotekoshi disaster was mediated by increasing development in river valleys due to factors like the concentration of economic activity near key border corridors, a focus on hydropower construction, and population movement from high villages and hillslopes to valleys due to past earthquakes and environmental and climate pressures that made it increasingly difficult to sustain livelihoods in those regions. This analysis also points to the importance of identifying and mapping multi-hazard risk, and using this information to develop and enforce risk sensitive land use plans, restrict new development in unsafe areas, and relocate or upgrade settlements and infrastructure

where risks cannot be adequately reduced. However, in a highly mountainous context where habitable land is constrained, population is increasing, and economic activity is dependent on rivers, it would be socially, economically and politically difficult to eliminate exposure in riverine valleys meaning that residual risks - losses and damages - remain.

There is also an opportunity to have more systematic and institutionalised arrangements for transboundary earth observation, research, and risk information sharing to enhance routine, timely and operational exchange of early warnings on rapidly evolving mountain hazards upstream of the border.

The magnitude and speed of the debris flow was much larger than typical infrastructure design standards and is beyond what risk-informed land management can reasonably protect against (typically 1-100 or rarely a 1-500 year flood, for example), highlighting limits to adaptation. Given climate change is increasingly creating conditions in which this type of event may re-occur, there is a need to have a dialogue around the new and transformative types of systems that would be required to build resilience to this type of event. For example, moving forward will require reckoning with broader questions like, *where can soft limits to adaptation be overcome to finance and implement necessary upgrades to early warning systems to capture fast-onset cascading hazards of this magnitude?*

This event was yet another warning sign of the rapidly changing risk profile in high mountain regions around the world where climate change creates conditions that support the development of similar rock-ice avalanches or other cascading hazard chains capable of producing extreme flow events that have yet to be fully understood or integrated into risk management. This event shows that limits to adaptation are already being reached and transformative actions are needed at local and global levels to avert, minimize and address losses and damages.

Data availability

All time series used in the attribution analysis are available via the Climate Explorer.

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This work used Imperial College Research Computing Service, DOI: 10.14469/hpc/2232.

This work used the KNMI Climate explorer web tool (<https://climexp.knmi.nl/start.cgi>).

The field data of Langtang are collected in different projects financially supported by the European Research Council and the Netherlands Organisation for Scientific Research.

Romain Hugonnet provided glacier thinning rates for the region.

References

All references are given as hyperlinks in the text.

Appendices

A1 Glacier changes

We used a series of satellite imagery (declassified (orthorectified, 5-7 m resolution), Sentinel (10 m resolution), Landsat (15 m panchromatic and 30 m colour resolution)) (Table A1.1) and analysis of DEMs of glacier elevation change (*dhdt*) (Pleiades ([Berthier, 2026](#)), ASTER ([Hugonnet et al., 2021](#))) to provide estimates of glacier area change and thinning at a multidecadal timescale. Declassified spy satellite imagery included georeferenced and co-registered Corona KH-4 (~5 m resolution) and Hexagon KH-9 (~7 m resolution) imagery. A scene acquired by the Hexagon KH-9 panoramic camera on 09/02/1972 (D3C1202-300210F073) was accessed from the United States Geological Survey (USGS) declassified spy satellite image archive (U.S. Geological Survey, 2026). A central subset (~27 x 15 km) of the individual image strip covering the study area was orthorectified to a snow- and cloud-free Sentinel 2A scene acquired on 12/08/2026 using 18 manually identified control points and a spline transformation. The 1964 Corona KH-4 image was sourced from [Silwal et al. 2026](#) and [Bhattacharya et al. 2021](#).

Table A1.1: Image source information for the satellite observations of observations Langtang-Lirung Glacier.

Date	Sensor / source	Image resolution	Reference	Image information
01/01/1815	Geomorphology and Lee et al 2021	10 m	Modified from lee et al 2021	Using Sentinel 2 from 16th Dec 2020
26/11/1964	Corona KH4	~ 5 m		KH4_Langtang_26111964_ortho_5m.tif
09/02/1972	Hexagon KH-9 Panoramic	~ 7m		D3C1202-300210F073_g
22/11/1990	Modified from ICIMOD inventory. Date uncertain. Cross checked with Landsat5 image.	10 m	Maharjan S. B. and Sherpa T. C., (2026).	LT05_L1TP_141040_19921226_20200914_02_T1_refl.tif
22/11/2000	RGIv7 and Landsat 7 ETM+ image	30 m		LE07_L1TP_141040_20001122_20200917_02_T1
20/12/2010	Landsat 7 ETM+	30 m		LE07_L1TP_141040_20101220_20200910_02_T1
28/12/2015	Sentinel-2A	10 m		S2A_MSIL2A_20151228T050222_N0500_R119_T45RUM_20231015T203435.SAFE
12/12/2017	Sentinel-2A	10 m		S2B_MSIL2A_20171212T050159_N0500_R119_T45RUM_20230923T124558.SAFE
16/12/2020	Sentinel-2A	10 m		S2B_MSIL2A_20201216T050219_N0500_R119_T45RUM_20230328T103237.SAFE

16/12/2022	Sentinel-2A	10 m		S2B_MSIL2A_20221216T050219_N0510_R119_T45RUM_20240807T014903.SAFE
24/08/2026	Sentinel-2A	10 m		S2A_MSIL2A_20260824T050231_N0512_R119_T45RUM_20260824T115710.SAFE
01/09/2026	Sentinel-2A and Landsat 9	10 m		S2A_MSIL2A_20260824T050231_N0512_R119_T45RUM_20260824T115710.SAFE; LC09_L1TP_141040_20260826_20260826_02_T1_refl.tif

Sentinel and Landsat satellite imagery were acquired in the period of minimum snow cover (Nov-Dec), with minimum cloud cover. Where the snowcover was uncertain, multiple images were checked. Images are frequently snowy, which makes mapping difficult, and is uncertain in particular in the SW part of the upper cirque, and glacier coverage here has the highest uncertainty. Some glacier ice and snow is difficult to tell apart particularly in 2022, which may mean recession to 2026 is over estimated.

The glacier outline of the Randolph Glacier Inventory (RGI v7.0) was used as a baseline, but was first compared against a contemporaneous Landsat 7 ETM+ satellite image (see Appendix A3) and corrected. Several individual glacier outlines within the cirque were merged to one polygon. The glacier outline was manually edited in line with glacier ice observed in the satellite imagery. DEMs of difference were used for additional evidence of glacier extent where satellite imagery was unclear. The LIA extent was modified from ([Lee et al., 2021](#)) from evaluation of mapped geomorphology. Glacier extent in 1990 was modified from the ICIMOD glacier inventory ([Maharjan and Sherpa, 2026](#)), in line with Landsat 5 imagery.

Geomorphological mapping used a 2 m Pleiades DEM (Berthier, 2026), Sentinel, Landsat and Planet Scope (3.7 m resolution) imagery. Buried ice was identified using the thinning detected from the 2015-2019 Pleiades DEM and the DEMs by [Hugonnet et al., 2021](#). The valley's river channel was identified, pre-event, in the 2019 2-m Pleiades DEM and Sentinel image taken on 24 August 2026. The vegetation-free zone was mapped, as this indicates where fluvial erosion was current. The scour after the event was mapped from sentinel and pansharpened Landsat imagery. Moraines were mapped where a sharp ridge crest is visible in satellite imagery and DEMs.

A2 Data and methods: Temperature and precipitation analyses

A2.1 Observational data

We use observational and reanalysis data to assess historical trends. The datasets used are as follows:

ERA5-Land - This product is a replay of the land component of the ERA5 climate reanalysis ([Muñoz-Sabater et al., 2021](#)) produced by the European Centre for Medium-Range Weather Forecasts, with a finer spatial resolution of 0.1° ($\sim 9\text{km}$ grid spacing), at hourly time steps from 1950 to 5 days before the current date. The land model used is the tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). We use daily and monthly mean temperature data and daily precipitation data from this product from the years 1950 to present. For the precipitation analysis however, we restrict ERA5-Land data to begin from 1979 onwards to match the satellite period, due to difficulties in resolving some of the large variability in the precipitation records '50s and '60s without station data.

MSWX - The Multi-Source Weather dataset ([Beck et al., 2022](#)), which combines various observational and reanalysis-based data (including ERA5) for reliable bias-corrected weather variable estimates, at 3-hourly intervals from 1979 to near real-time, and at 0.1° spatial resolution globally. We use daily mean and precipitation data from this product.

CHELSA - CHELSA is a global, kilometer-scale (30 arc sec, $\sim 1\text{ km}$) climate dataset generated with the CHELSA (Climatologies at High Resolution for the Earth's Land Surface Areas) downscaling model ([Karger et al. 2017](#)), consisting of daily surface variables. The underlying downscaling algorithm statistically downscales atmospheric temperatures based on mean lapse rates and elevation, and derives precipitation using orographic predictors such as wind fields, valley exposure, and boundary layer height, with subsequent bias correction. We use daily mean and daily precipitation (pr) data from this product ([Karger, D. N. 2025](#)), covering the period 1941 to August 2025 for tas and 1980–2019 for precipitation. We use both the nearest grid cell and the average across grid cells matching the nearest ERA5-Land grid cell ().

WRF - This dataset contains hourly Weather Research and Forecasting (WRF v4.7) model output. The dataset provides 2 m air temperature, total precipitation, rainfall, and snowfall at the nearest grid cell and as an areal mean across a 3×3 neighbouring grid-cell area. The data are derived from a one-way nested WRF configuration with 20 km and 4 km horizontal grid spacing, 50 vertical levels extending to 50 hPa, and ~ 11 levels within the lowest 1 km. WRF is forced by 6-hourly ERA5 reanalysis fields at the lateral boundaries of the outer domain, with grid analysis nudging applied above the planetary boundary layer.

In-situ stations - We use combined measurements from a number of in-situ stations in the Langtang Valley, based between 3862m.a.s.l and 5090m.a.s.l ([Kwadijk et al., 2026 - in review](#)). Hourly temperature and precipitation records begin from 01/03/2016 and extend to 07/11/2025 for precipitation and 01/09/2026 for temperature. Estimates of temperature at the slope failure elevation are computed using linear extrapolation based on locally observed lapse rates. Precipitation is not scaled with elevation, but precipitation phase is determined based on temperature: below -2°C is

snow, -2 to +2°C is wet snow, above +2°C is rain. For station details and processing methods see Kwadijk et al. ([2026 - in review](#)).

CHIRPS - The rainfall product developed by the UC Santa Barbara Climate Hazards Group called “Climate Hazards Group InfraRed Precipitation with Station data” (CHIRPS; [Funk et al. 2015](#)). Daily data are available at 0.05° resolution, from 1981-31 July 2026. The product incorporates satellite imagery with in-situ station data.

IMERG - This product uses NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm for combining information from the GPM satellite constellation to estimate precipitation over the majority of the Earth's surface ([Rozante et al. 2010](#)). IMERG fuses precipitation estimates collected during the TRMM satellite's operation (1998 - 2015) with recent precipitation estimates collected by the GPM mission (2014 - present). IMERG is available from 1998 to present in near real-time with estimates of Earth's precipitation updated every half-hour. Here daily data is used with a spatial resolution of 0.5 x 0.5 degrees.

Covariates

As a measure of anthropogenic climate change we use the (low-pass filtered) global mean surface temperature (GMST), where GMST is taken from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, [Hansen et al., 2010](#) and [Lenssen et al. 2019](#)). To remove the effect of the El Niño - Southern Oscillation on global mean temperatures, we use a four-year running mean of the GMST, centred on the third year.

Other

As a measure of elevation over the affected region, we used the The General Bathymetric Chart of the Oceans (GEBCO) [2026 global dataset](#). This provides a continuous terrain elevation above sea level for land and oceans on a 15 arc-second grid. The grid uses as a ‘base’ Version 2.8 of the SRTM15+ data set ([Tozer et al 2019](#)) largely between latitudes of 50° South and 60° North. This data set is a fusion of land topography with measured and estimated seafloor topography - predictions based on satellite-derived gravity data. The SRTM15+ base grid has been augmented with the gridded bathymetric data sets developed by the four Seabed 2030 Regional Centers to produce the GEBCO_2026 Grid. Data for the study region were obtained from the GEBCO_2026 grid [available online](#).

A2.2 Model and experiment descriptions

We use two ensembles of climate models from climate modelling experiments using very different framings ([Philip et al., 2020](#)): Sea Surface Temperature (SST) driven global circulation high resolution models, coupled global circulation models and regional climate models.

1. CORDEX WAS-22 - Coordinated Regional Climate Downscaling Experiment CORDEX-CORE over the West-Asia domain with 0.22 km resolution (WAS-22) (Teichman et al., 2021). The ensemble

consists of 3 regional climate models each downscaling one of 6 GCMs. These simulations are composed of historical simulations up to 2005, and extended to the year 2100 using the RCP8.5 scenario.

2. HighResMIP SST-forced model ensemble ([Haarsma et al. 2016](#)), the simulations for which span from 1950 to 2050. The SST and sea ice forcings for the period 1950-2014 are obtained from the 0.25° x 0.25° Hadley Centre Global Sea Ice and Sea Surface Temperature dataset that have undergone area-weighted regridding to match the climate model resolution. For the ‘future’ time period (2015-2050), SST/sea-ice data are derived from RCP8.5 (CMIP5) data, and combined with greenhouse gas forcings from SSP5-8.5 (CMIP6) simulations (see Section 3.3 of Haarsma et al. 2016 for further details).

A2.3 Statistical methods

Methods for observational and model analysis and for model evaluation and synthesis are used according to the World Weather Attribution Protocol, described in [Philip et al., \(2020\)](#), with supporting details found in [van Oldenborgh et al., \(2021\)](#), [Ciavarella et al., \(2021\)](#), [Otto et al., \(2024\)](#) and [here](#). The key steps, presented in sections 3-6, are: (3) trend estimation from observations; (4) model validation; (5) multi-model attribution; and (6) synthesis of the attribution statement.

In this report we analyse time series of July-August and Annual average of daily mean temperature at the nearest grid cell to and the wider Himalayan region. A nonstationary normal distribution is used to model the time series, with the distribution assumed to shift linearly with the covariates, while the variance remains constant. The parameters of the statistical model are estimated using maximum likelihood. Using the fitted model for each time series we calculate the change in intensity of expected conditions for the 2026 GMST compared to a 1.4°C cooler GMST: this allows us to compare the climate of now and of the preindustrial past without human-caused warming (based on [Forster et al., 2026](#)).

A2.4 Elevation correction

In order to estimate indices such as the height of the 0C isotherm and the temperature at approximate slope failure elevation (5150m), it is necessary to adjust for differences in elevation between the areas within different grid cell dimensions covering different topographical regions, as well as assumed nominal elevation levels built into any land surface models. To do this, where elevation data was available (as set out in section 3.1.1) we adjusted daily temperature time series using the seasonal lapse rates in Table A2.X. The season definitions are based on [Immerzeel et al., 2014](#), while the lapse rates have been updated from that paper using the more recent in-situ data from the past 10 years, with mean values estimated from all data available within each season.

Table A2.1: The dates and derived lapse rates for each season in the valley in which the slope failure occurred, based on measurements from in-situ weather stations.

Season	Dates	Lapse rate (°C/m)
--------	-------	-------------------

Winter	1st Jan - 28th Feb	-0.00574
Premonsoon	1st March - 15th June	-0.00638
Monsoon	16th June - 30th September	-0.00526
Postmonsoon	1st October - 31st December	-0.00539

A3 Additional tables and figures

Table A3.1: Area and rates of area change for Langtang-Lirung Glacier.

Date	Area (km ²)	Area change (km ²)	Time difference (years)	Km ² a ⁻¹	% area change	% a ⁻¹
01/01/1815	18.87					
26/11/1964	11.69	-7.18	149.0	-0.05	-38.03	-0.26
09/02/1972	11.56	-0.13	8.2	-0.02	-1.13	-0.14
22/11/1990	10.90	-0.66	17.8	-0.04	-5.74	-0.32
22/11/2000	10.36	-0.53	10.0	-0.05	-4.91	-0.49
20/12/2010	9.88	-0.48	10.1	-0.05	-4.65	-0.46
28/12/2015	8.75	-1.13	5.0	-0.22	-11.44	-2.28
12/12/2017	8.32	-0.43	2.0	-0.22	-4.97	-2.54
16/12/2020	7.85	-0.46	3.0	-0.15	-5.57	-1.85
16/12/2022	7.78	-0.07	2.0	-0.03	-0.89	-0.44
24/08/2026	7.34	-0.45	3.7	-0.12	-5.75	-1.56
01/09/2026	6.88	-0.46	0.02	-20.98	-6.27	-285.94

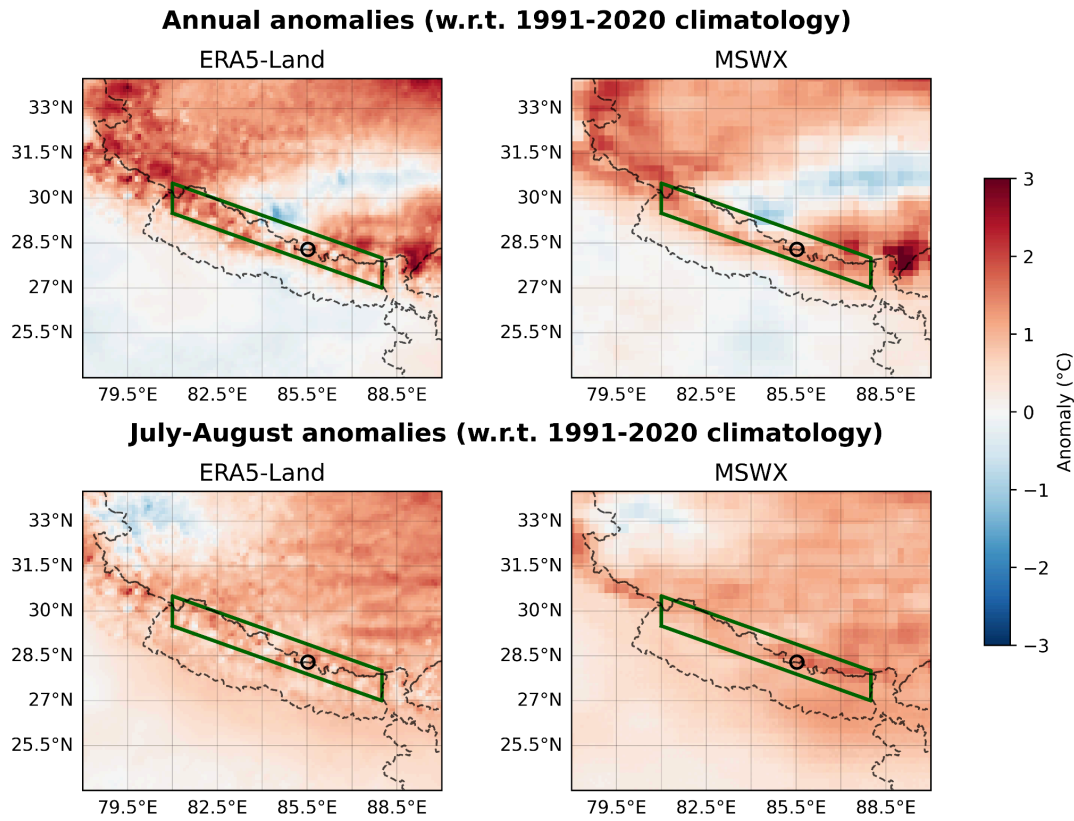


Figure A3.1: Anomalies in average daily mean temperature for the September 2025 - August 2026 period (top) and July-August 2026 (bottom) with respect to the 1991-2020 climatological period over Nepal and surrounding regions for each grid cell in two reanalyses (ERA5-Land and MSWX). The wider Himalayan region is shown with the dark green box and the approximate location of the slope failure is shown by the black dot.

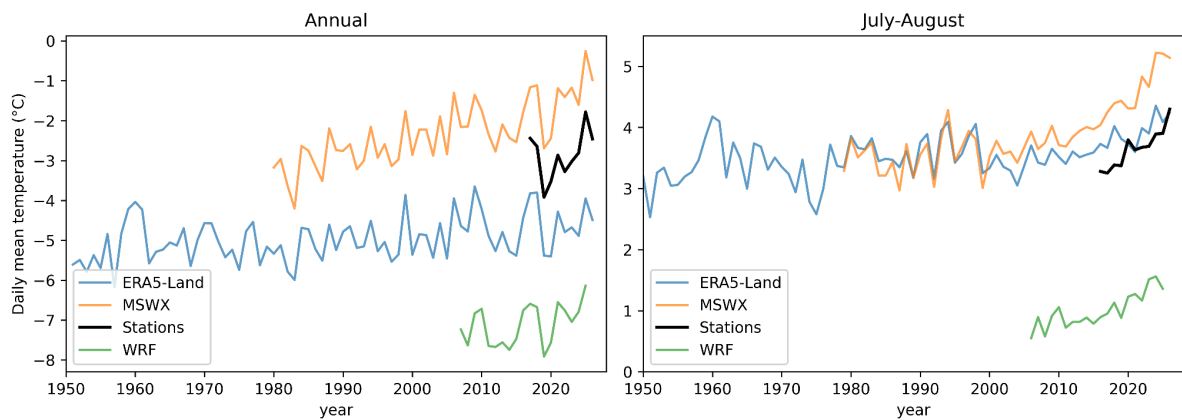


Figure A3.2: Time series of annual (left) and July-August (right) average of daily mean temperature at the location of the ice-rock avalanche for several gridded observation-based datasets and in-situ measurements. Time series are adjusted for elevation according to the methods described in section 3.1.1 and A2.4. For gridded datasets, we select the nearest grid cell to the coordinates of the slope failure (28.288708°N, 85.528159°E).

Table A3.2: Change in temperature for the annual and July-August average of daily mean temperatures at the location of the slope failure (left) and the wider Himalayas region (right), associated with a 1.4°C increase in GMST. In addition to the datasets included in Table 3.1, this table shows the CHELSA data aggregated to the same dimensions as the ERA5-Land grid box, and the WRF dataset aggregated over the 3x3 grid cells around the nearest grid cell.

Dataset	Change due to 1.4C global warming (95% C.I.)			
	Nearest grid cell		Nepal Himalayas	
	Annual	July-August	Annual	July-August
ERA5-Land	0.784 (0.331, 1.21)	0.700 (0.394, 0.901)	1.53 (0.934, 2.04)	1.10 (0.846, 1.32)
MSWX	2.90 (2.15, 3.58)	2.08 (1.56, 2.47)	2.56 (1.70, 3.31)	1.57 (1.09, 1.91)
CHELSA	2.86 (2.37, 3.35)	3.04 (2.73, 3.34)		
CHELSA (ERA5-Land grid)	2.86 (2.34, 3.34)	2.86 (2.60, 3.15)		
WRF	2.09 (0.45, 3.40)	1.74 (1.08, 2.33)		
WRF (3x3)	2.29 (-0.11, 4.18)	2.42 (1.48, 3.28)		

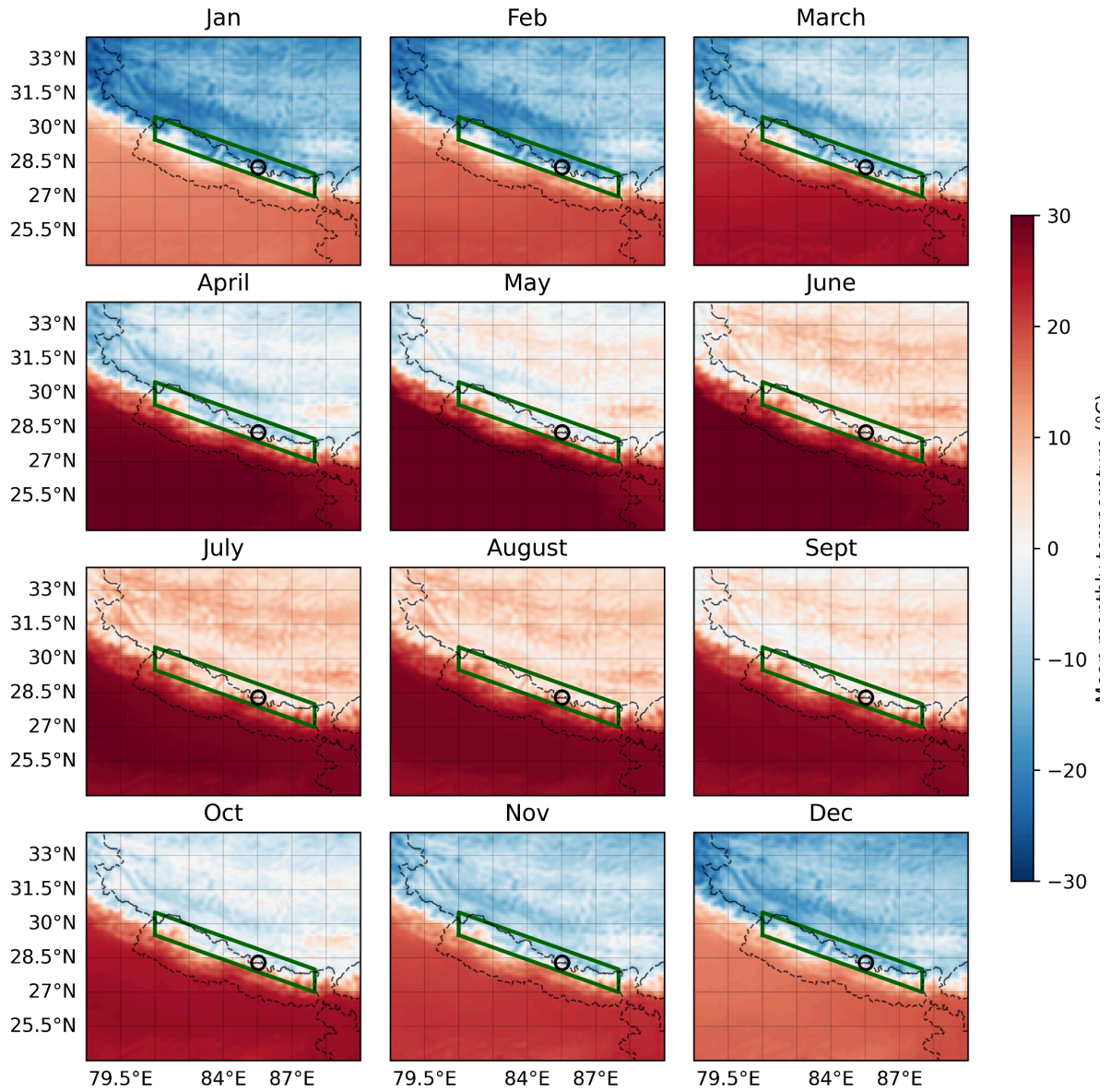


Figure A3.3: Monthly averages of daily mean temperatures in a region around Nepal. The wider Himalayan region is shown with the dark green box and the approximate location of the slope failure is shown by the black dot. Data: ERA5-Land.

A4 Model evaluation tables

Table A4.1: Evaluation results of the climate models considered for attribution analysis of Annual and July-August temperatures in the study regions. For each model, the best estimate of the Sigma parameter is shown along with a 95% confidence intervals. Furthermore evaluation of the seasonal cycle and spatial pattern are shown.

				Himalayan Region		Grid Point	
Model	Version	Seasonal Eval.	Spatial Eval.	Sigma (T-JA)	Sigma (T-yr)	Sigma (T-JA)	Sigma (T-yr)
Observations							
MSWX				0.270 (0.206, 0.317)	0.561 (0.442, 0.642)	0.298 (0.230, 0.351)	0.508 (0.405, 0.579)
ERA5-Land				0.272 (0.226, 0.310)	0.604 (0.516, 0.662)	0.313 (0.256, 0.360)	0.512 (0.434, 0.572)
WRF				-	-	0.161 (0.116, 0.186)	0.426 (0.285, 0.510)
CHELSA				-	-	0.464 (0.375, 0.547)	0.580 (0.505, 0.643)
CORDEX (WAS-22)							
ICHEC-EC-EARTH_CLMcom-ETH-COSMO-crCLIM-v1-1	r12i1p1	good	good	0.26 (0.195, 0.31)	0.48 (0.390, 0.54)	0.29 (0.222, 0.35)	0.55 (0.446, 0.62)
MIROC-MIROC5_ORNL-RegCM4-7	r1i1p1	good	good	0.33 (0.247, 0.41)	0.51 (0.402, 0.59)	0.32 (0.249, 0.38)	0.86 (0.672, 1.00)
MOHC-HadGEM2-ES_GERICS-REMO2015	r1i1p1	good	good	0.96 (0.788, 1.08)	0.55 (0.413, 0.66)	1.98 (1.650, 2.20)	1.34 (1.092, 1.52)
MPI-M-MPI-ESM-LR_CLMcom-ETH-COSMO-crCLIM-v1-1	r1i1p1	good	good	0.26 (0.205, 0.30)	0.41 (0.319, 0.47)	0.29 (0.225, 0.33)	0.44 (0.354, 0.51)
MPI-M-MPI-ESM-LR_GERICS-REMO2015	r1i1p1	good	good	0.71 (0.544, 0.83)	0.57 (0.448, 0.65)	1.64 (1.304, 1.86)	1.26 (0.981, 1.48)
MPI-M-MPI-ESM-MR_ORNL-RegCM4-7	r1i1p1	good	good	0.44 (0.309, 0.56)	0.46 (0.362, 0.52)	0.34 (0.279, 0.39)	0.62 (0.455, 0.76)
NCC-NorESM1-M_CLMcom-ETH-COSMO-crCLIM-v1-1	r1i1p1	good	good	0.26 (0.205, 0.30)	0.37 (0.293, 0.42)	0.32 (0.257, 0.36)	0.42 (0.345, 0.49)
NCC-NorESM1-M_GERICS-REMO2015	r1i1p1	good	good	0.73 (0.581, 0.83)	0.52 (0.415, 0.60)	1.45 (1.105, 1.71)	1.40 (1.147, 1.56)
NCC-NorESM1-M_ORNL-RegCM4-7	r1i1p1	good	good	0.36 (0.288, 0.40)	0.45 (0.345, 0.52)	0.37 (0.294, 0.43)	0.58 (0.442, 0.66)

HighResMIP							
CNRM-CM6-1-HR	r1i1p1f2	good	good	0.40 (0.338, 0.43)	0.49 (0.450, 0.53)	0.40 (0.362, 0.42)	0.44 (0.398, 0.46)
CNRM-CM6-1	r1i1p1f2	good	bad	0.37 (0.344, 0.42)	0.56 (0.506, 0.58)	0.37 (0.339, 0.43)	0.70 (0.593, 0.75)
EC-Earth3P-HR	r1i1p1f1	good	good	0.43 (0.424, 0.43)	0.74 (0.684, 0.77)	0.42 (0.420, 0.43)	0.66 (0.604, 0.67)
EC-Earth3P-HR	r2i1p1f1	good	good	0.37 (0.321, 0.44)	0.65 (0.482, 0.73)	0.36 (0.321, 0.44)	0.55 (0.420, 0.62)
EC-Earth3P-HR	r3i1p1f1	good	good	0.36 (0.302, 0.42)	0.71 (0.637, 0.73)	0.36 (0.292, 0.42)	0.59 (0.507, 0.58)
EC-Earth3P	r1i1p1f1	good	bad	0.43 (0.411, 0.43)	0.66 (0.639, 0.69)	0.44 (0.426, 0.45)	0.82 (0.805, 0.85)
EC-Earth3P	r2i1p1f1	good	bad	0.40 (0.355, 0.42)	0.74 (0.590, 0.78)	0.42 (0.382, 0.44)	0.90 (0.694, 0.98)
EC-Earth3P	r3i1p1f1	good	bad	0.36 (0.343, 0.39)	0.55 (0.507, 0.64)	0.40 (0.379, 0.44)	0.70 (0.661, 0.78)
HadGEM3-GC31-HM	r1i1p1f1	good	good	0.30 (0.275, 0.29)	0.51 (0.442, 0.51)	0.32 (0.284, 0.34)	0.55 (0.469, 0.55)
HadGEM3-GC31-HM	r1i2p1f1	good	good	0.30 (0.251, 0.32)	0.41 (0.367, 0.45)	0.30 (0.278, 0.32)	0.46 (0.436, 0.53)
HadGEM3-GC31-HM	r1i3p1f1	good	good	0.34 (0.272, 0.36)	0.40 (0.376, 0.43)	0.33 (0.266, 0.37)	0.47 (0.446, 0.51)
HadGEM3-GC31-LM	r1i1p1f1	good	bad	0.29 (0.235, 0.34)	0.43 (0.374, 0.45)	0.31 (0.238, 0.33)	0.38 (0.307, 0.39)
HadGEM3-GC31-MM	r1i1p1f1	good	bad	0.27 (0.221, 0.30)	0.45 (0.424, 0.49)	0.25 (0.215, 0.27)	0.33 (0.259, 0.38)
HadGEM3-GC31-MM	r1i2p1f1	good	bad	0.30 (0.268, 0.31)	0.61 (0.489, 0.73)	0.27 (0.237, 0.28)	0.38 (0.323, 0.42)
HadGEM3-GC31-MM	r1i3p1f1	good	bad	0.30 (0.254, 0.33)	0.49 (0.448, 0.55)	0.30 (0.261, 0.35)	0.30 (0.270, 0.35)
MPI-ESM1-2-HR	r1i1p1f1	good	bad	0.39 (0.352, 0.40)	0.54 (0.390, 0.63)	0.39 (0.340, 0.40)	0.54 (0.413, 0.64)
MPI-ESM1-2-XR	r1i1p1f1	good	good	0.36 (0.342, 0.38)	0.59 (0.542, 0.58)	0.33 (0.304, 0.36)	0.53 (0.480, 0.51)

A5 Estimated trends in climate models

This section shows the change in intensity ΔI for models that passed model evaluation and also includes the values calculated from the fits with observations.

Table A5.1. Change in intensity for July-August and Annual temperature in the study regions for observational datasets and each model that passed the evaluation tests. (a) from pre-industrial climate to the present and (b) from the present to 2.8°C above pre-industrial climate.

				Himalayan Region		Grid Point	
Model	Version	Seasonal Eval.	Spatial Eval.	Intensity Delta [°C] (T-JA)	Intensity Delta [°C] (T-yr)	Intensity Delta [°C] (T-JA)	Intensity Delta [°C] (T-yr)
Observations							
MSWX				1.57 (1.09, 1.91)	2.56 (1.70, 3.31)	2.08 (1.56, 2.47)	2.90 (2.15, 3.58)
ERA5-Land				1.10 (0.846, 1.32)	1.53 (0.934, 2.04)	0.670 (0.394, 0.901)	0.784 (0.331, 1.21)
WRF						1.74 (1.08, 2.33)	2.09 (0.448, 3.40)
CHELSA						3.04 (2.73, 3.34)	2.86 (2.37, 3.35)
CORDEX (WAS-22)							
ICHEC-EC-EARTH_CLMcom-ETH-COSMO-crCLIM-v1-1	r12i1p1	good	good	1.57 (1.341, 1.81)	1.78 (1.380, 2.14)	1.73 (1.462, 2.03)	1.86 (1.439, 2.25)
MIROC-MIROC5_ORNL-RegCM4-7	r1i1p1	good	good	1.98 (1.615, 2.35)	2.44 (1.961, 3.00)	1.57 (1.261, 1.89)	2.39 (1.709, 3.15)
MOHC-HadGEM2-ES_GERICS-REMO2015	r1i1p1	good	good	2.52 (1.880, 3.20)	1.89 (1.504, 2.30)	2.18 (0.804, 3.61)	2.26 (1.300, 3.23)
MPI-M-MPI-ESM-LR_CLMcom-ETH-COSMO-crCLIM-v1-1	r1i1p1	good	good	1.61 (1.410, 1.79)	1.58 (1.301, 1.84)	1.73 (1.519, 1.94)	1.70 (1.391, 1.99)

MPI-M-MPI-ESM-LR_G ERICS-REMO2015	r1i1p1	good	good	2.25 (1.533, 2.91)	1.85 (1.342, 2.36)	2.45 (0.727, 3.99)	1.39 (0.313, 2.58)
MPI-M-MPI-ESM-MR_O RNL-RegCM4-7	r1i1p1	good	good	1.90 (1.447, 2.30)	2.63 (2.069, 3.15)	1.74 (1.409, 2.03)	2.79 (2.139, 3.46)
NCC-NorESM1-M_CLM com-ETH-COSMO-crC LIM-v1-1	r1i1p1	good	good	1.37 (1.176, 1.58)	1.80 (1.427, 2.16)	1.45 (1.180, 1.71)	1.88 (1.445, 2.29)
NCC-NorESM1-M_GER ICS-REMO2015	r1i1p1	good	good	2.50 (1.726, 3.30)	2.15 (1.617, 2.68)	3.20 (1.901, 4.54)	3.04 (1.523, 4.50)
NCC-NorESM1-M_ORN L-RegCM4-7	r1i1p1	good	good	2.34 (1.882, 2.79)	2.57 (2.052, 3.11)	1.72 (1.342, 2.03)	2.58 (1.946, 3.31)
HighResMIP							
CNRM-CM6-1-HR	r1i1p1f2	good	good	1.33 (1.186, 1.53)	2.02 (1.968, 2.18)	1.24 (1.192, 1.43)	1.98 (1.895, 2.19)
CNRM-CM6-1	r1i1p1f2	good	bad	1.12 (0.879, 1.36)	1.88 (1.567, 2.15)	1.20 (0.915, 1.47)	2.17 (1.675, 2.43)
EC-Earth3P-HR	r1i1p1f1	good	good	0.08 (0.066, 0.10)	0.10 (0.071, 0.16)	0.09 (0.069, 0.11)	0.10 (0.078, 0.15)
EC-Earth3P-HR	r2i1p1f1	good	good	1.54 (1.498, 1.74)	1.98 (1.811, 2.20)	1.55 (1.518, 1.79)	1.72 (1.538, 2.04)
EC-Earth3P-HR	r3i1p1f1	good	good	1.33 (1.142, 1.35)	1.64 (1.180, 1.99)	1.37 (1.160, 1.42)	1.56 (1.186, 1.94)
EC-Earth3P	r1i1p1f1	good	bad	0.09 (0.087, 0.12)	0.07 (0.033, 0.11)	0.10 (0.089, 0.12)	0.08 (0.032, 0.13)
EC-Earth3P	r2i1p1f1	good	bad	1.53 (1.487, 1.60)	1.36 (1.112, 1.80)	1.63 (1.555, 1.68)	1.36 (1.021, 1.99)
EC-Earth3P	r3i1p1f1	good	bad	1.54 (1.535, 1.64)	0.56 (0.593, 1.12)	1.68 (1.676, 1.77)	0.48 (0.520, 1.08)
HadGEM3-GC31-HM	r1i1p1f1	good	good	1.53 (1.340, 1.61)	1.29 (1.095, 1.61)	1.47 (1.270, 1.51)	1.37 (0.948, 1.64)
HadGEM3-GC31-HM	r1i2p1f1	good	good	1.42 (1.253, 1.60)	1.88 (1.787, 2.34)	1.38 (1.251, 1.58)	1.95 (1.783, 2.48)
HadGEM3-GC31-HM	r1i3p1f1	good	good	1.31 (1.166, 1.46)	1.68 (1.640, 2.13)	1.28 (1.129, 1.40)	1.81 (1.696, 2.35)
HadGEM3-GC31-LM	r1i1p1f1	good	bad	1.07 (0.892, 1.12)	1.47 (1.232, 1.76)	1.11 (0.904, 1.11)	1.15 (1.001, 1.30)

<i>HadGEM3-GC31-MM</i>	<i>r1i1p1f1</i>	good	bad	1.38 (1.218, 1.29)	1.18 (1.172, 1.62)	1.13 (0.954, 1.07)	1.09 (0.862, 1.38)
<i>HadGEM3-GC31-MM</i>	<i>r1i2p1f1</i>	good	bad	1.22 (0.981, 1.33)	1.51 (1.335, 1.95)	1.02 (0.817, 1.06)	1.11 (1.071, 1.40)
<i>HadGEM3-GC31-MM</i>	<i>r1i3p1f1</i>	good	bad	1.30 (1.123, 1.37)	1.46 (1.320, 2.09)	1.06 (0.744, 1.07)	1.17 (1.066, 1.45)
<i>MPI-ESM1-2-HR</i>	<i>r1i1p1f1</i>	good	bad	1.81 (1.697, 2.12)	2.10 (1.728, 2.35)	1.88 (1.718, 2.16)	2.10 (1.733, 2.38)
<i>MPI-ESM1-2-XR</i>	<i>r1i1p1f1</i>	good	good	1.76 (1.549, 1.73)	1.76 (1.511, 2.03)	1.72 (1.498, 1.69)	1.67 (1.338, 1.86)