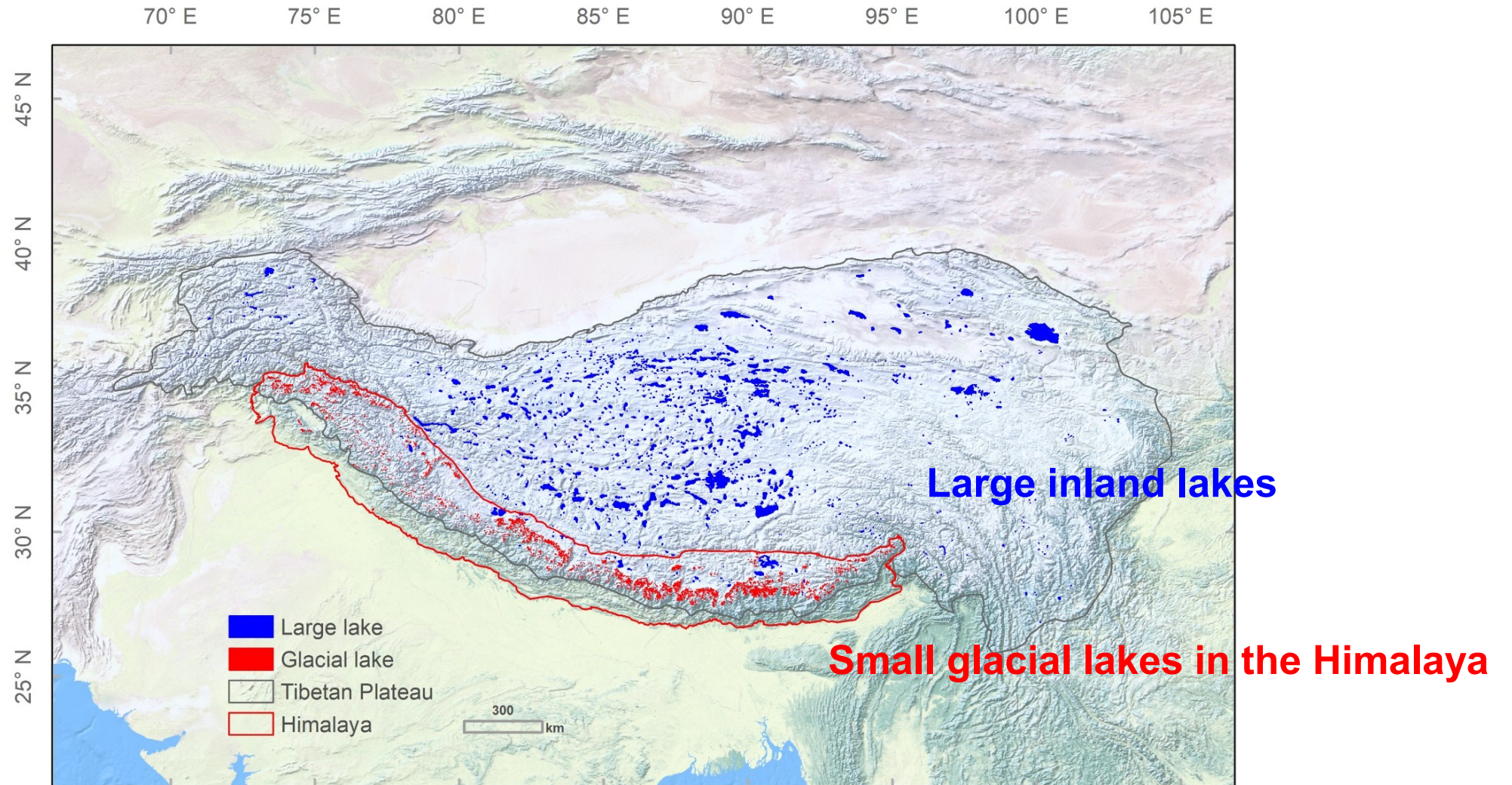


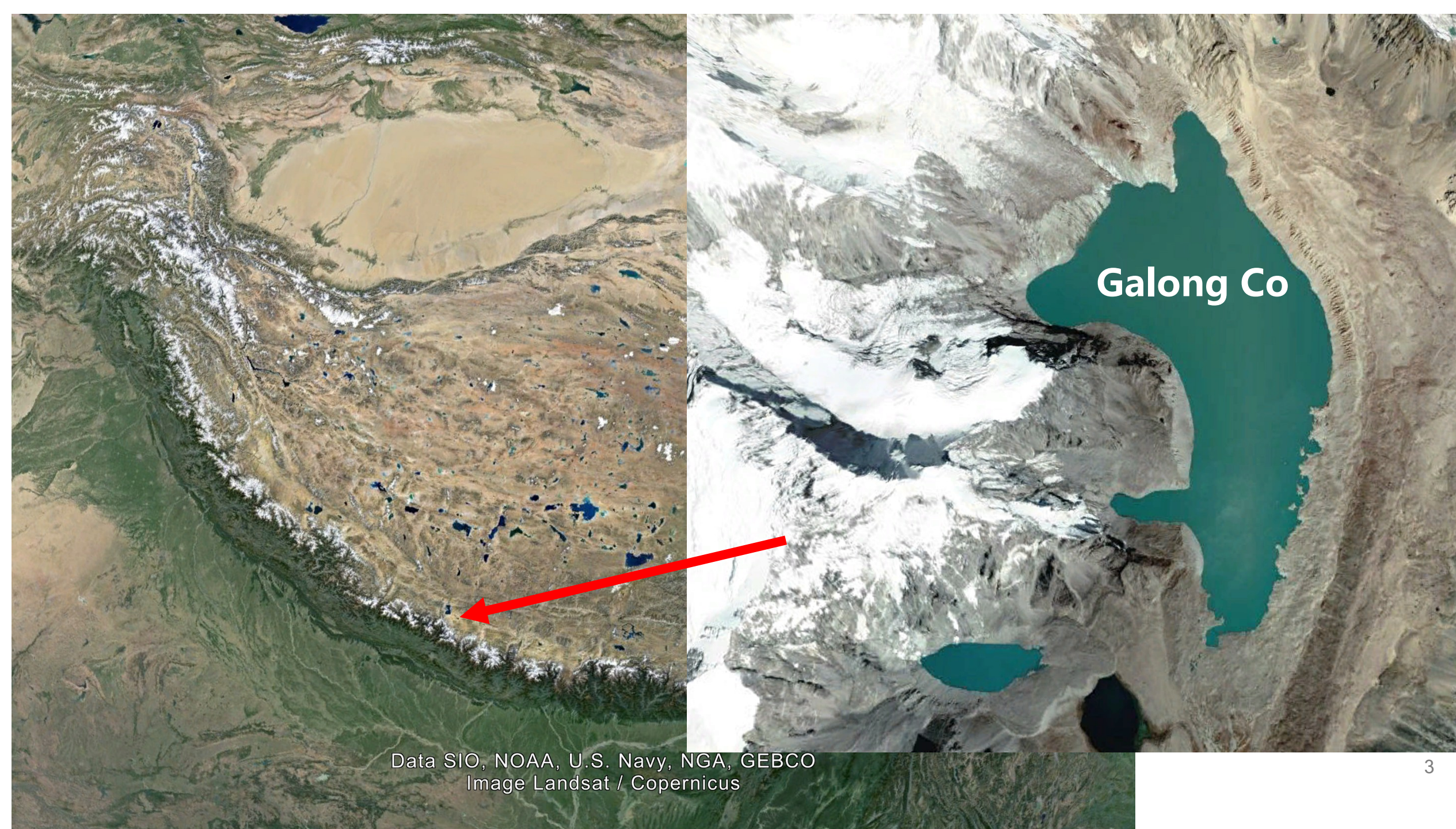


Recent Advances in Glacial Lake Monitoring, Risk Assessment, and Early Warning of Glacial Lake Outburst Floods in the Himalaya

Guoqing Zhang
Xizang University / TPE

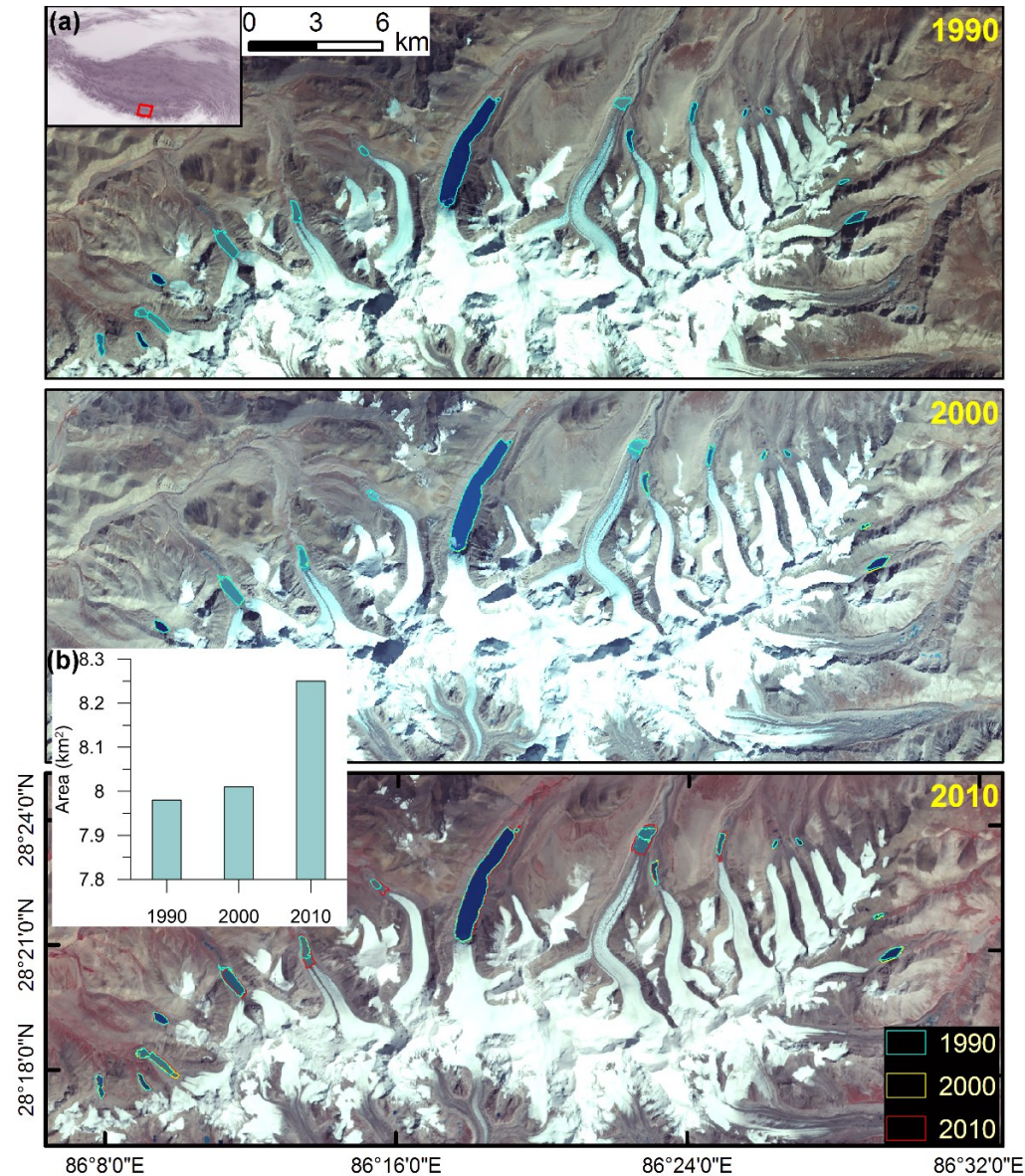
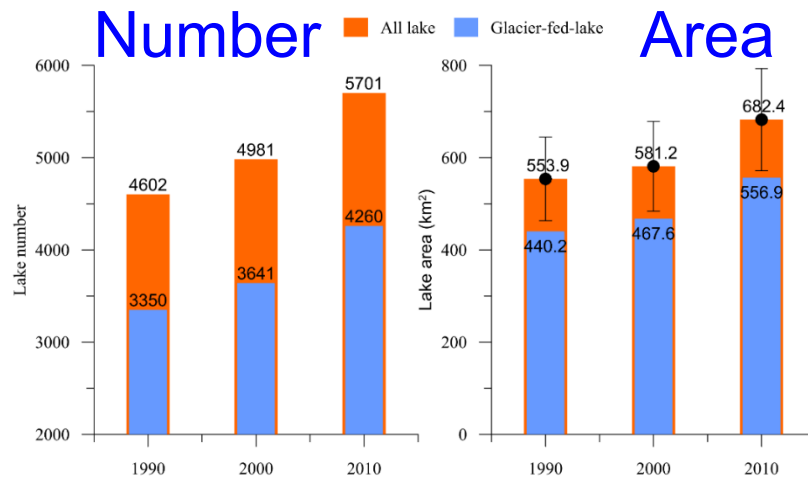
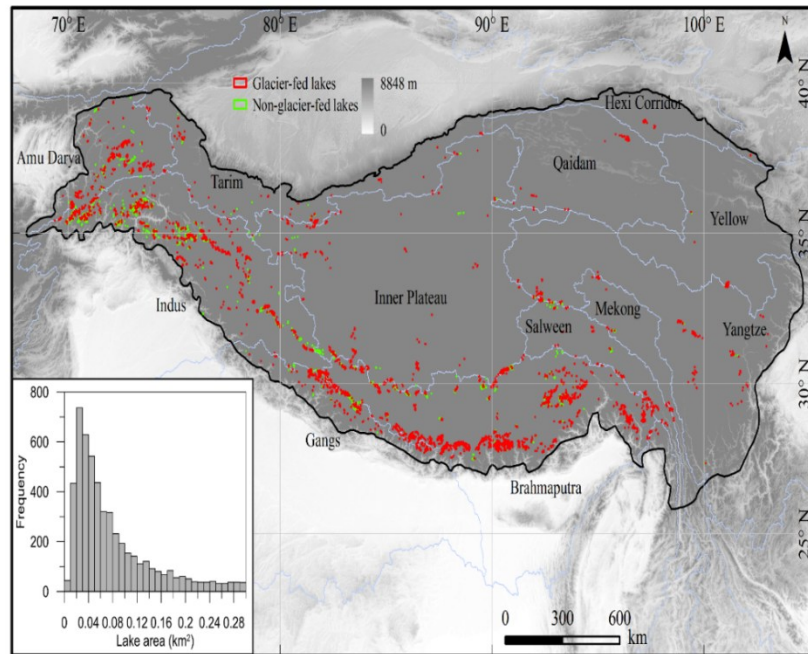
Distribution of lakes in the Third Pole regions





Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

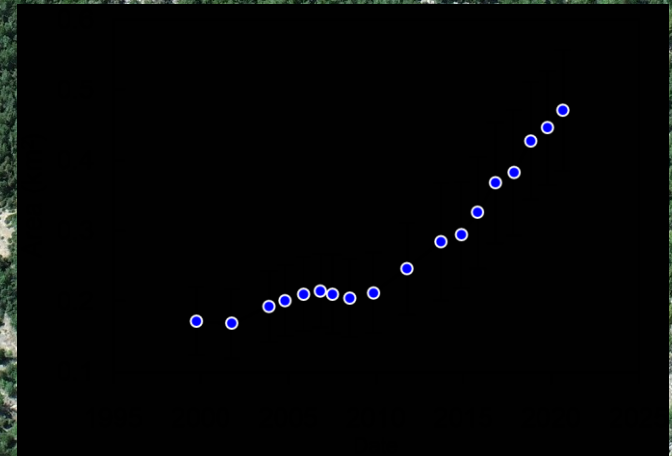
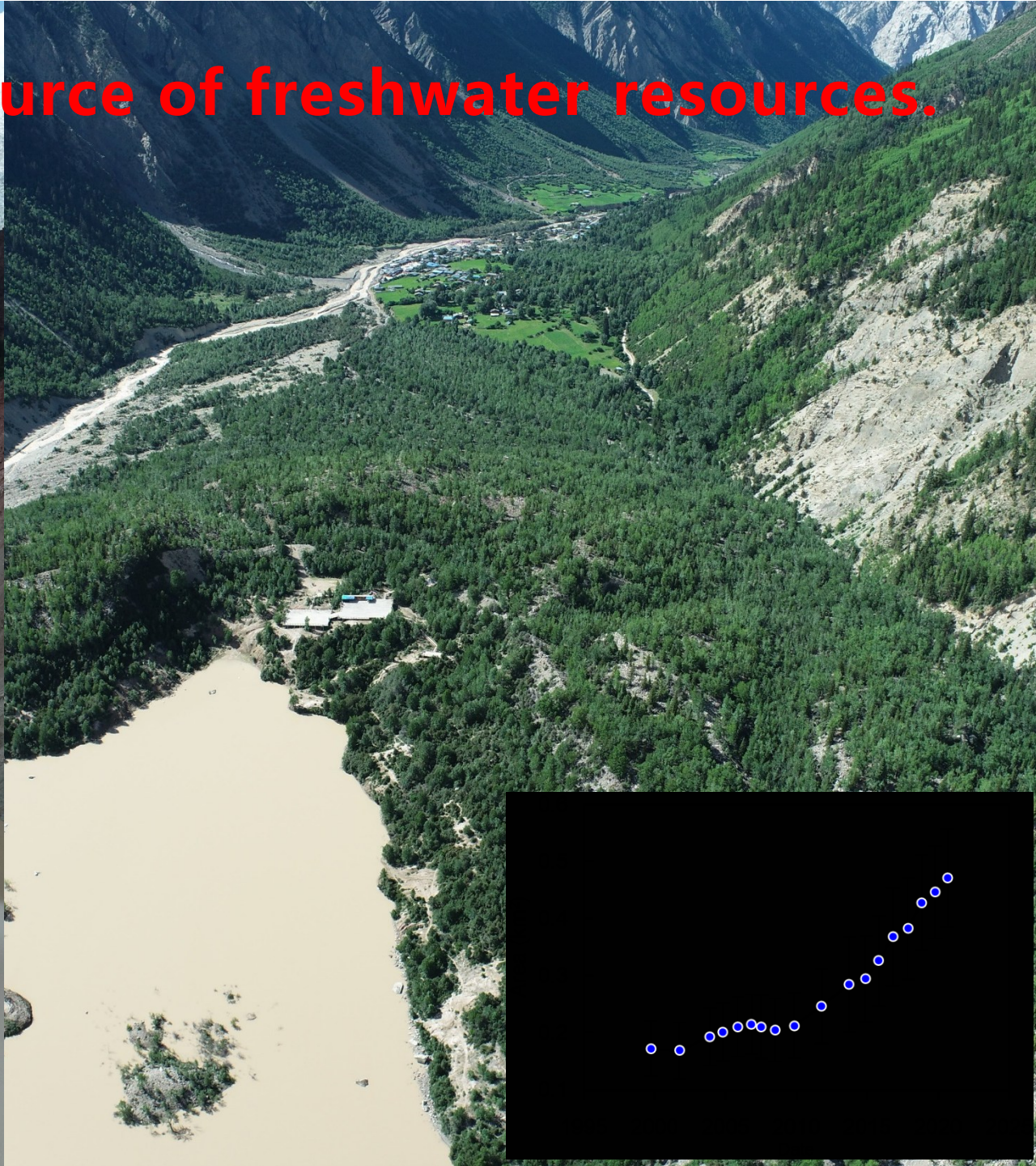
Number and area of **glacial lakes** increasing rapidly



Glacial lakes are a critical source of freshwater resources.



Guangxie Co



Himalayan glacier mass loss

Past

Future

Article

Accelerated global glacier mass loss in the early twenty-first century

<https://doi.org/10.1038/s41586-021-03436-z>

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Accepted: 9 March 2021

Romain Hugonnet^{1,2,3,4,5}, Robert McNabb^{6,8}, Etienne Berthier¹, Brian Menounos^{6,7}, Christopher Nuth^{4,8}, Luc Girod⁴, Daniel Farinotti^{2,9}, Matthias Huss^{2,3,9}, Ines Dussallant¹⁰, Fanny Brun¹¹ & Andreas Kääb⁵

Global glacier mass loss rate from 2000 to 2019 is ~267 Gt/yr, 14 Gt/yr in Himalaya

all of Earth's glaciers. We extensively validate our estimates against independent, high-precision measurements and present a globally complete and consistent estimate of glacier mass change. We show that during 2000–2019, glaciers lost a mass of 267 ± 16 gigatonnes per year, equivalent to 21 ± 3 per cent of the observed sea-level rise⁶. We identify a mass loss acceleration of 48 ± 16 gigatonnes per year per decade, explaining 6 to 19 per cent of the observed acceleration of sea-level rise. Particularly, thinning rates of glaciers outside ice sheet peripheries doubled over the past two decades. Glaciers currently lose more mass, and at similar or larger acceleration rates, than the Greenland or Antarctic ice sheets taken separately^{7–9}. By uncovering the patterns of mass change in many regions, we find contrasting glacier fluctuations that agree with the decadal variability in precipitation and temperature. These include a North Atlantic anomaly of decelerated mass loss, a strongly accelerated loss from northwestern American glaciers, and the apparent end of the Karakoram anomaly of mass gain¹⁰. We anticipate understanding of drivers that our capabilities of predicting benchmarked against observations for the local- and regional-scale risks, as well as for the global

the alteration of coastal areas due to sea-level rise⁴, and to assess the impacts on ecosystems¹⁶ and cryosphere-related hazards⁵. Nevertheless, glacier mass change stands out as one of the least-constrained elements of the global water cycle, identified as a critical research gap in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) of the Intergovernmental Panel on Climate Change (IPCC)⁴. Observational limits stem from the fragmented expanse of glacierized surfaces around the globe. Largely inaccessible, only a few hundred of the more than 200,000 glaciers are monitored in situ¹⁷. Notwithstanding recent progress in glacier monitoring from space¹⁸, global-scale remote-sensing-based studies have been so far limited by (i) the coarse spatial resolution of satellite gravimetry, which

About 200 million people live on land that is predicted to fall below the high-tide lines of rising sea levels by the end of the century¹⁹, whereas more than one billion could face water shortage and food insecurity within the next three decades⁴. Glaciers distinct from the ice sheets hold a prominent role in these outcomes as the largest estimated contributor to twenty-first century sea-level rise after thermal expansion⁷, and as one of the most climate-sensitive constituents of the world's natural water towers^{12,13}. Current glacier retreat temporarily mitigates water stress on populations reliant on ice reserves by increasing river runoff⁸, but this short-lived effect will eventually decline¹⁴. Understanding present-day and future glacier mass change is thus crucial to avoid water-scarcity-induced sociopolitical instability¹⁵, to predict

¹LEGOS, Université de Toulouse, CNRS, CNRS, IRD, UPS, Toulouse, France. ²Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland. ³Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland. ⁴School of Geography and Environmental Sciences, Uster University, Coleraine, UK. ⁵Department of Geosciences, University of Oslo, Oslo, Norway. ⁶Geography Earth and Environmental Sciences, University of Northern British Columbia, Prince George, BC, Canada. ⁷The Norwegian Defense Research Establishment, Kjeller, Norway. ⁸Department of Geosciences, University of Zurich, Zurich, Switzerland. ⁹IGE, Université Grenoble Alpes, CNRS, IRD, Grenoble INP, Grenoble, France. ¹⁰met

RESEARCH

GLACIERS

Global glacier change in the 21st century: Every increase in temperature matters

David R. Rounce^{1,2,*}, Regine Hock^{2,3}, Fabien Maussion⁴, Romain Hugonnet^{5,6,7}, William Kochtitzky^{8,9}, Matthias Huss^{5,6,10}, Etienne Berthier⁷, Douglas Brinkerhoff¹¹, Loris Compagno^{5,6}, Luke Copland⁸, Daniel Farinotti^{5,6}, Brian Menounos^{12,13}, Robert W. McNabb¹⁴

flowline model (7) based on the shallow-ice approximation (16), the effects of debris thickness on sub-debris melt rates (17), and frontal ablation (8). Our estimates of glacier contribution to sea level rise also account for the ~15% of ice from marine-terminating glaciers that is already below sea level (18). Projections are also reported for SSPs and RCPs to highlight differences compared with previous studies.

Global glacier mass loss of 44% by 2100 under SSP5-8.5 scenario, more than 70% in the Himalaya, with glaciers in the southeast largely disappearing

Glaciers, here referring to all glacial land ice excluding the Greenland and Antarctic ice sheets, are responsible for $21 \pm 3\%$ of sea level rise from 2000 to 2019, contributing 0.74 ± 0.04 mm sea level equivalent (SLE) yr^{-1} (1). Projections suggest this contribution could increase to 2.5 mm SLE yr^{-1} by 2100 (2). Glaciers are also a critical water resource for ~1.9 billion people (3),

results were extended to shared socioeconomic pathways (SSPs) using statistical models of these simulations (6). GlacierMIP provided these projections at regional scales based on simulations from 11 glacier evolution models that varied with respect to the complexity of model physics, simulated physical processes, model calibration, spatial resolution, and modeling domain. Calibration data varied from in situ

is of less than 300 of the world's 5,000 glaciers to regional geogravitric mass balance observations. Furthermore, only one global model glacier dynamics using a flowline whereas all others relied on eme-area scaling or parameterizations of mass redistribution; only one model accounted for frontal ablation (i.e., the sum of iceberg calving and submarine melt) of marine-terminating glaciers (8), whereas all others treated any glacier as land-terminating; further, no global model accounted for debris cover. Existing multimodel projections (2, 6, 9) are thus limited to regional scales and neglect key physical processes controlling glacier mass loss.

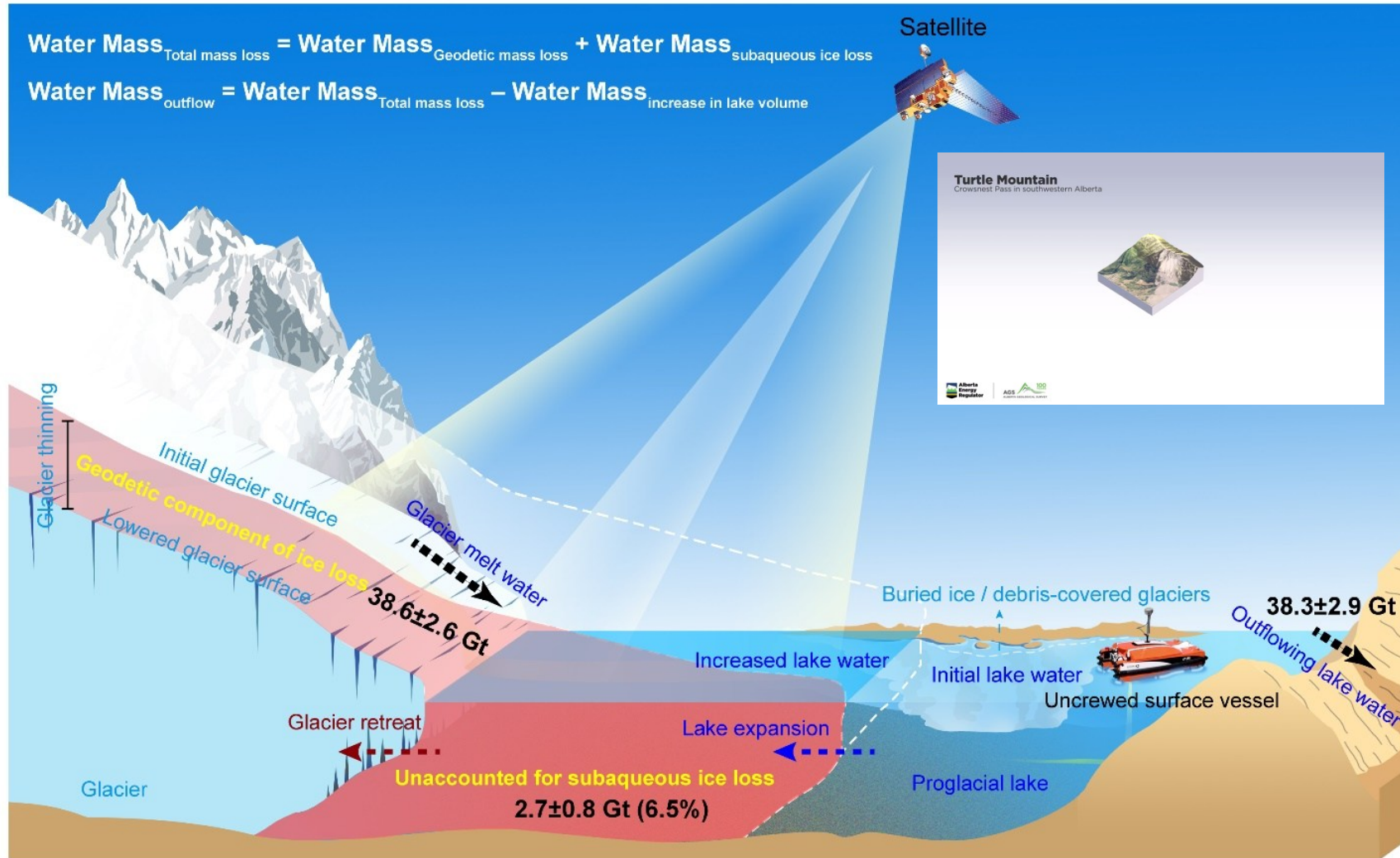
We produce a set of global glacier projections for every glacier on Earth for SSPs from 2015 to 2100 by leveraging global glacier mass balance data (1) and near-global frontal ablation data (10–13). To provide policy-relevant scenarios, our projections are grouped based on mean global temperature increases by the

mean temperature increases, the glacier projections are aggregated into +1.5°C, +2°C, +3°C, and +4°C temperature change scenarios by 2100 relative to preindustrial levels (Fig. 1).

Globally, glaciers are projected to lose $26 \pm 6\%$ (+1.5°C) to $41 \pm 11\%$ (+4°C) of their mass by 2100, relative to 2015 [ensemble median $\pm 95\%$ confidence interval (CI)]. This mass loss would increase mean sea level by 90 ± 26 mm SLE under the +1.5°C scenario and 99 ± 31 mm SLE under the +2°C scenario. The higher temperature change scenarios of +3°C and +4°C lead to contributions of 125 ± 39 and 154 ± 44 mm SLE, respectively, highlighting a 71% increase between the +1.5°C and +4°C scenarios.

The rate of sea level rise from glacier mass loss near the end of the 21st century ranges from 0.70 ± 0.45 to 2.23 ± 1.08 mm SLE yr^{-1} depending on the temperature change scenario (fig. S1). For +1.5°C, the rate of sea level rise peaks at 1.29 ± 0.59 mm SLE yr^{-1} around 2035 and declines thereafter whereas the rate for +4°C steadily increases for the remainder of this century. Similar trends are observed in the area-averaged mass loss rate, where the maximum loss rate of 0.82 ± 0.36 m water equivalent (w.e.) yr^{-1} occurs around 2035 before diminishing to 0.59 ± 0.34 m w.e. yr^{-1} at the end of the century for the +1.5°C scenario; the mass

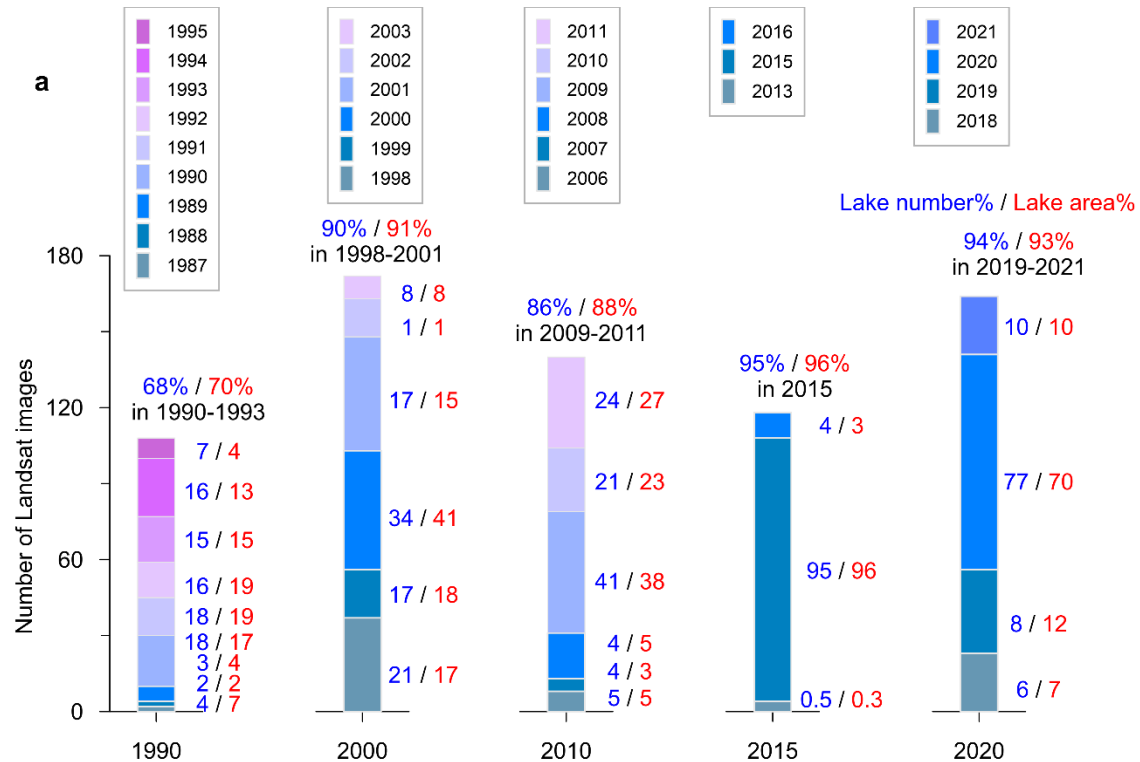
Hidden Himalayan glacier melt



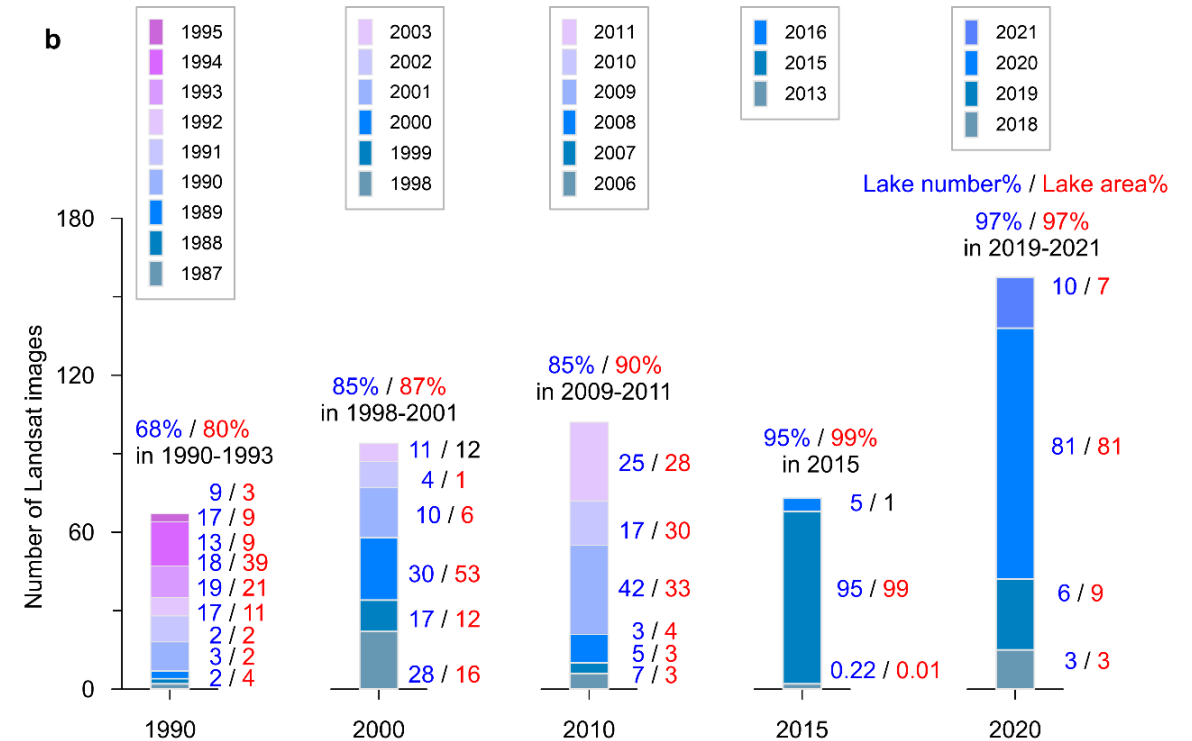
Mapping of Himalayan glacial lakes from 1990 to 2020

Landsat imagery used, 702 scenes, over 120 scenes per period

All glacial lakes

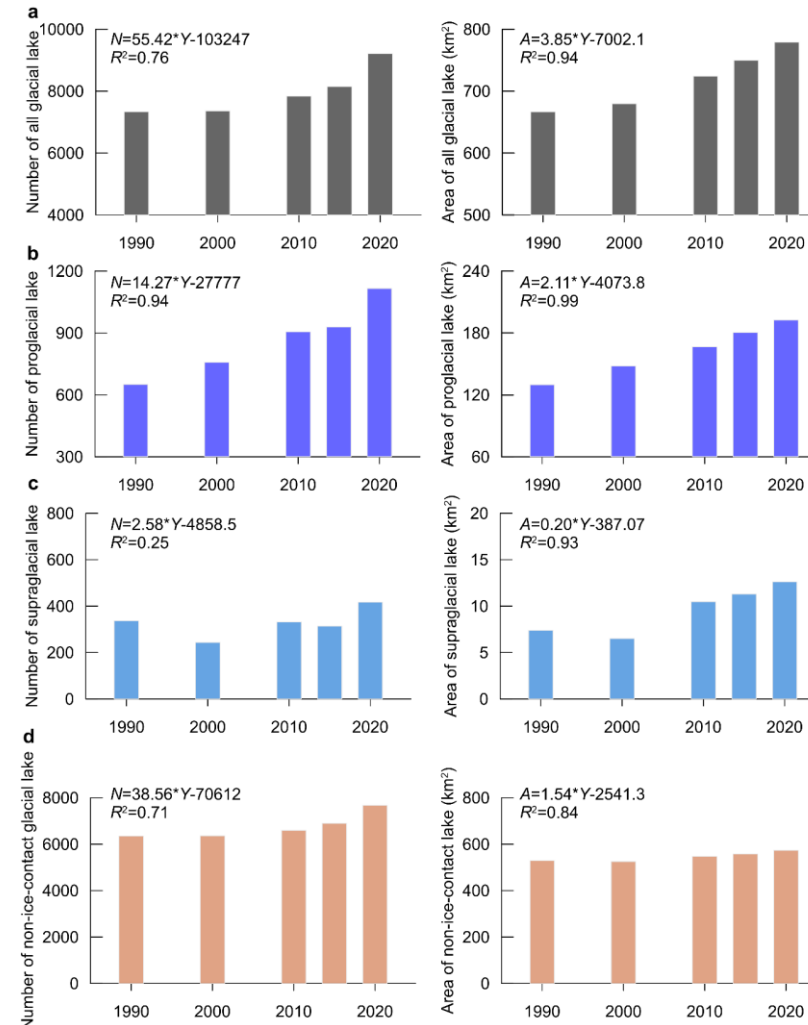
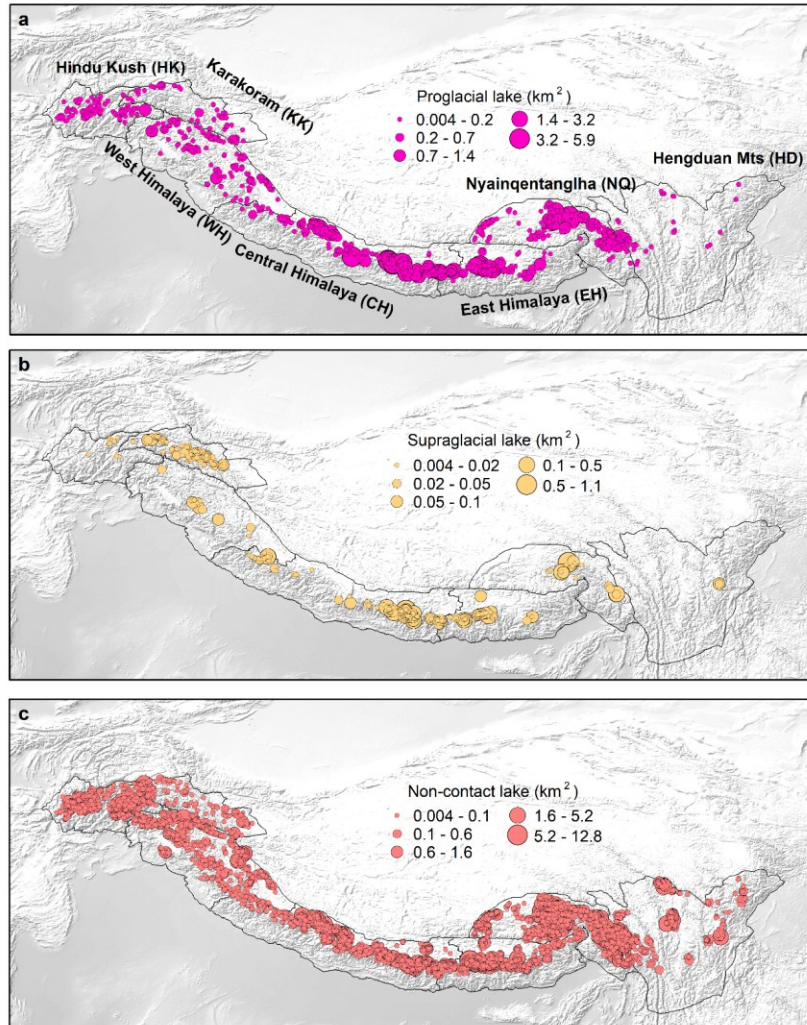


Proglacial lakes



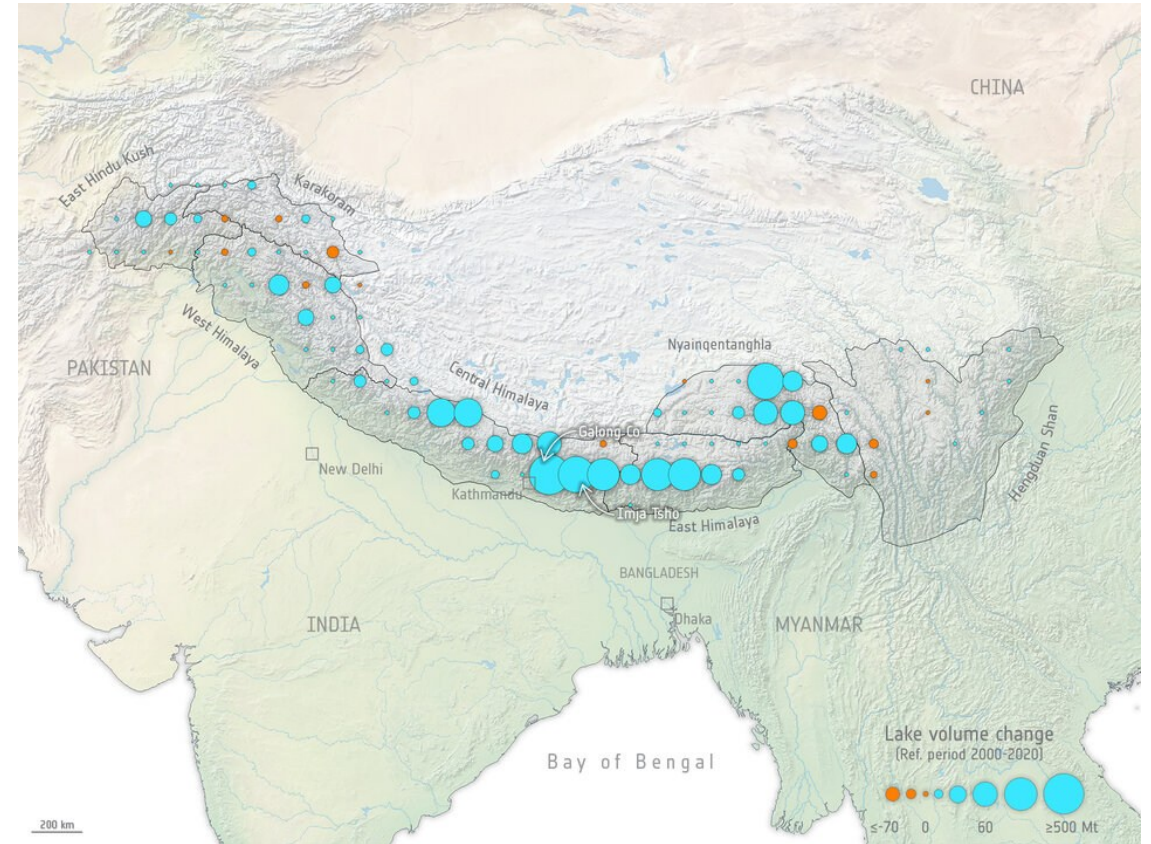
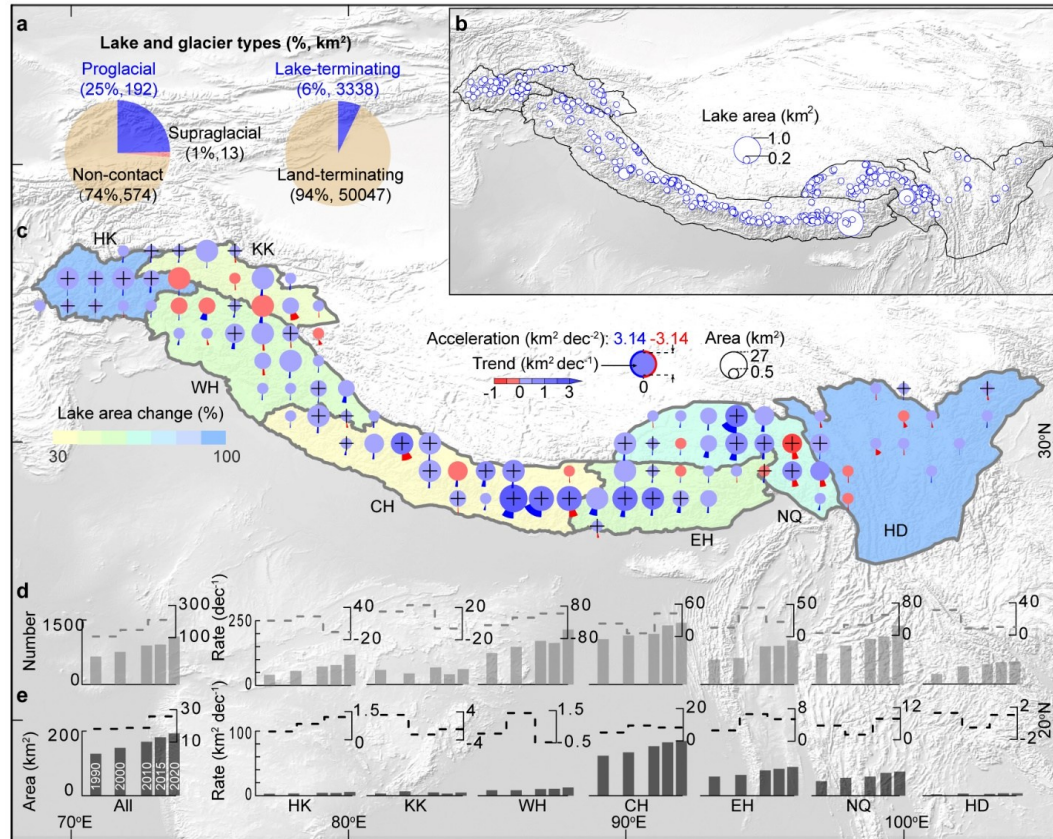
Distribution and variability of Himalayan glacial lakes

9,209 glacial lakes in 2020, 1,115 are proglacial lakes, accounting for 12% of total number and 25% of total area, 25% increase in number and 17% increase in area in 1990-2020.



Spatio-temporal variations of proglacial lakes

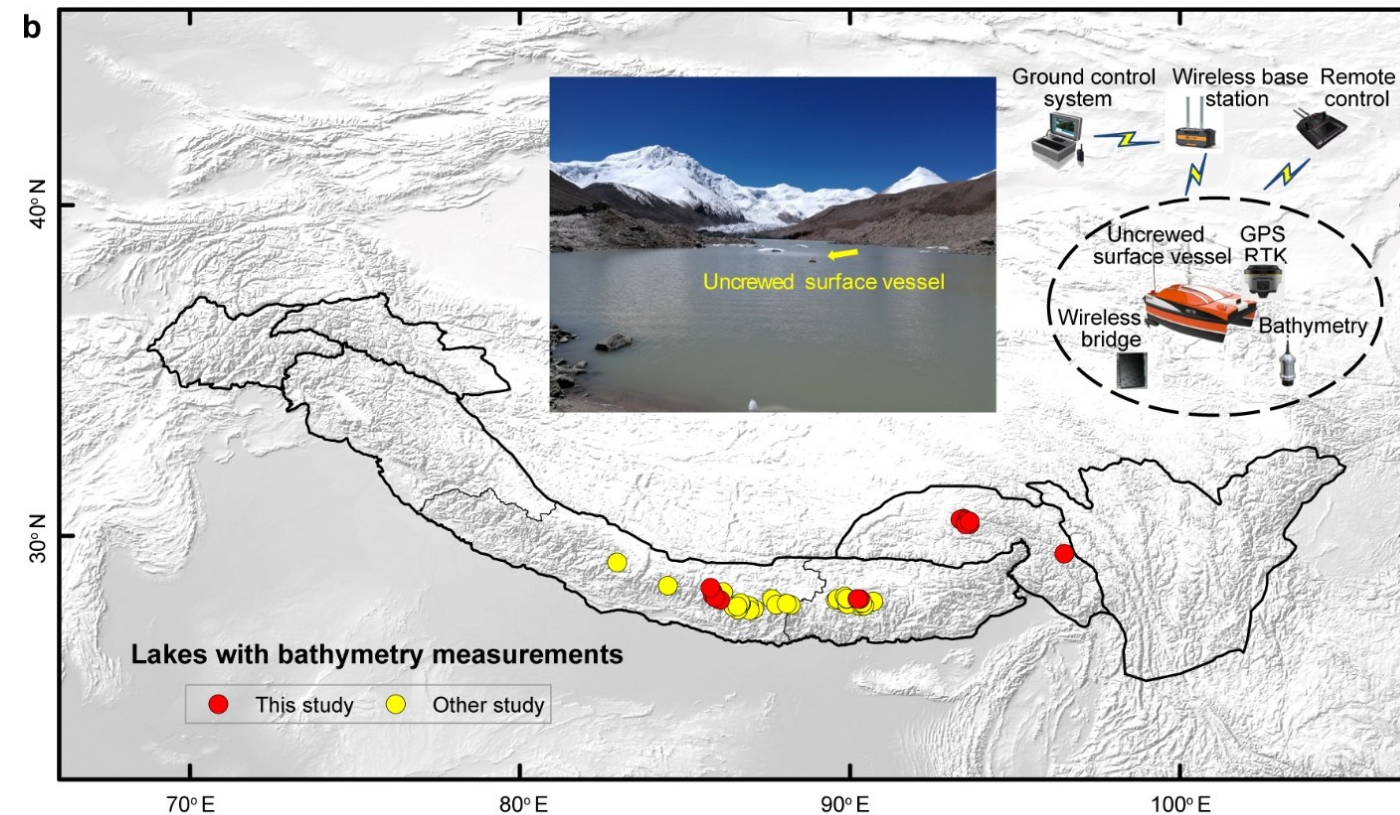
Increase in number of proglacial lakes from 651 in 1990 to 1,115 in 2020 (+71%), area from 129.76 to 192.42 km² (+48%).



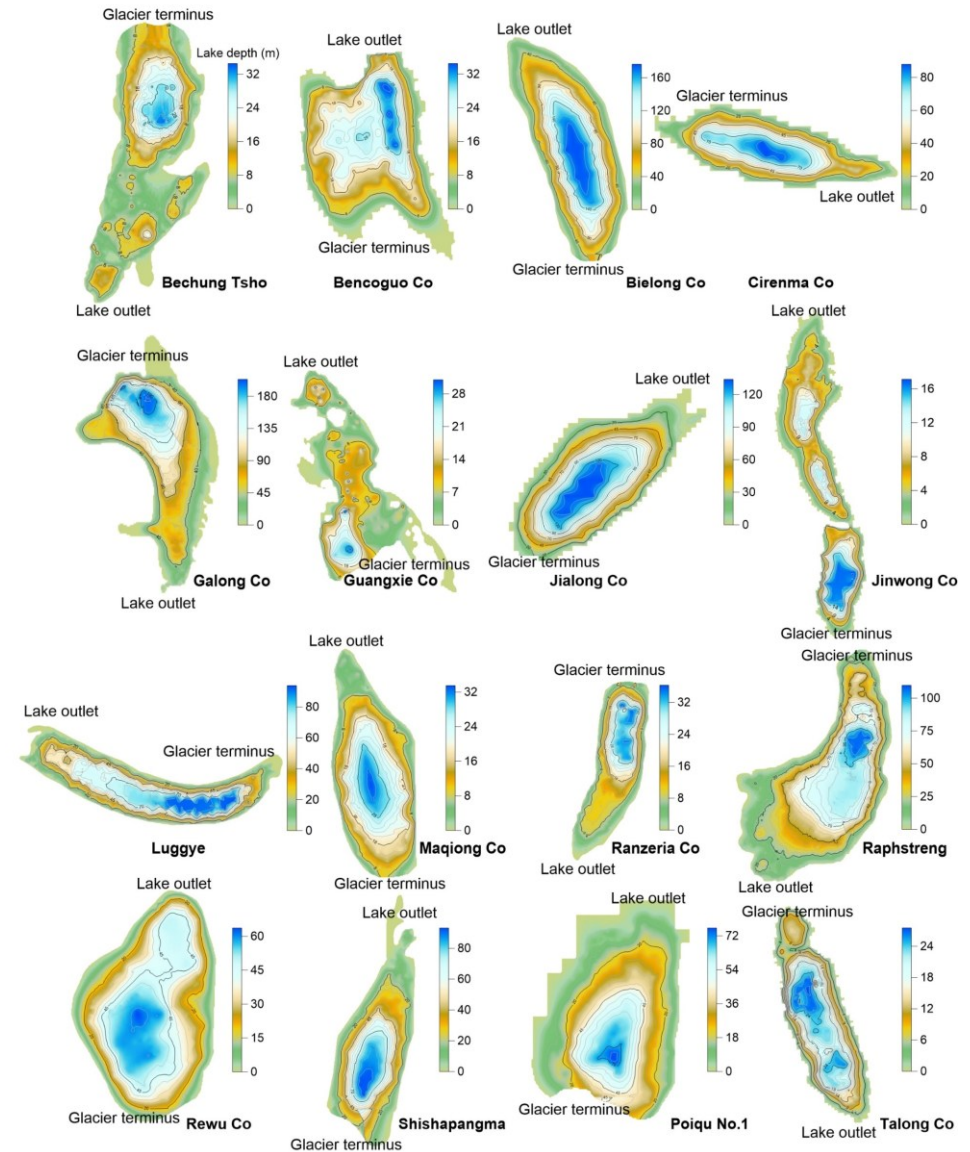
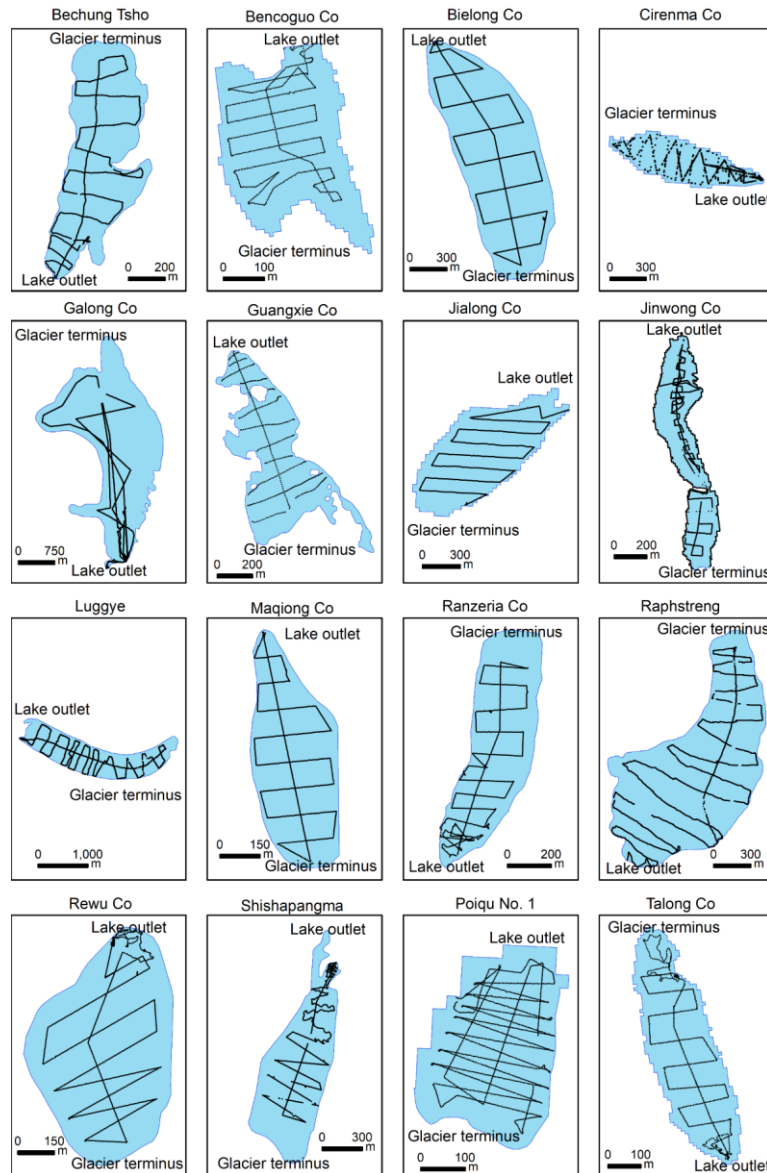
16 glacial lakes surveyed from 2017 to 2022

47 lakes (59 times) bathymetry measurements

16 lakes in this study



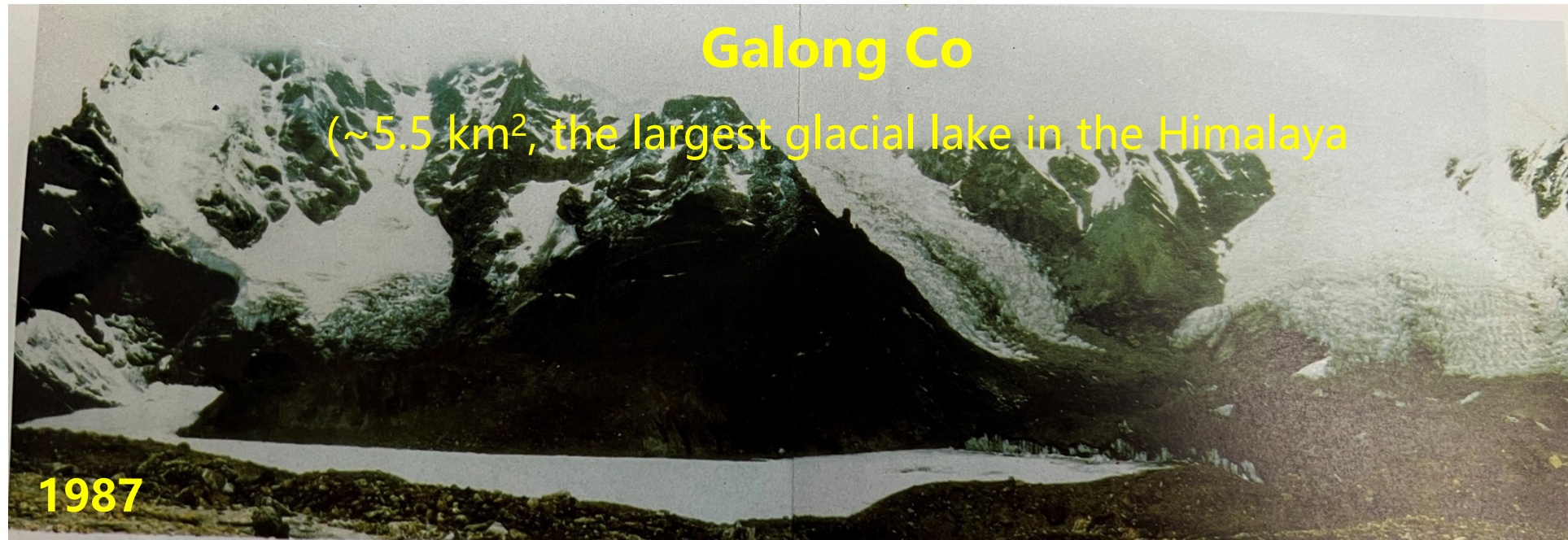
Bathymetries of 16 glacial lakes measured



Jialong Co

Glacier retreat and glacial lake expansion

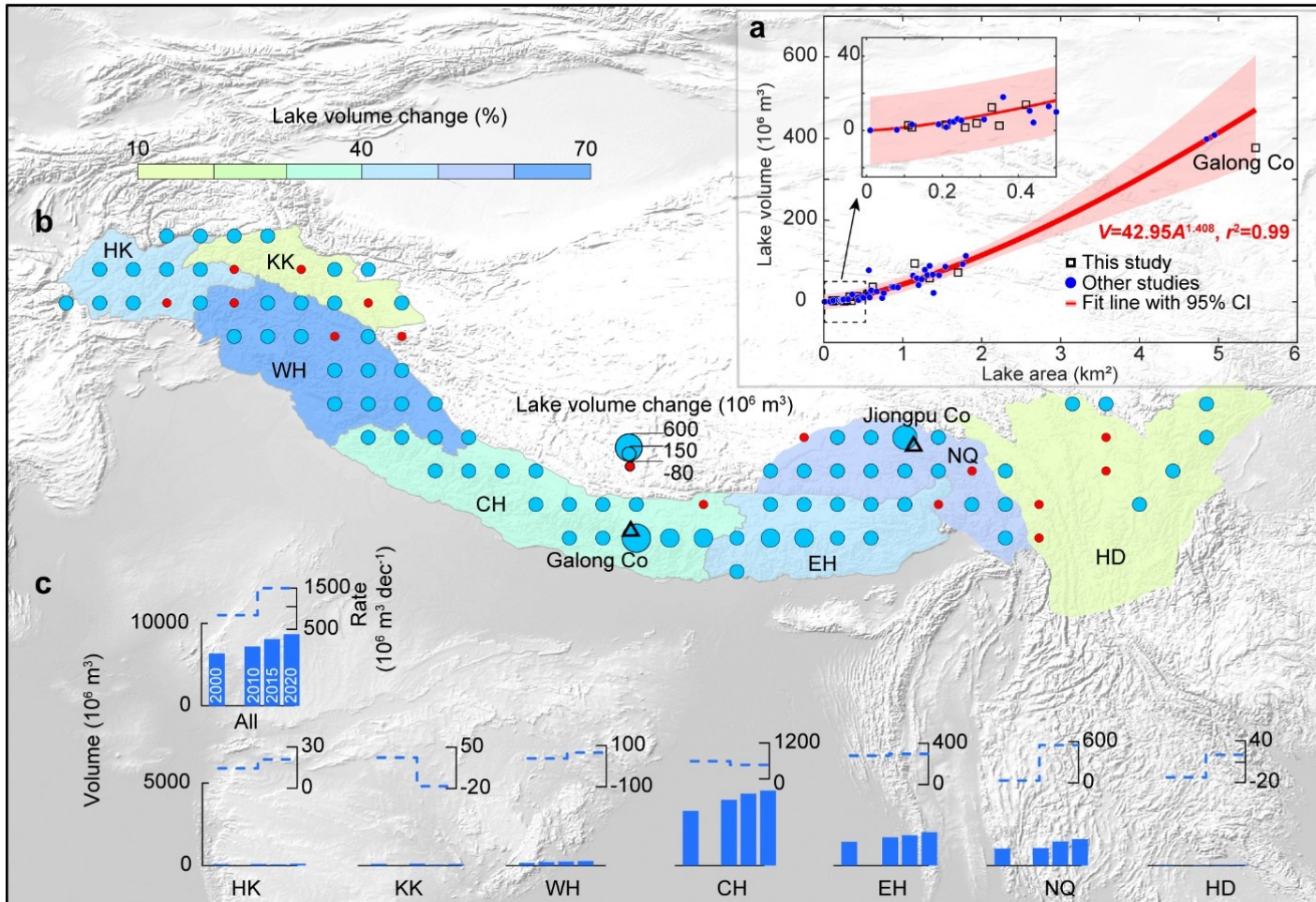






Galong Co

Changes in proglacial lake volume

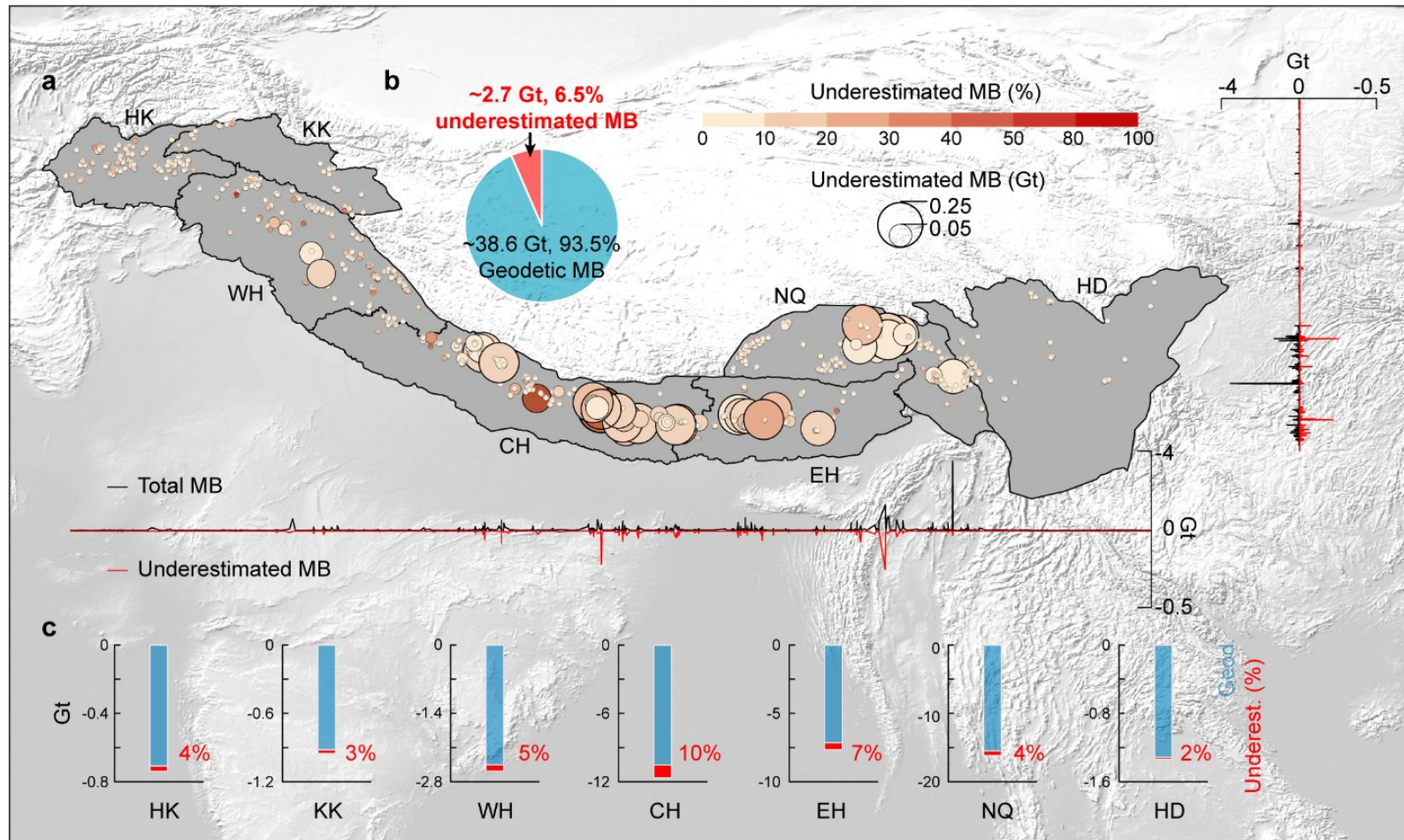


Establishment of an empirical formulae for lake volume-area of 47 (59 times) measured glacial lakes.

The volume of lake water increased from **6.1 km³ in 2000 to 8.7 km³ in 2020**, an increase of 42%.

Hidden glacier mass loss in the Himalaya

About 2.7 Gt of subaqueous mass loss has been underestimated from 2000 to 2020, representing ~6.5% of total mass loss of lake-terminating glaciers.



Glacial Lake Outburst Floods (GLOFs) and their damage

GLOF of Poiqu No.1 in 2002



GLOF of Ranzeria Co in 2013



GLOF of Gongbatongsha Co in 2016





GLOF of Jinweng Co in 2020



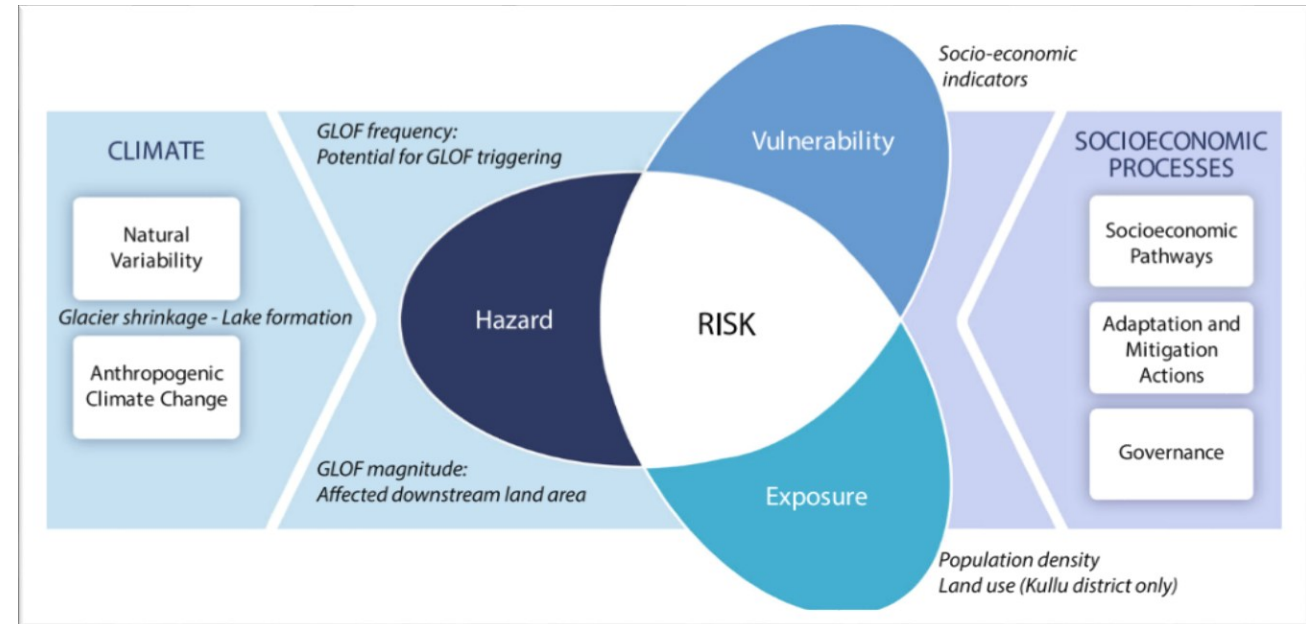
GLOF of South Lhonak Lake in Sikkim, India on 4 October 2023

GLOF in Thame village, Everest Region on 16 August 2024



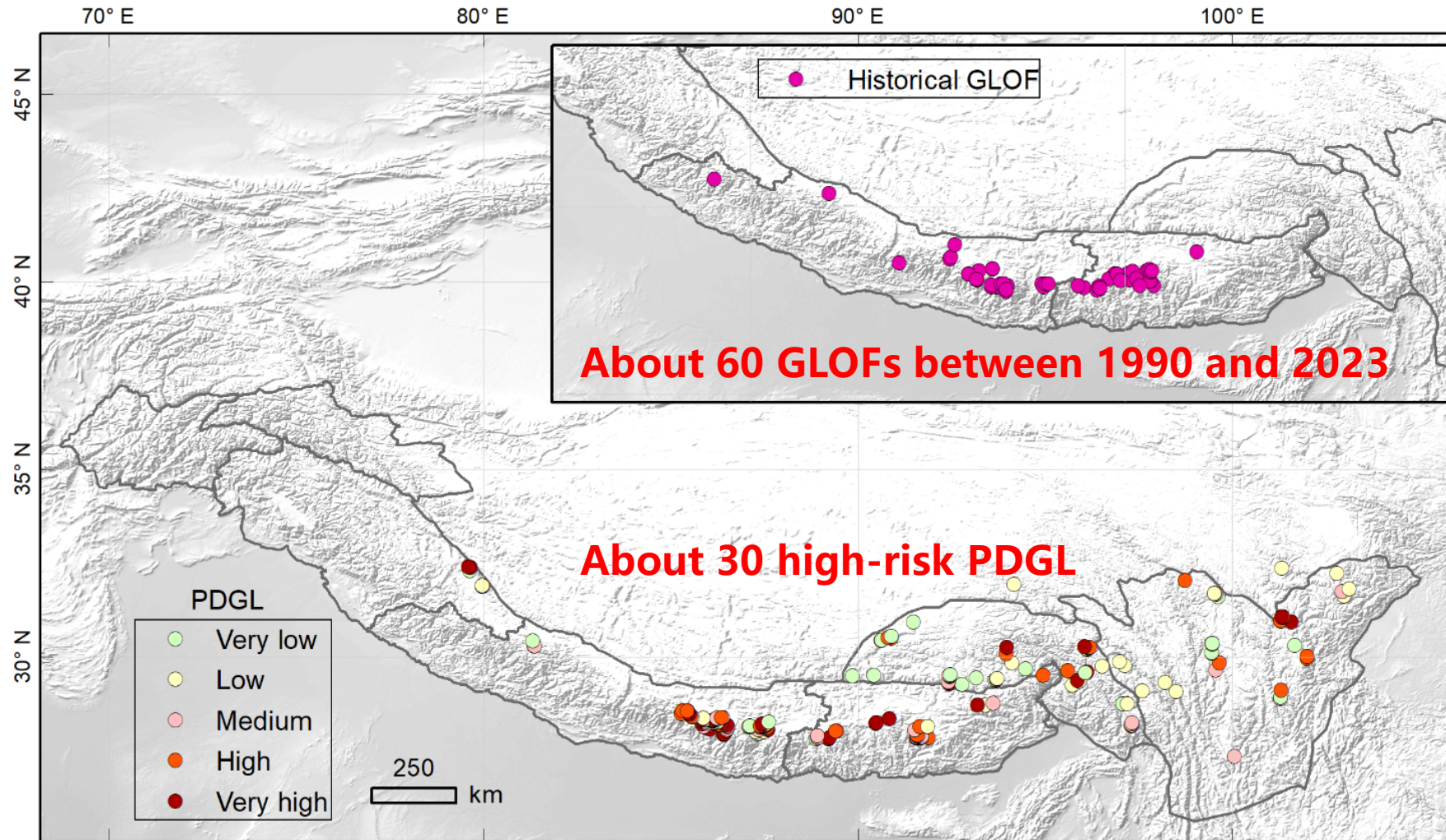
Photo: Pasanglhamu Rural Municipality

GLOF impact and risk assessment



Allen et al., 2016, Nat Hazards

Historical GLOFs and potential dangerous glacial lakes in China



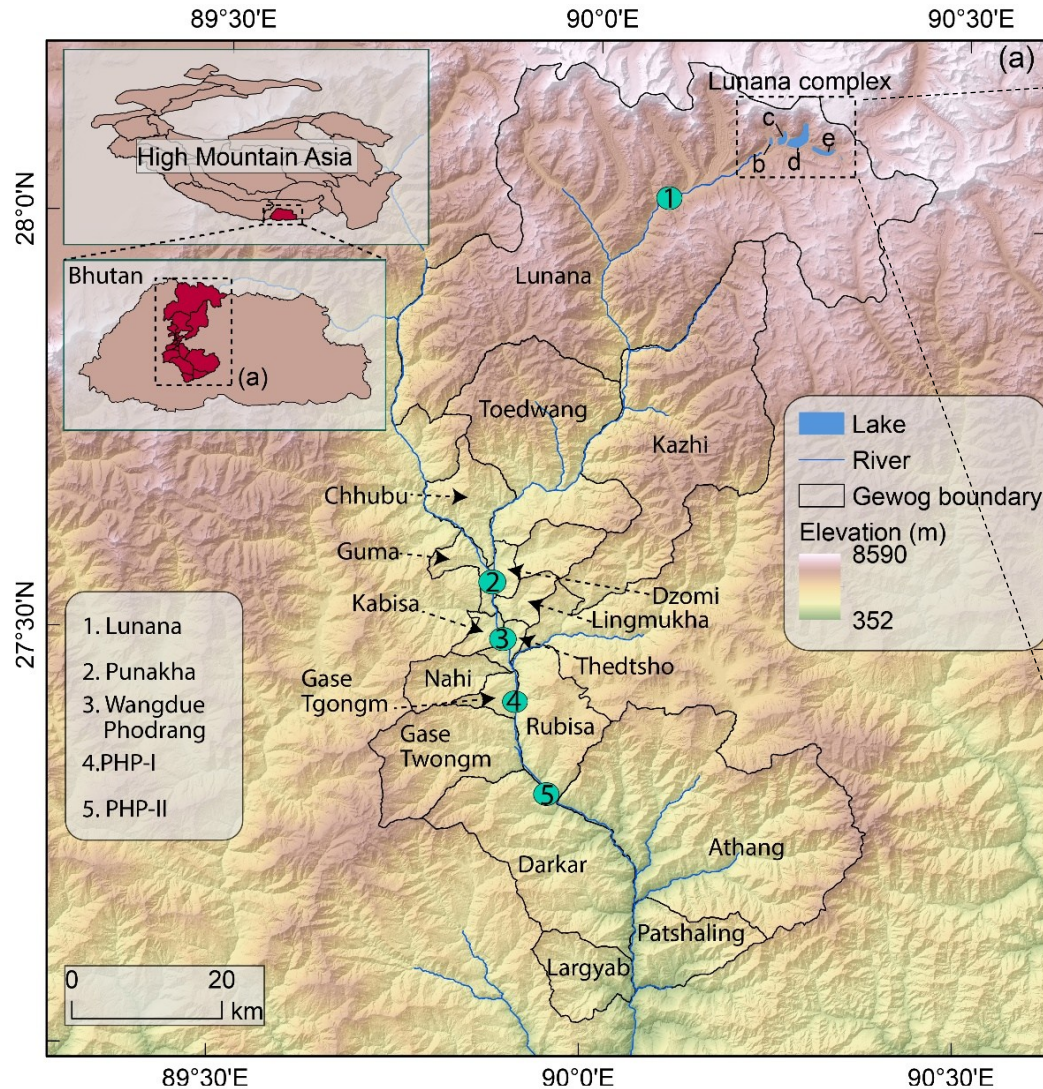
Risk of potentially dangerous glacial lakes in the Bhutan Himalaya

The Lunana glacier complex contains **4** of the most PDGLs, where Lugge Tsho has caused a significant outburst flood disaster and more than **30 deaths** in 1994



Rinzin, Zhang et al., JoH, 2023

Locations of 4 potentially dangerous glacial lakes



Field photos

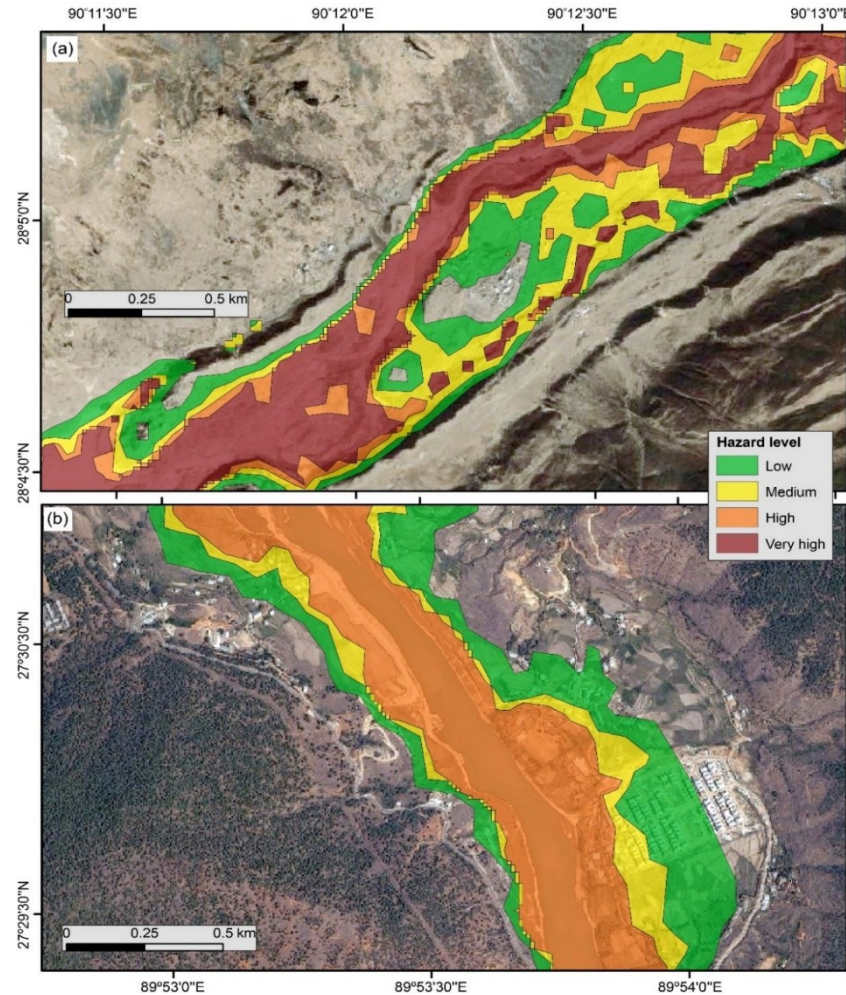


Bechung Tsho

Raphstreng Tsho

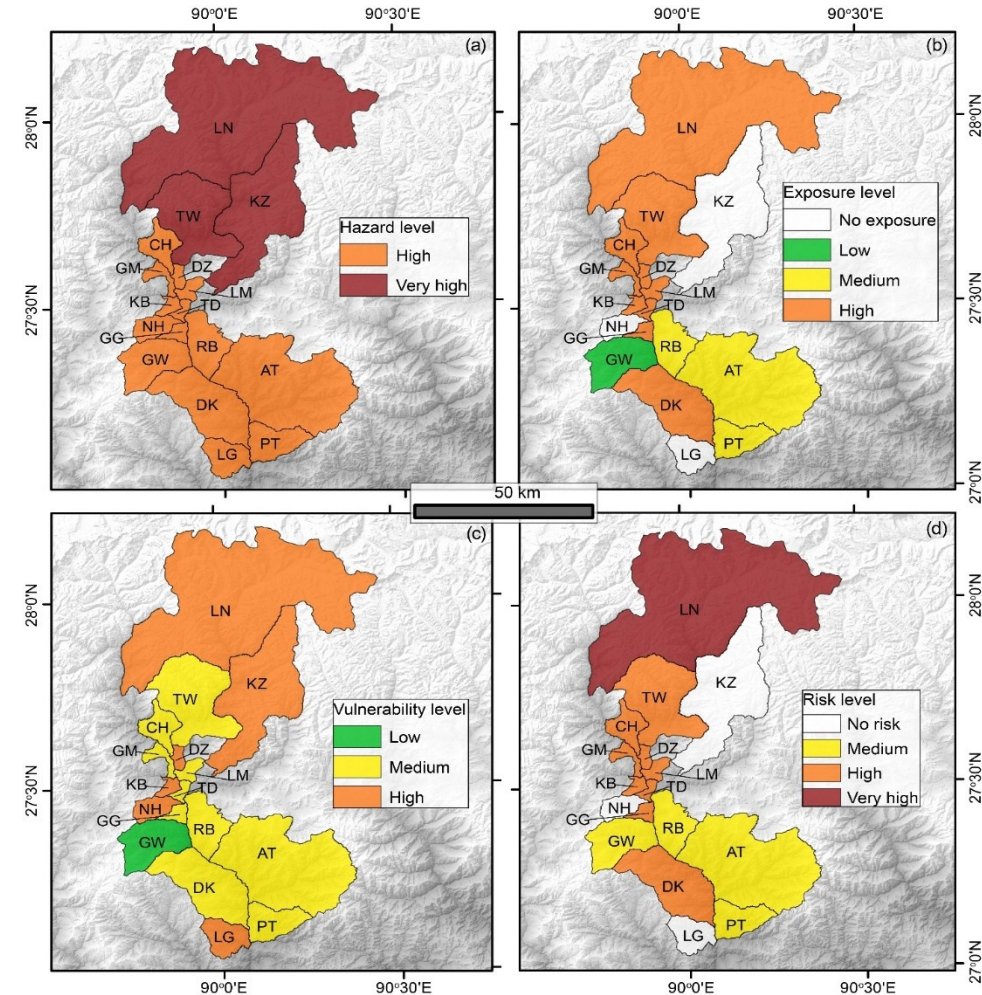
Thorthormi Tsho

Downstream **hazard**, **exposure**, and **risk**



Hazard zone

Very high: 15.6% Medium: 14.5%
High: 42.4% Low: 27.4%



Exposed items

2 hydropower projects, and 2,721 buildings affecting 16,062 people

GLOF: 30 October 2023, trigger: glacier avalanche



Credit: <https://www.bbs.bt/news>

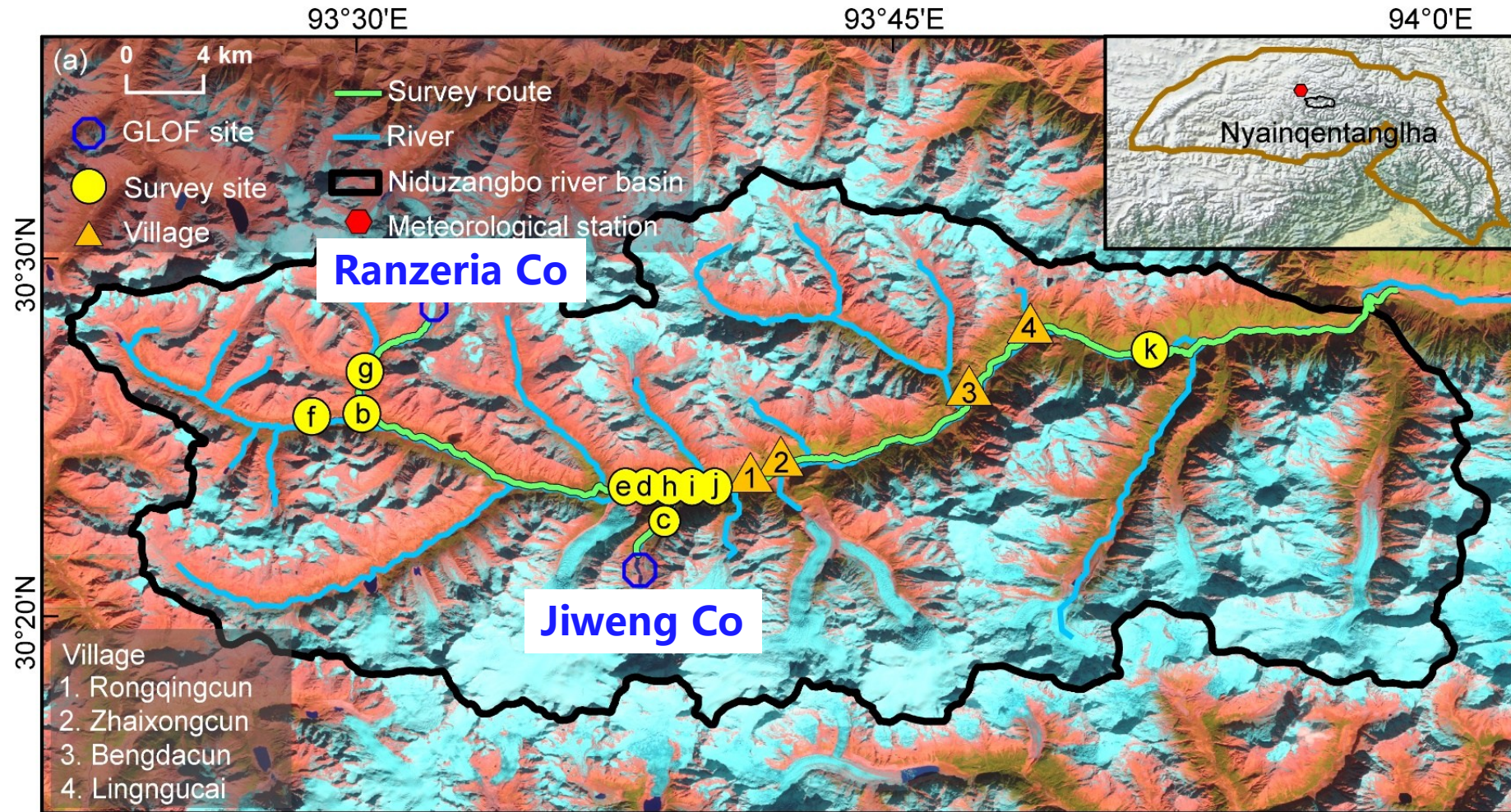
Cascading hazards from two recent GLOFs

In the past decade, two lakes ([Ranzeria Co in 2013](#) and [Jiweng Co in 2020](#)) burst within a single river basin in the eastern Nyainqêntanglha range.



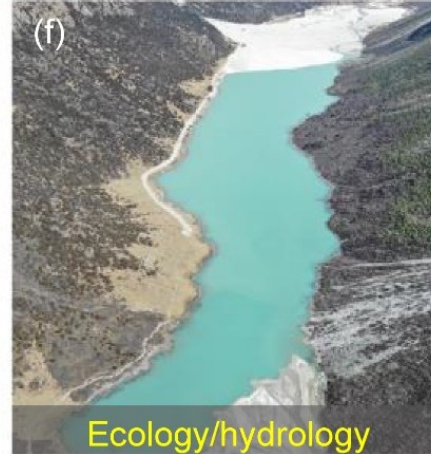
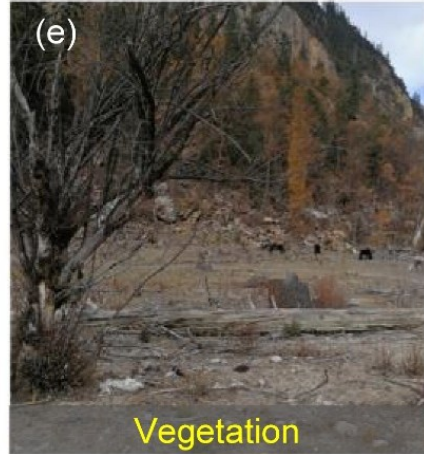
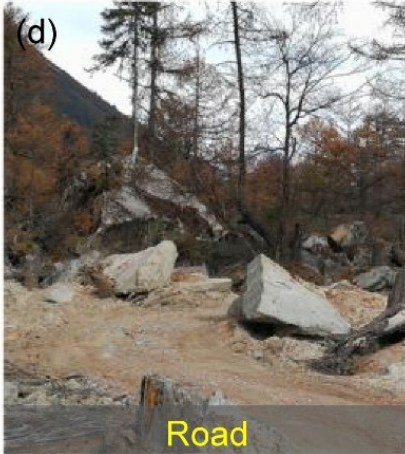
Peng, Wang, Zhang et al., JoH, 2023

Locations of Ranzeria Co and Jiweng Co

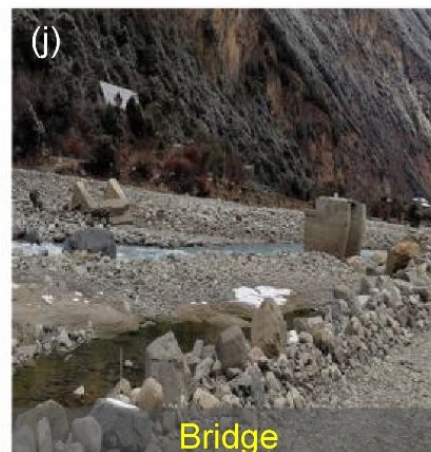
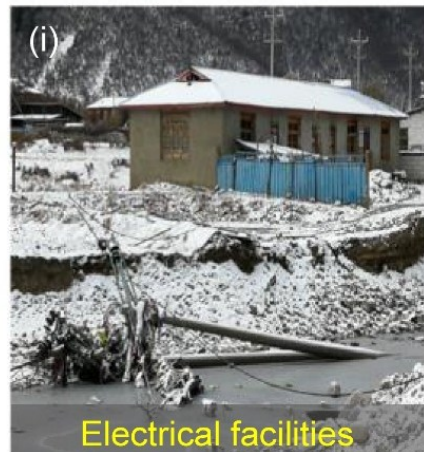


Damage from two GLOFs

Ranzeria Co



Jiweng Co





18 Nov. 2020



Erosion

18 Nov. 2020



Ranzeria Co

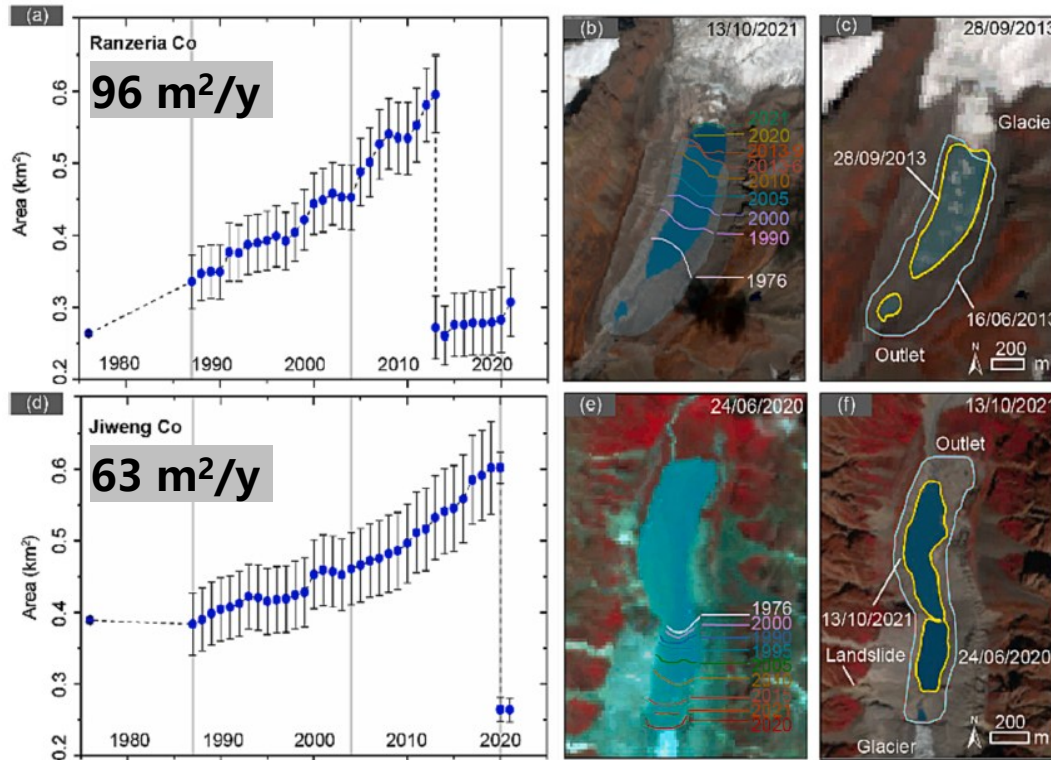


Landslide

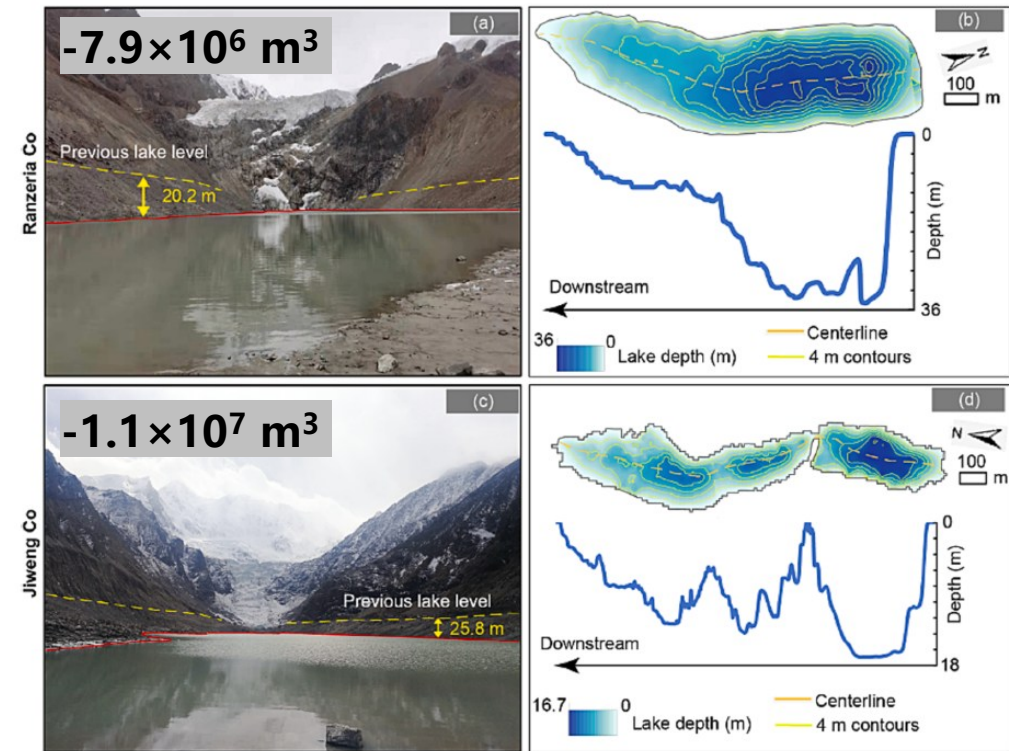
Jiweng Co

Changes of glacial lake area and volume

Ranzeria Co expanded by **123%** from 1976 to 2012 and contracted by **53%** in 2013 due to the outburst. Jiweng Co grew by **54%** from 1976 to 2020 and shrank by **57%** after the dam breach.



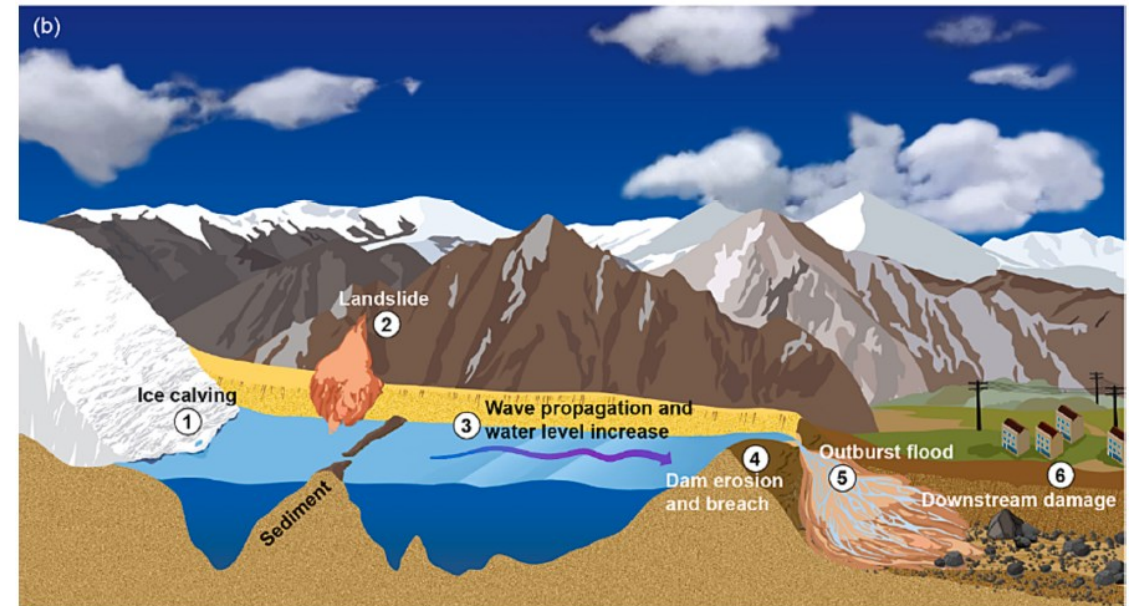
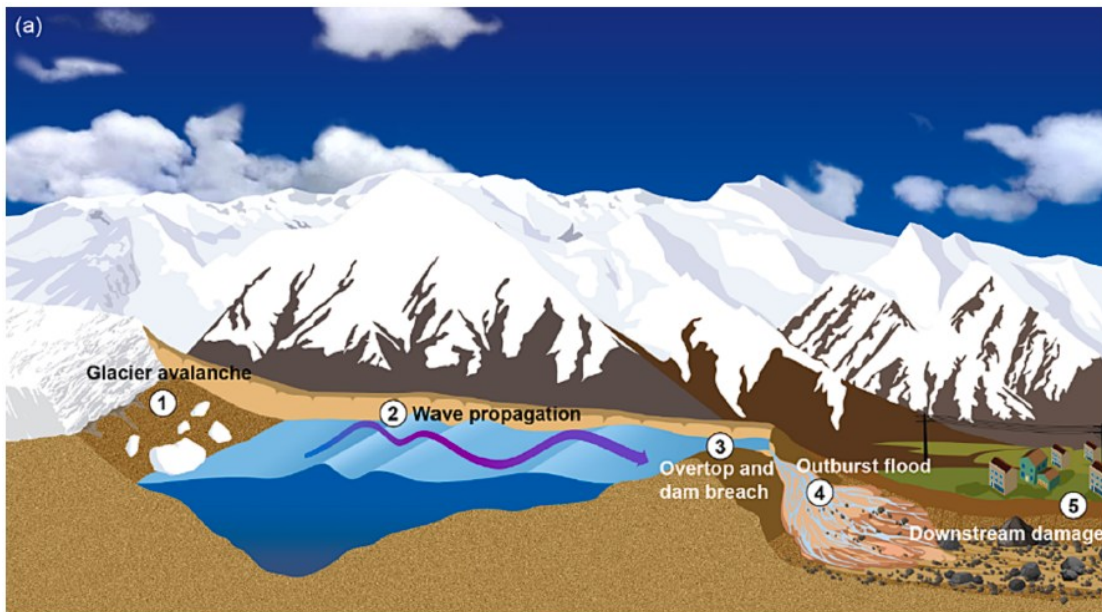
Change in lake area between 1976 and 2021



Change in level/volume pre/post-outburst

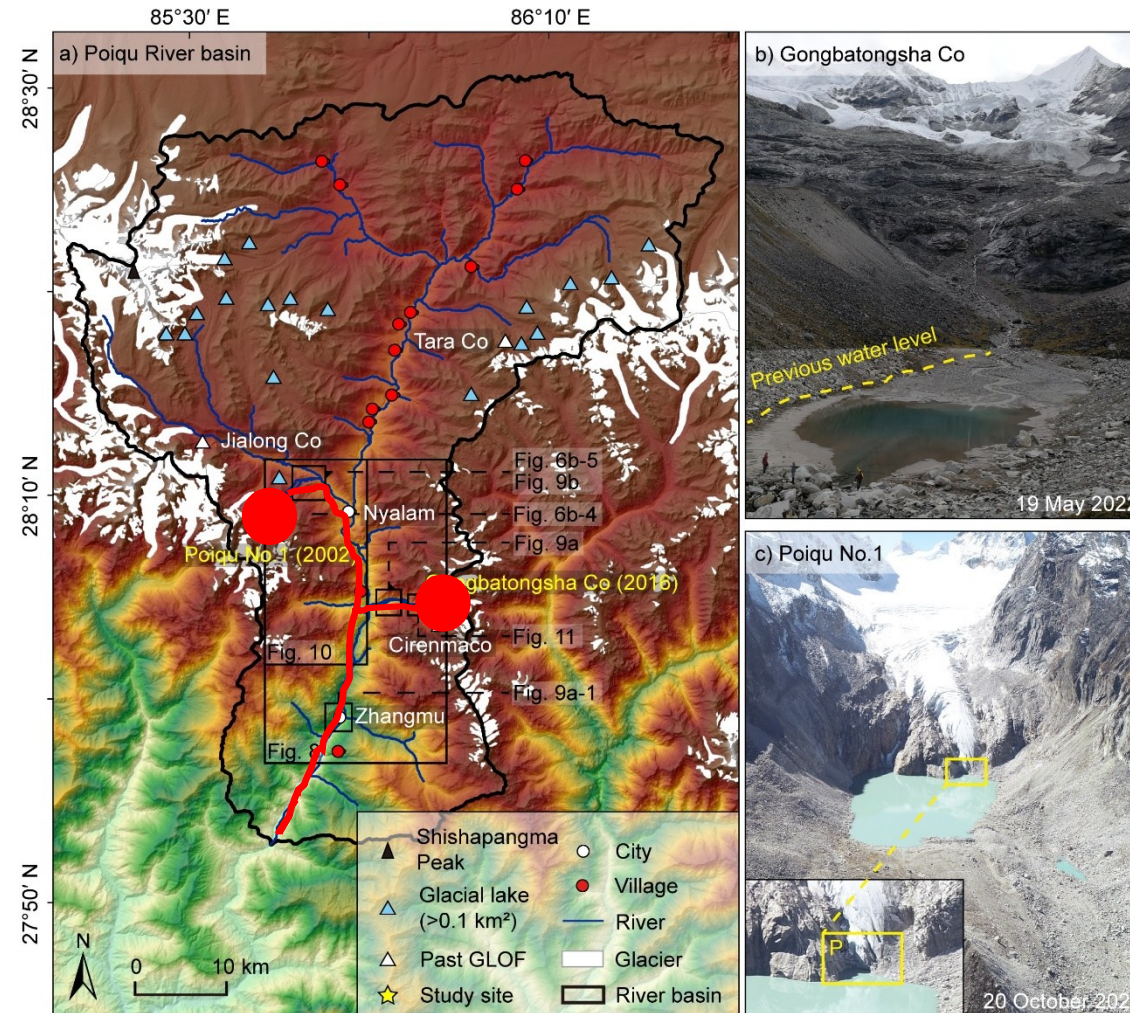
Chain process of two GLOF events

Ranzeria Co: outburst immediately by glacier avalanche and **overtopping**;
Jiweng Co: outburst gradually because of **dam erosion** caused by successive landslides

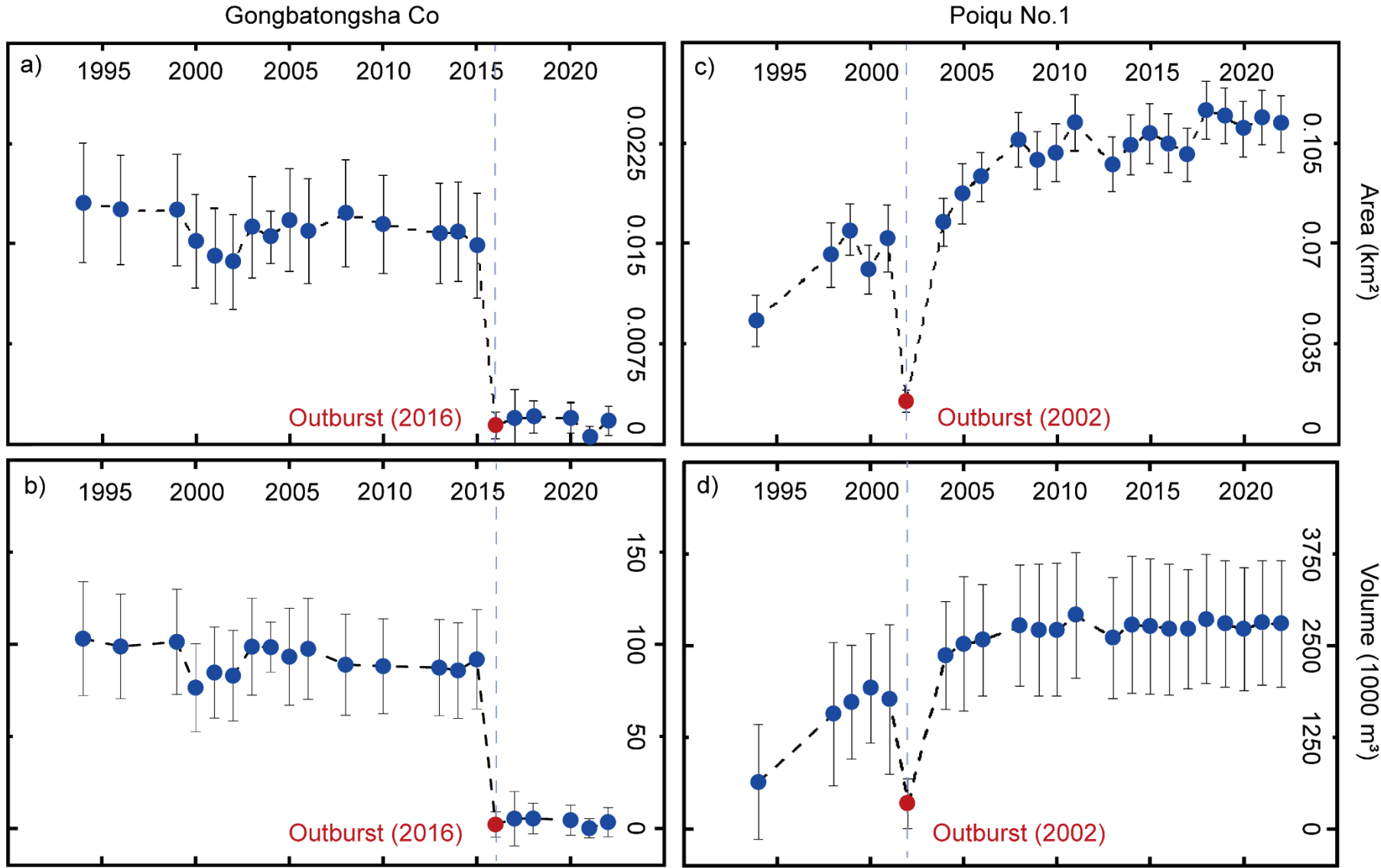


Reconstruction of GLOFs in the Nyalam Poiqu River basin

GLOFs of Gongbatongsha Co on 5 July 2016 and Poiqu No.1 on 23 May 2002



Changes in area and volume before and after dam failure





Gongbatongsha Co

19 May 2022



19 May 2022

An aerial photograph of a high-altitude mountain landscape. A central glacier flows downwards from a mountain peak, branching out into a fan-like shape at the bottom. The surrounding terrain is rugged and rocky, with patches of snow and ice. The text "Poiqu No.1" is overlaid in red in the upper center of the image.

Poiqu No.1

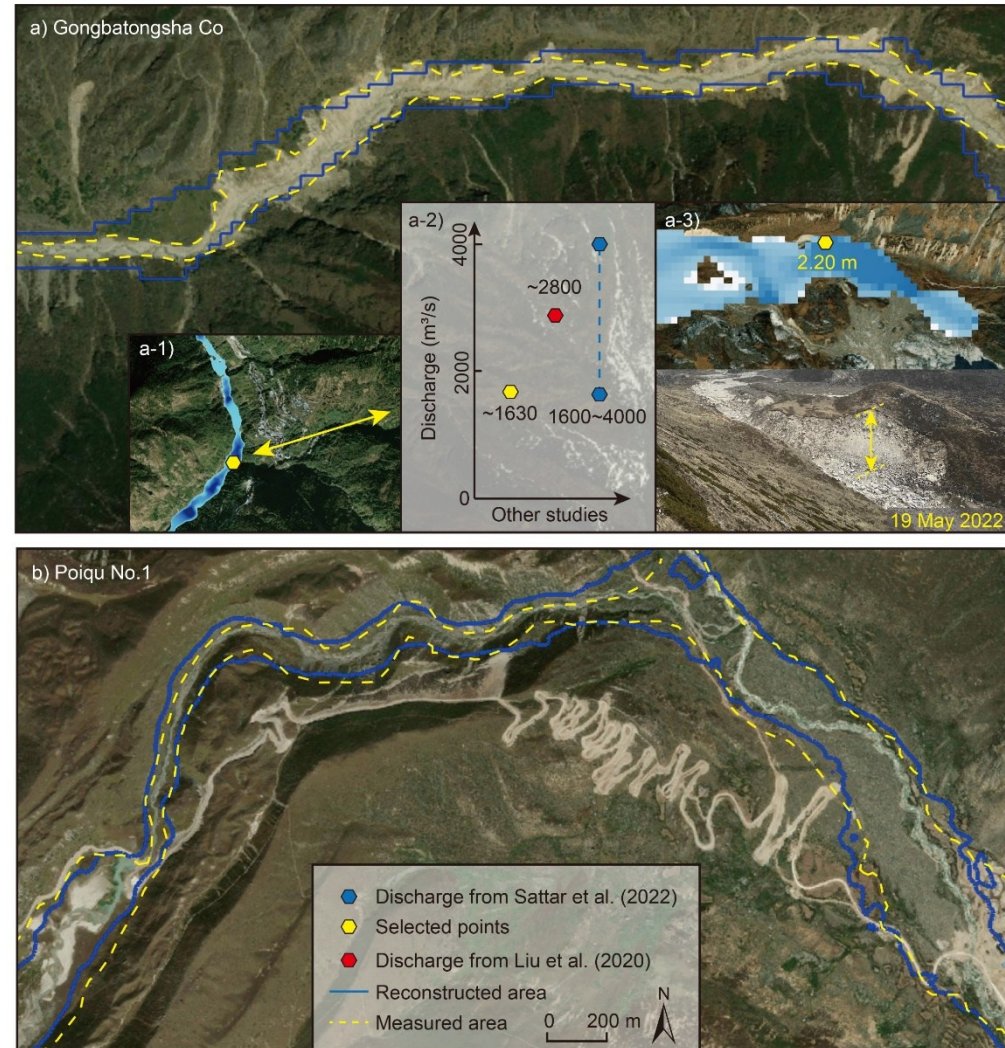
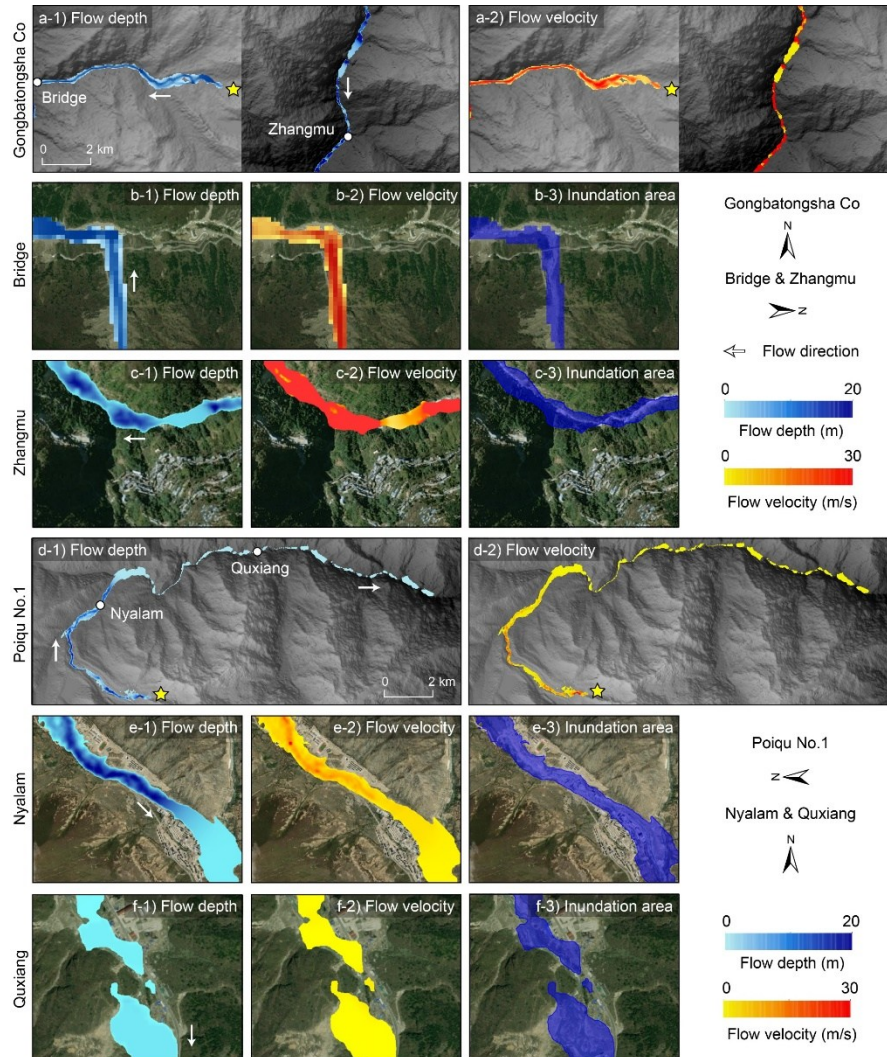
29 Sep. 2023



29 Sep. 2023

Flood water depth and flow velocity reconstruction

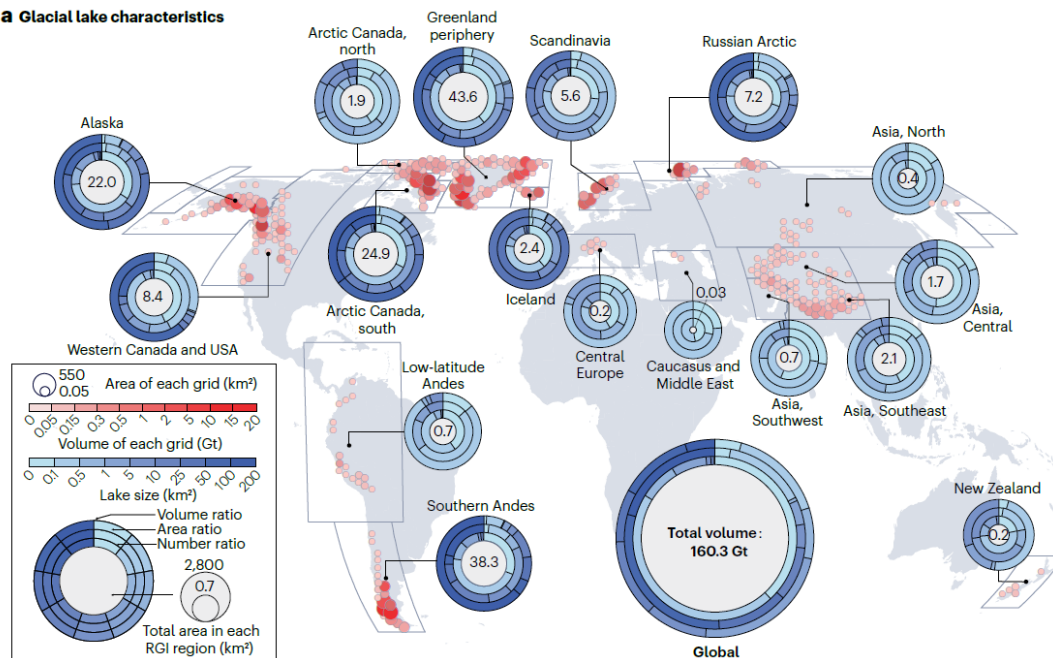
Peak discharge of Gongbatongsha Co in Zhangmu town is $\sim 1600 \text{ m}^3/\text{s}$, and Poiqu No.1 in Nyalam county is $\sim 1000 \text{ m}^3/\text{s}$.



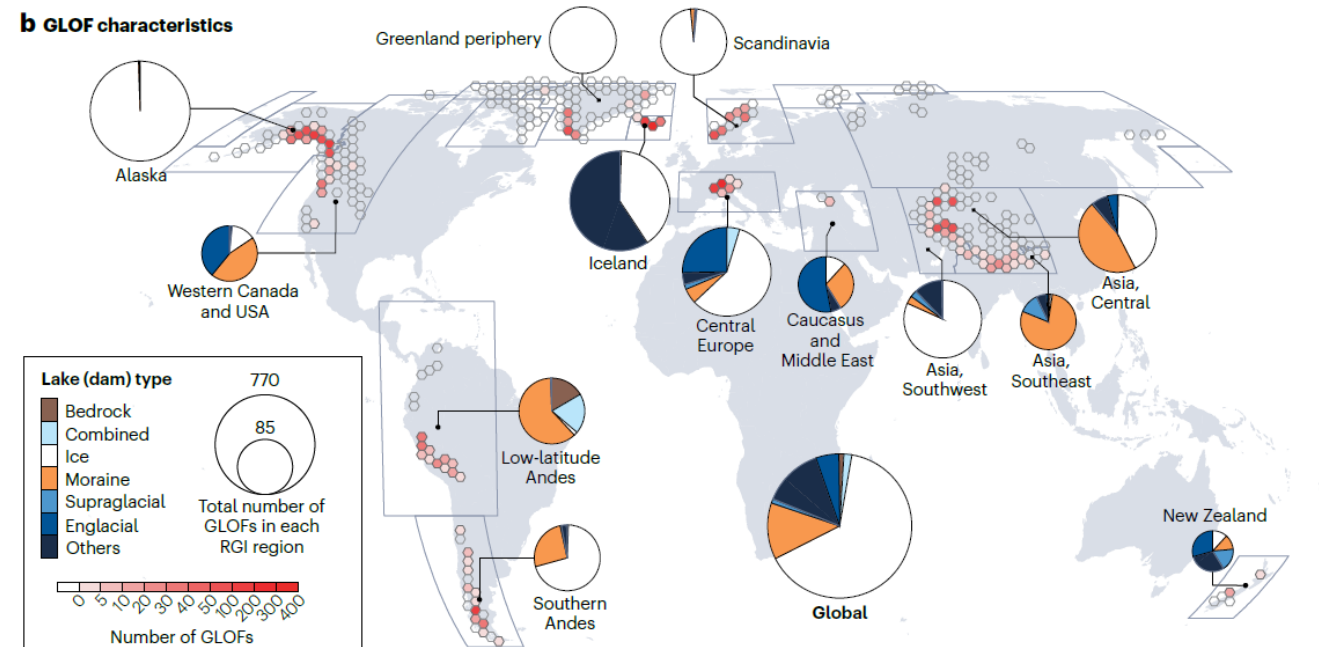
Global glacial lakes and historically recorded GLOFs

The number, area and volume of glacial lakes varies considerably, with glacial lakes predominantly found on the margins of Greenland (31%), in the southern Andes (16%), in Alaska and western Canada (16%), in the eastern Canadian Arctic (15%) and in HMA (6%).

a Glacial lake characteristics



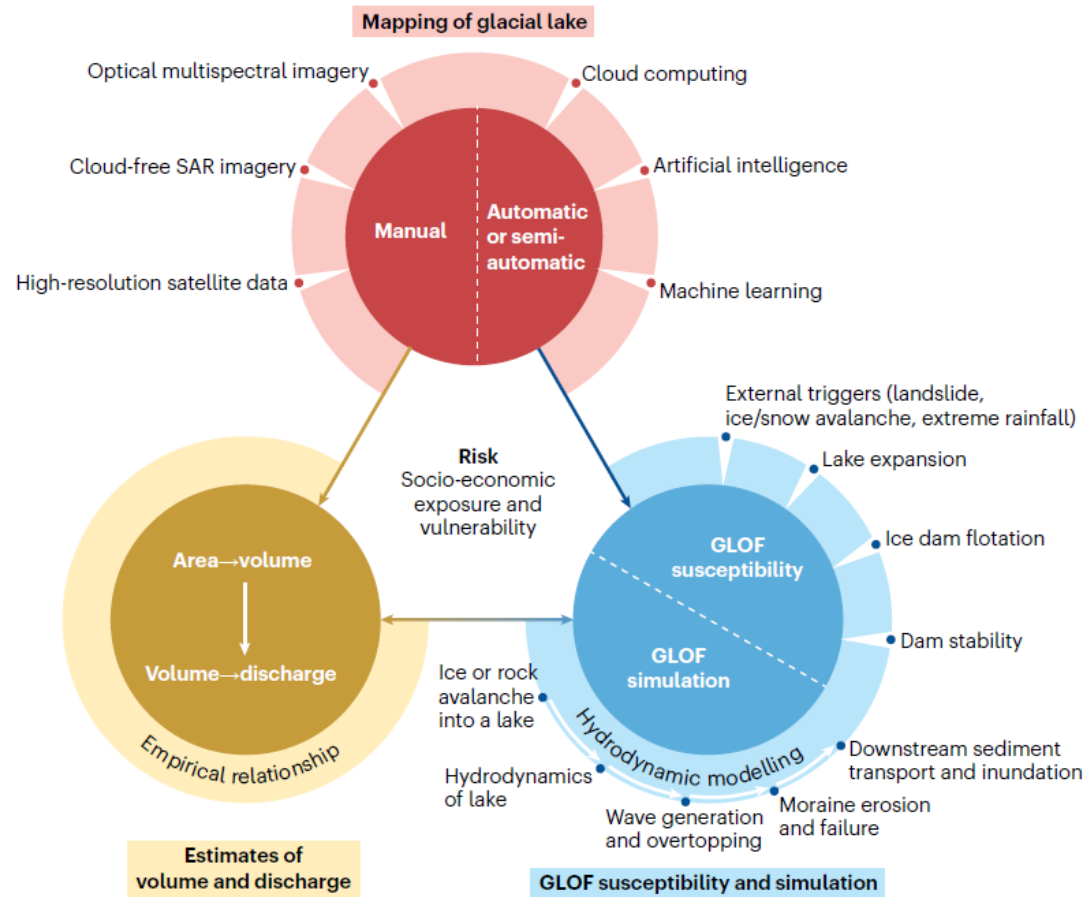
b GLOF characteristics



More than 3,000 GLOFs from 850 to 2022

See Himalaya from a global scale

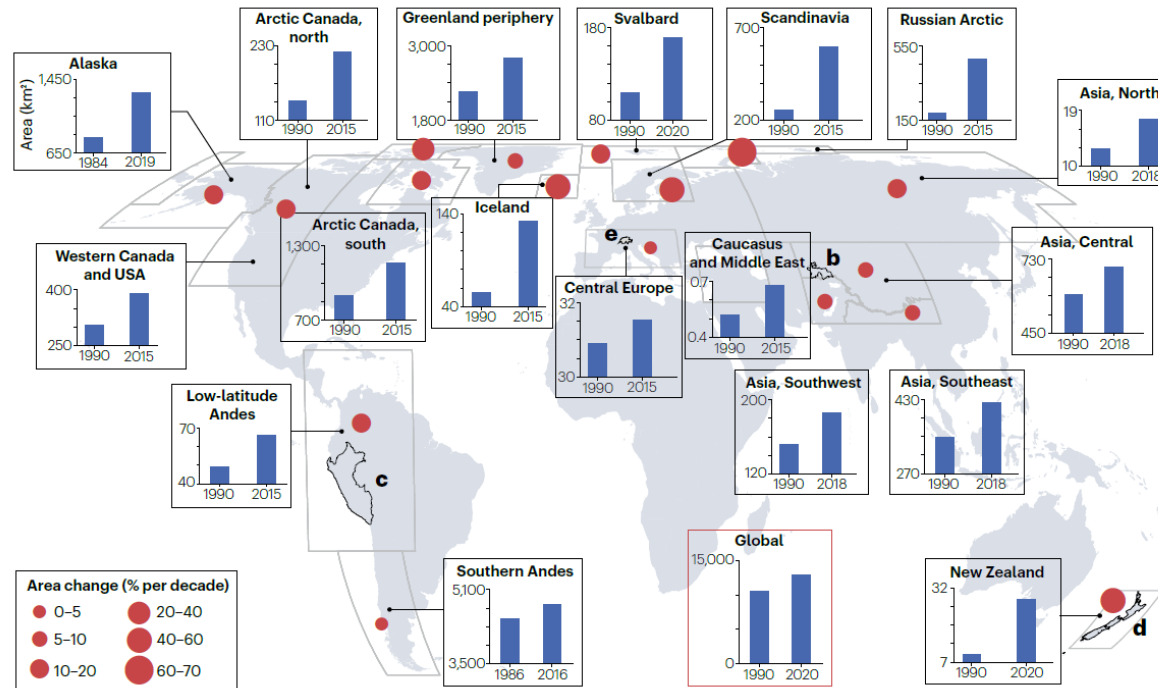
Methods for quantifying glacial lake changes and impacts



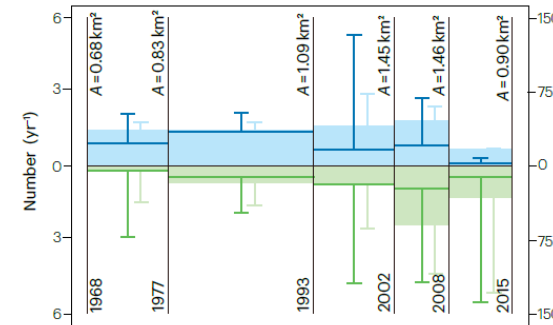
Global and regional changes in glacial lake area

Changes in the Andes, central Europe and Svalbard are relatively small, <10% per decade, and in Iceland, Scandinavia and the Russian Arctic are relatively large, >40% per decade.

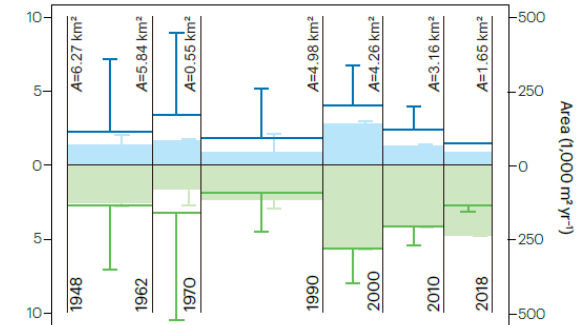
a Glacial lake area changes



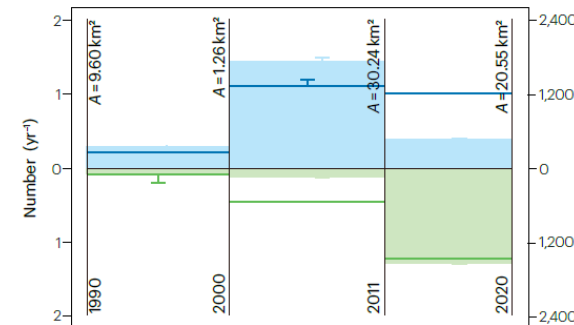
b Proglacial lake changes: Southern Pamir



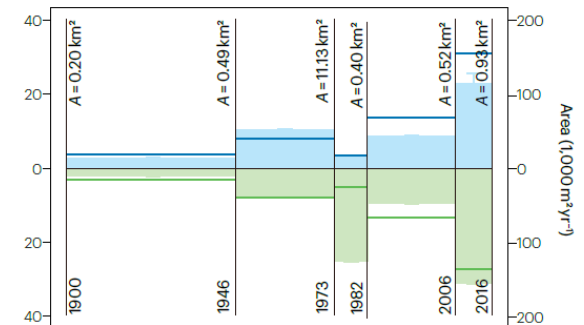
c Proglacial lake changes: Peruvian Andes



d Proglacial lake changes: New Zealand



e Proglacial lake changes: Switzerland

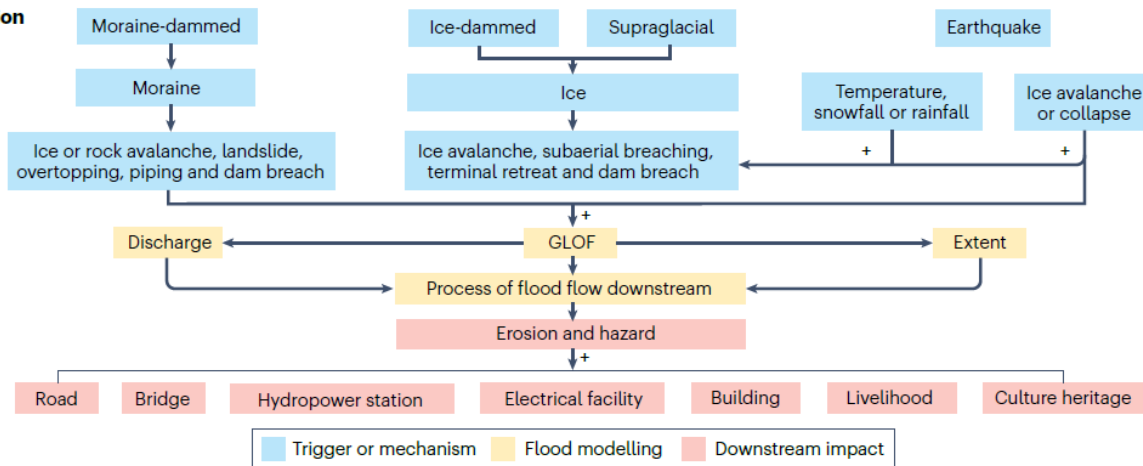


Number of new lakes Number of detached lakes Area of new lakes Area of detached lakes

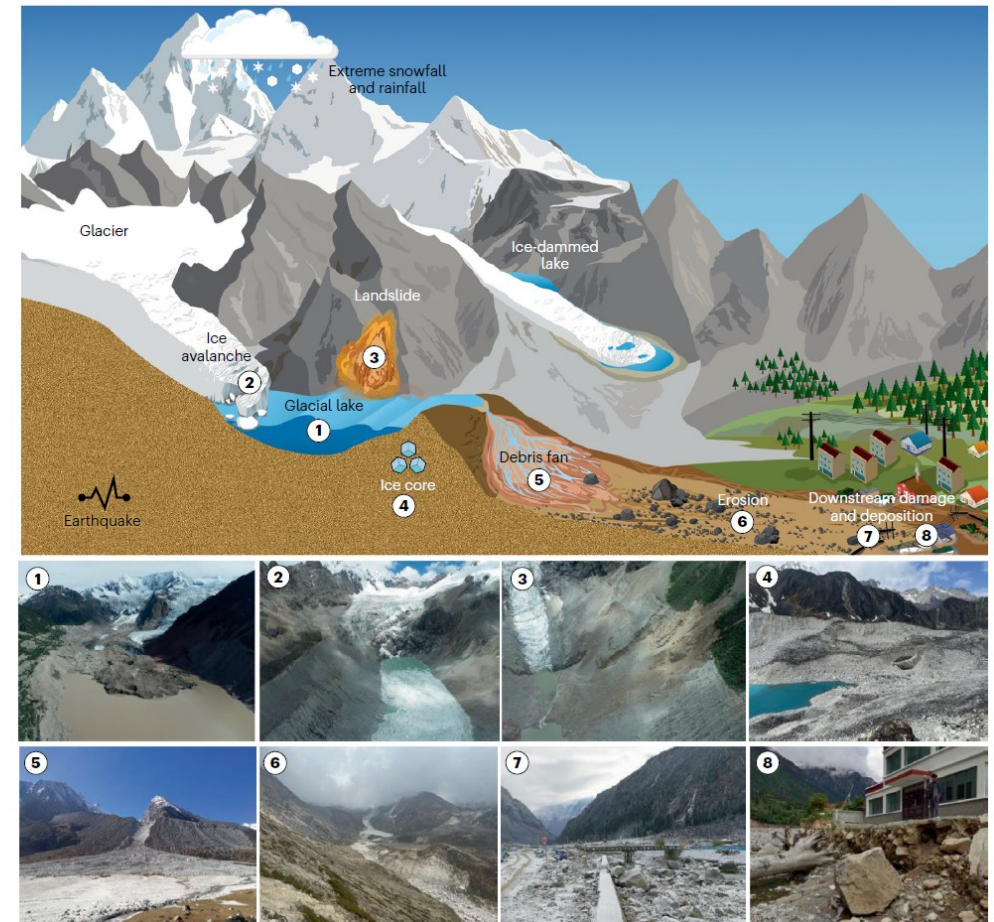
Triggers and mechanisms of GLOFs

Ice-dammed lakes are the dominant type of GLOF. Moraine lakes are also a major source of GLOFs, particularly in the Andes and the Himalaya, are usually triggered by pipe floods, buried ice degradation, or by ice avalanches, snow avalanches or landslides.

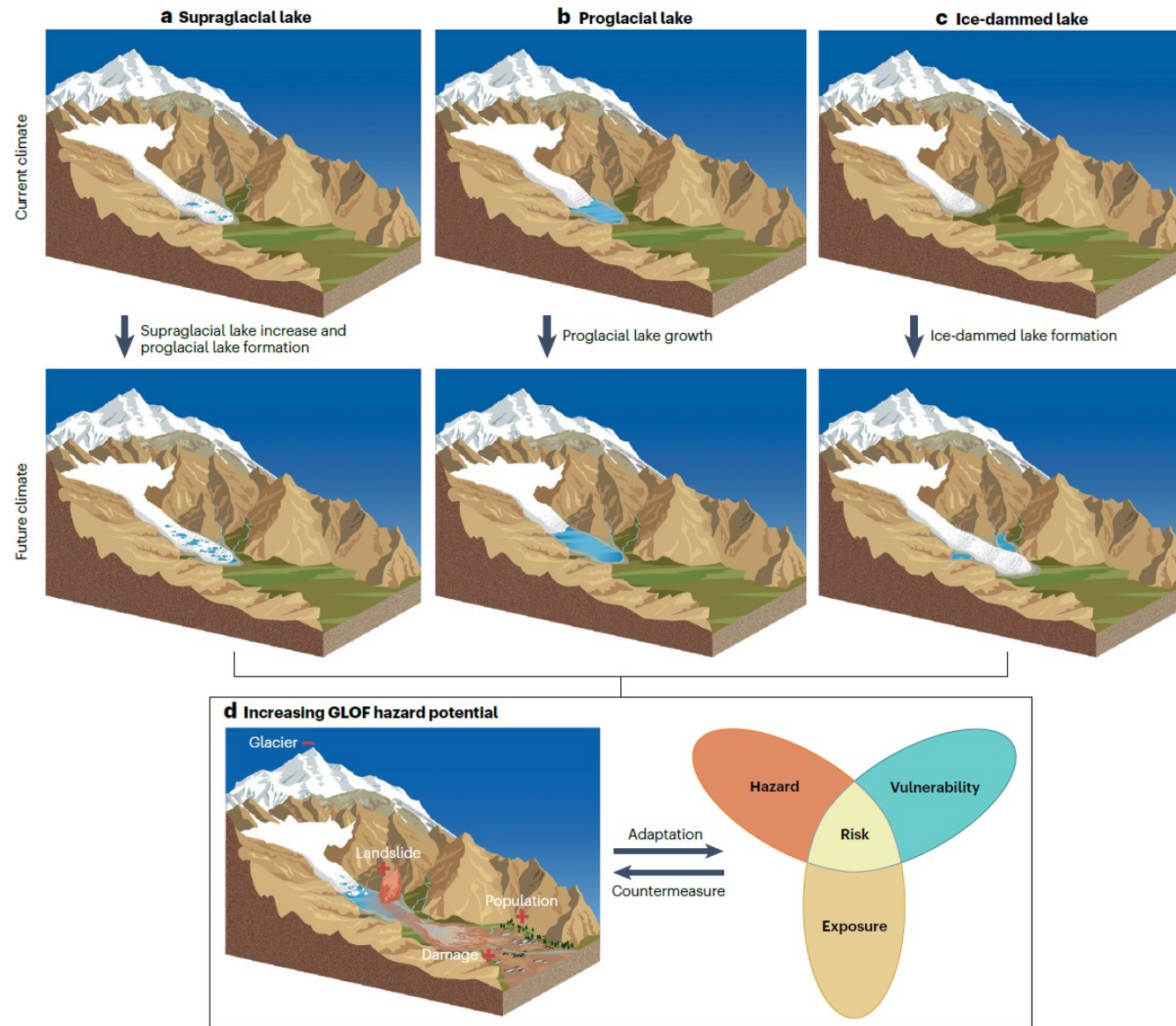
a GLOF Initiation



b GLOF hazard chain



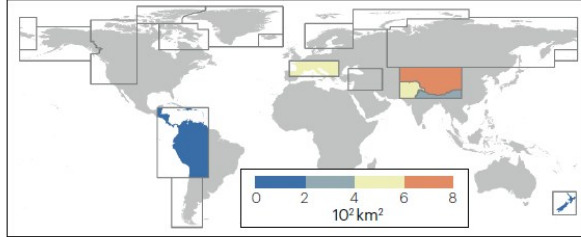
Future glacial lake development



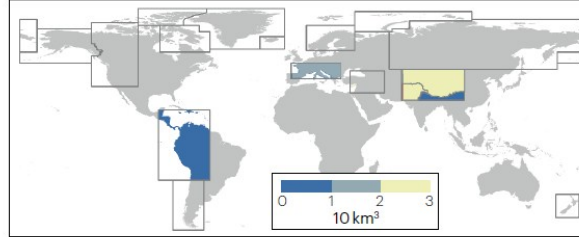
Future glacial lake development and GLOF hazards

Projections show an overall increase in the risk of future global GLOFs, but there are regional differences, with a tripling of future GLOFs expected in HMA, relatively low potential future GLOFs in the Western European Alps, the Cordillera Blanca in Peru.

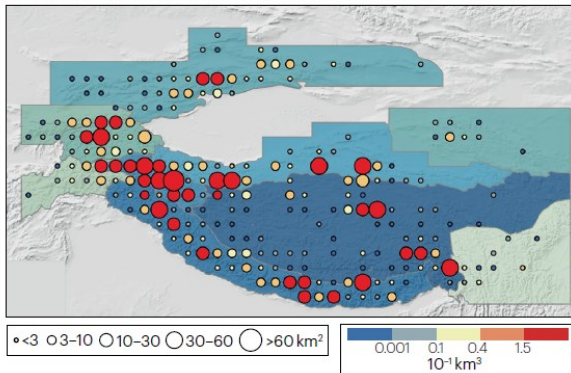
a Projected glacial lake area



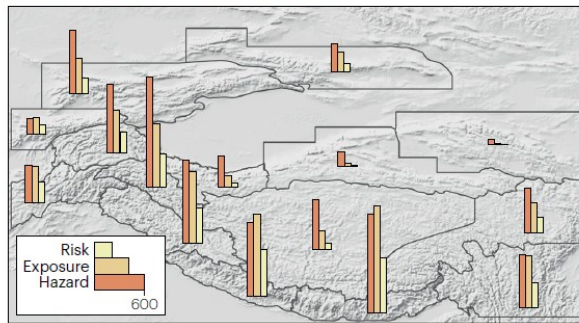
b Projected glacial lake volume



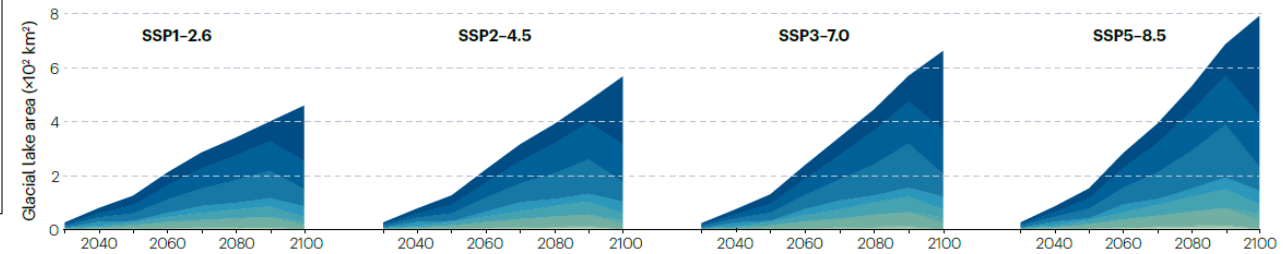
c Projected glacial lake area and volume in HMA



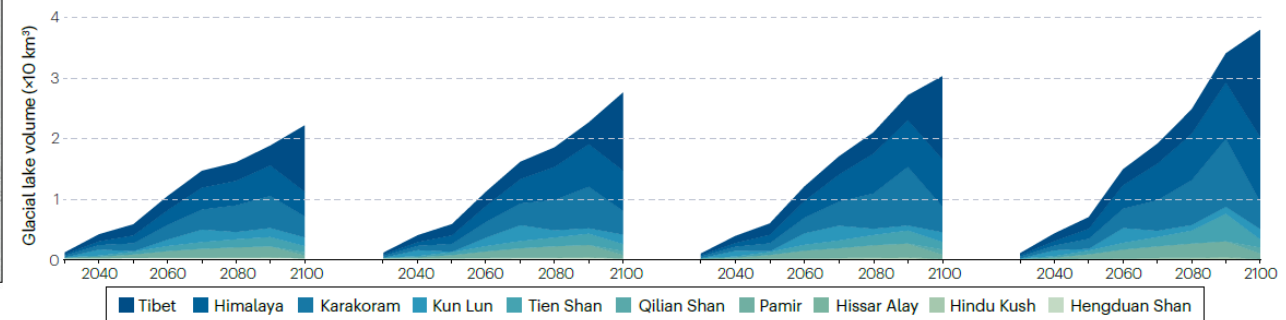
d Projected GLOF hazard and risk in HMA



e Scenario dependence of HMA glacial lake area

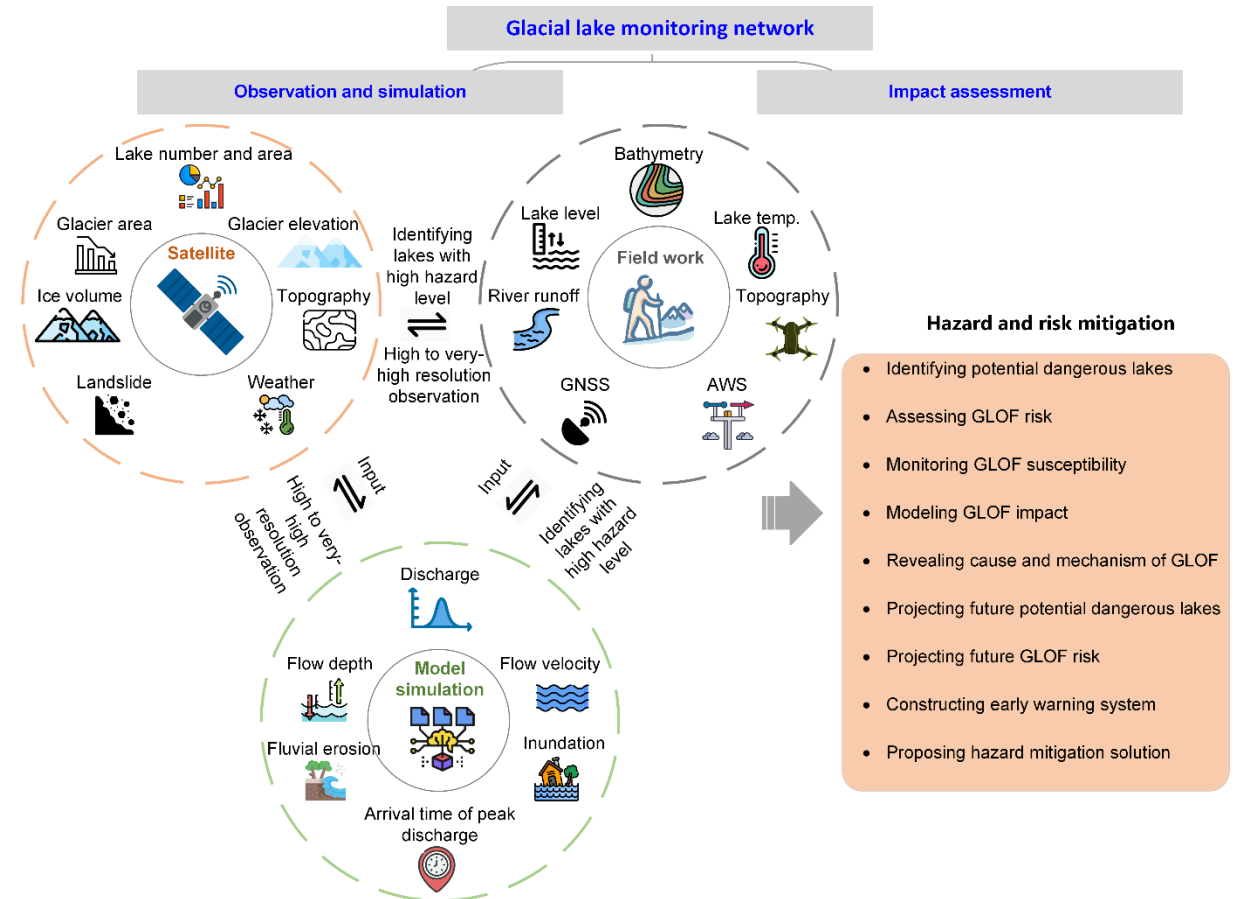
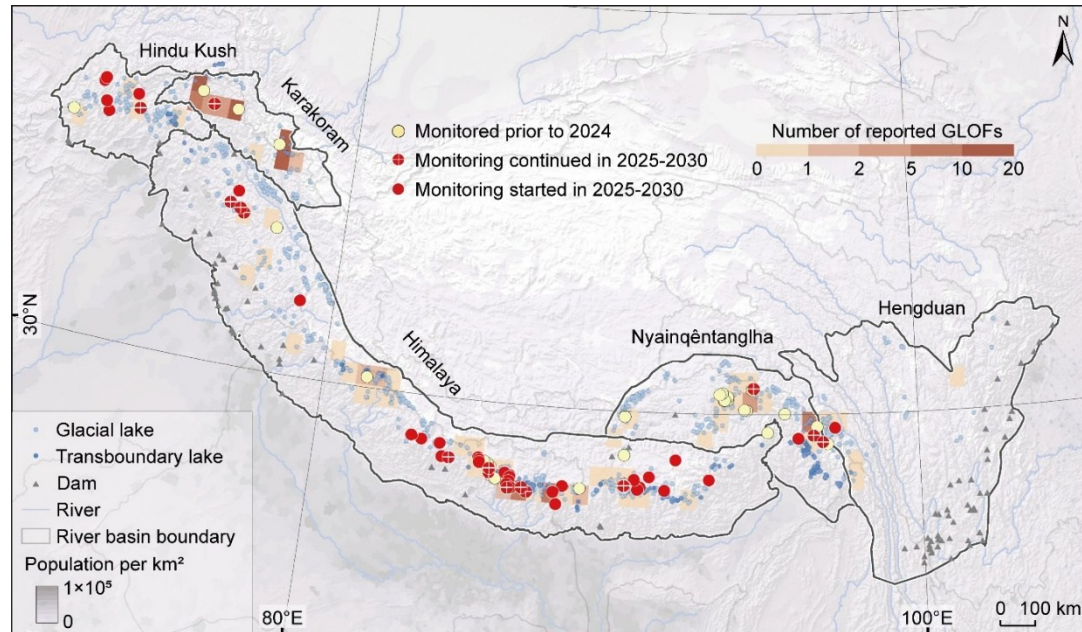


f Scenario dependence of HMA glacial lake volume



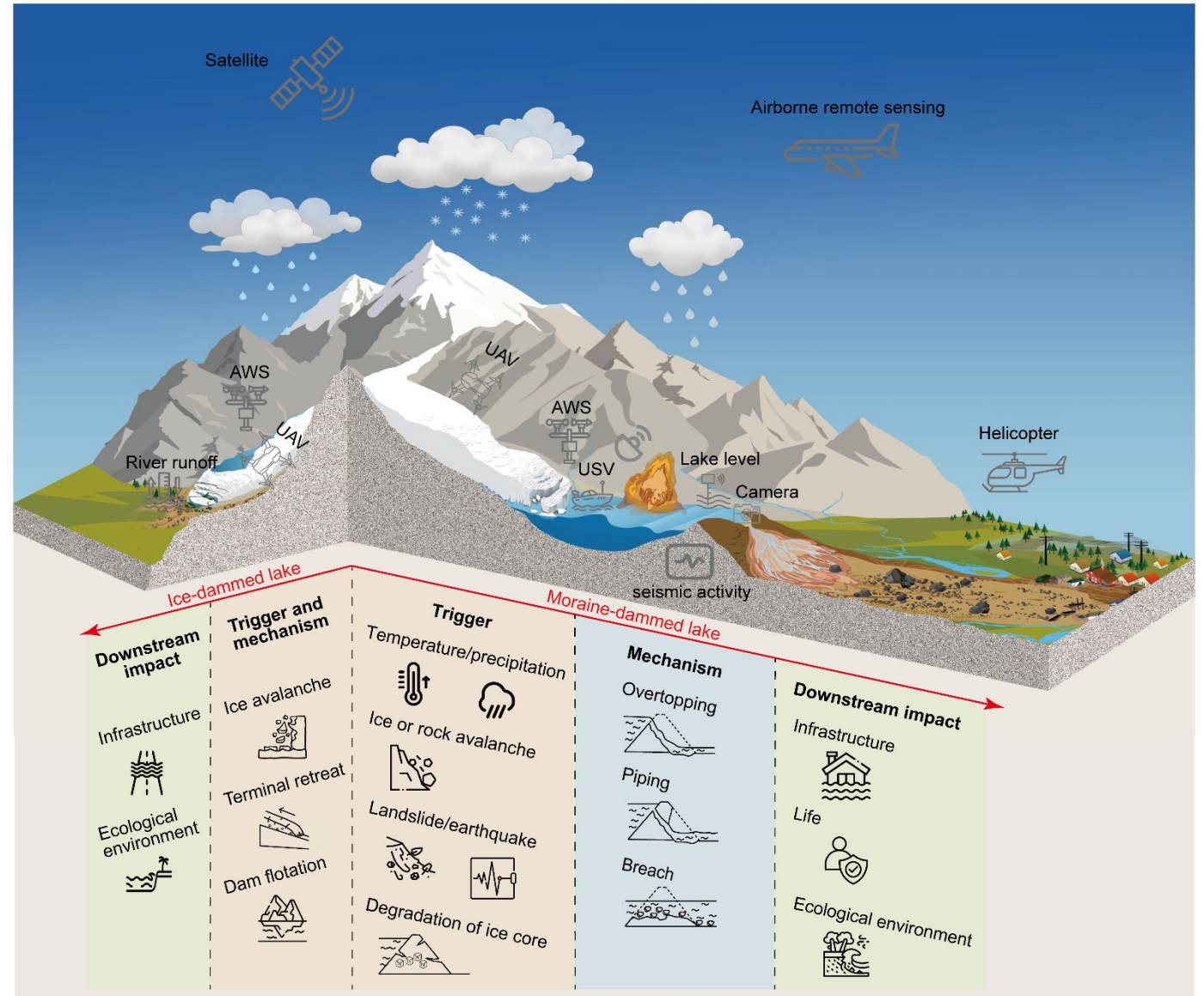
A monitoring network for mitigating Himalayan GLOFs

By integrating the hydrological and geomorphological characteristics of GLOFs, dam triggering mechanisms and downstream impacts, field observations, remote sensing techniques, and hydrodynamic modeling, this can provide support for early warning and disaster risk reduction.

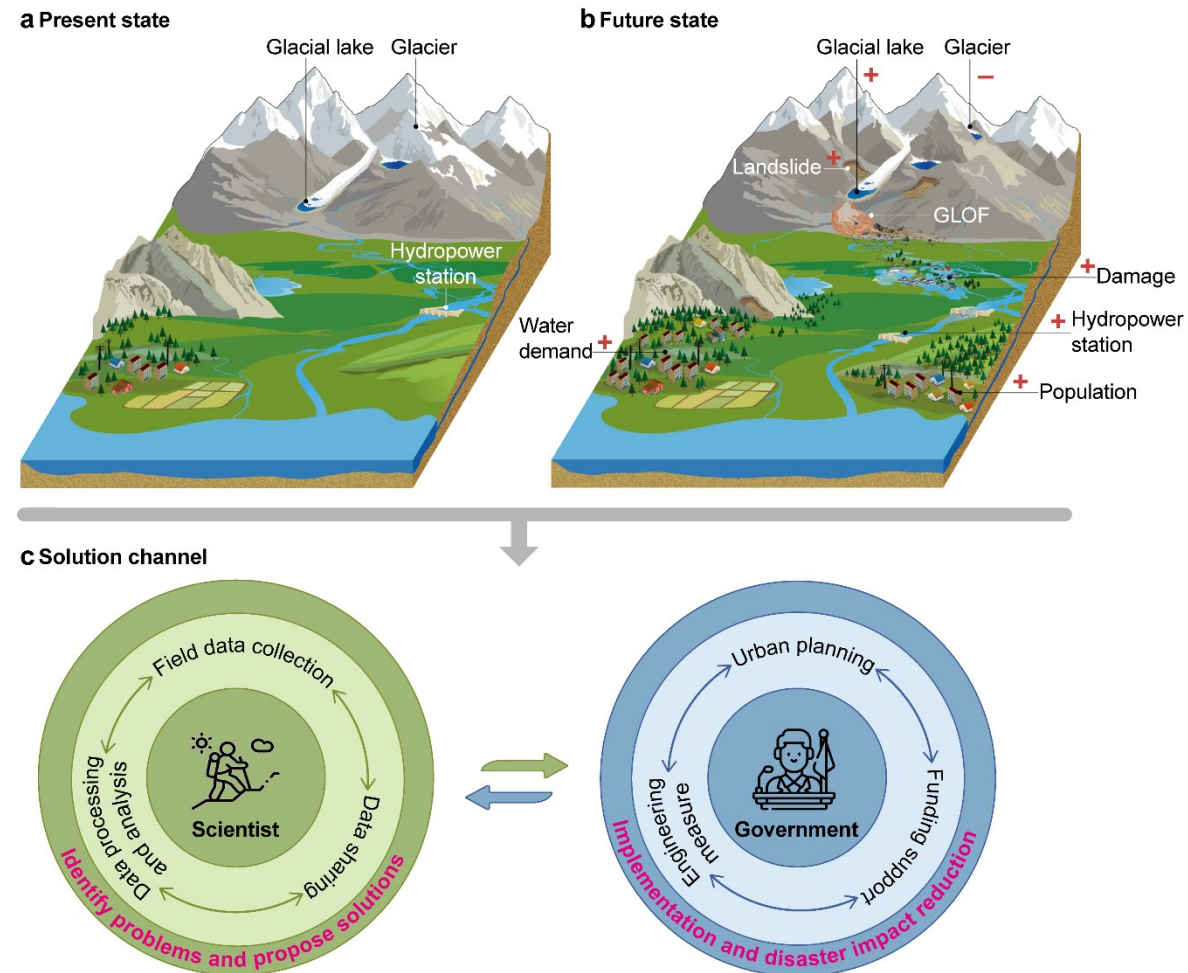
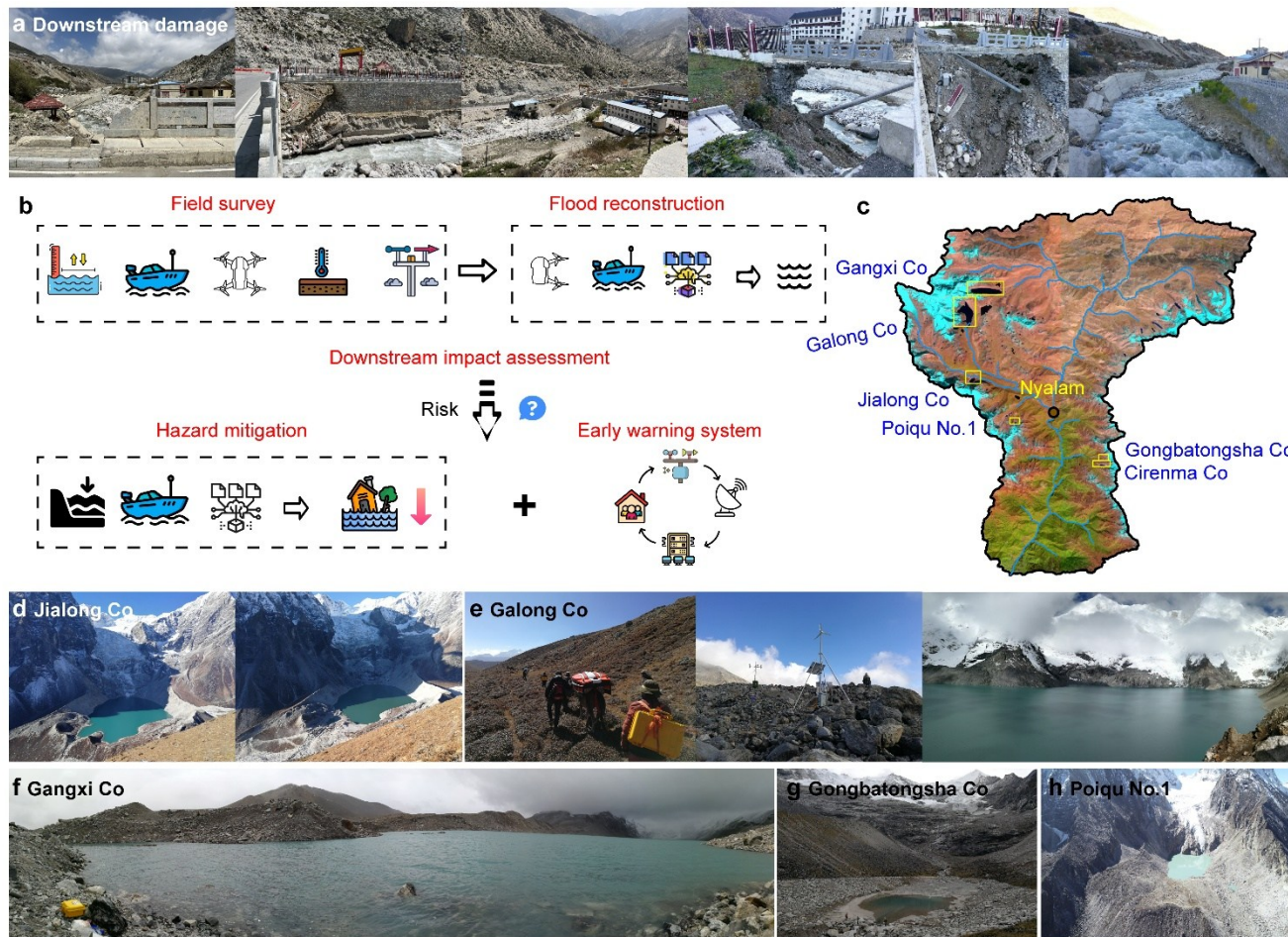


Field observations for Himalayan glacial lakes

Instrument name	Instrument picture	Observation frequency	Measurement item and application purpose
Yunzhou USV (unmanned surface vessel, M70, and SL20), CarlVinson inflatable boat (CND-470A)		Once for each glacial lake, every 3–5-yr interval for potentially high-dangerous glacial lakes, and annually for easily accessible lakes	Bathymetry for estimating lake water volume
HOBO Water-Level Data Logger (U20)		Two water-level loggers for each potentially high-dangerous glacial lake with continuous real-time data recording and transfer	Lake level and lake water temperature
HOBO Water Temperature Logger (MX2204)		Vertical section from lake surface to lake bottom	Vertical lake water temperature profile
Campbell Radar Water-Level Sensor (CR300 datalogger)		One set of radar water-level sensor for each potentially high-dangerous glacial lake	Lake and river water level
Acoustic Doppler Current Profiler (M9)		Five to six annual measurements of river discharge for each potentially high-dangerous glacial lake combined with water-level measurement	Outflow of a glacial lake, river discharge downstream
DJI UAV (unmanned aerial vehicle, Phantom 4 Pro)		Once for each glacial lake, every 2–3 years for potentially high-dangerous glacial lake and annually for easily accessible lakes	Geomorphological condition for DEM producing photo
RTK (real-time kinematic positioning, Trimble R12)		Once for each glacial lake, 2–3-yr interval for each potentially high-dangerous glacial lakes, and annual for easily accessible lakes	Lake surface elevation, lake shore topography
HOBO soil moisture sensor (S-SMC-M005) and temperature sensor (S-TMB_M006)		A set of soil moisture and temperature sensors for each potentially high-dangerous glacial lake with continuous data recording	Terminal and lateral moraine soil moisture and temperature
Forsafe Infrared Night Vision Timing-Lapse Camera (H6)		Two cameras for each potentially high-dangerous glacial lake with continuous data recording	Photo of parent glacier of the glacial lake
TCCORS-GNSS BeiDou monitoring system		One set of GNSS-BeiDou monitoring system for each potentially high-dangerous glacial lake	Displacement of the terminal moraine of a glacial lake
SmartSolo seismic sensor (IGU-BD3C-5)		One seismic sensor for each potentially high-dangerous glacial lake	Natural microseismical
Campbell AWS (automatic weather station, CR1000X)		A set of AWS for one potentially high-dangerous glacial lake	Wind speed and wind direction, air temperature and humidity, net radiation, air pressure



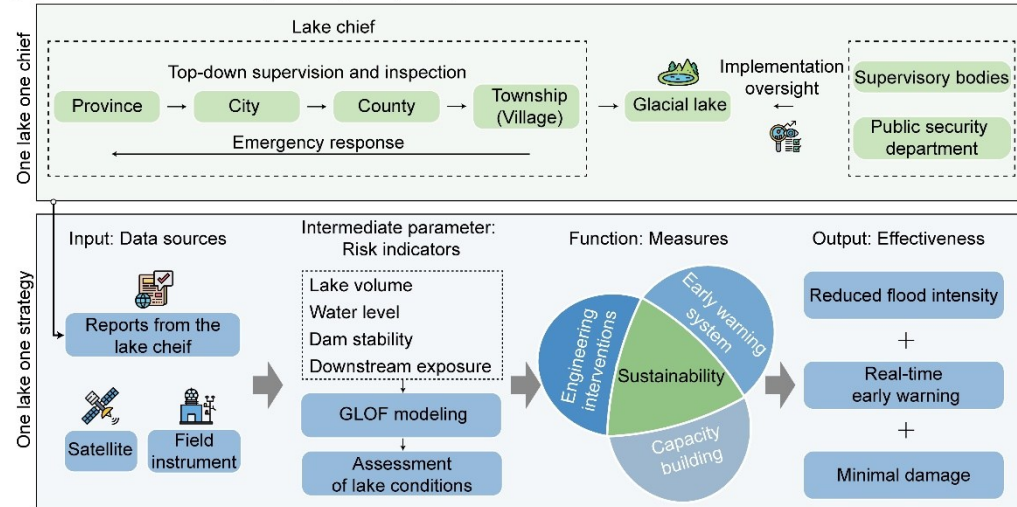
Field observation practices for Himalayan glacial lakes



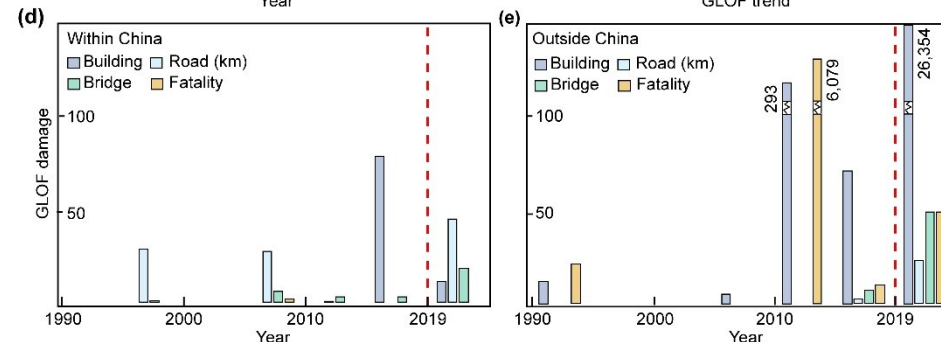
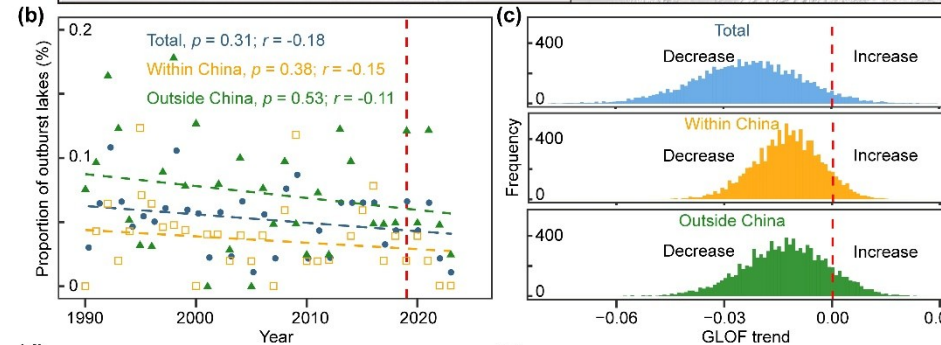
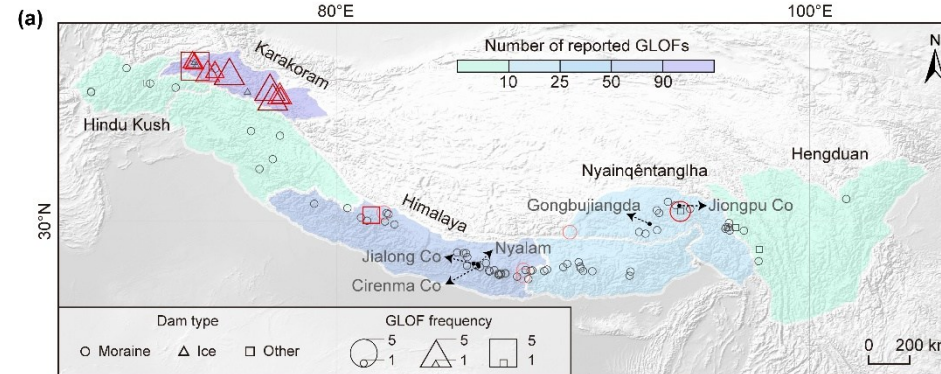
Mitigating future glacial lake outburst floods in the Himalaya

The disaster losses in the Himalaya during 1990-2023 intensified due to increasing downstream exposure and vulnerability.

(a) China's Glacial Lake Management System (GLMS)

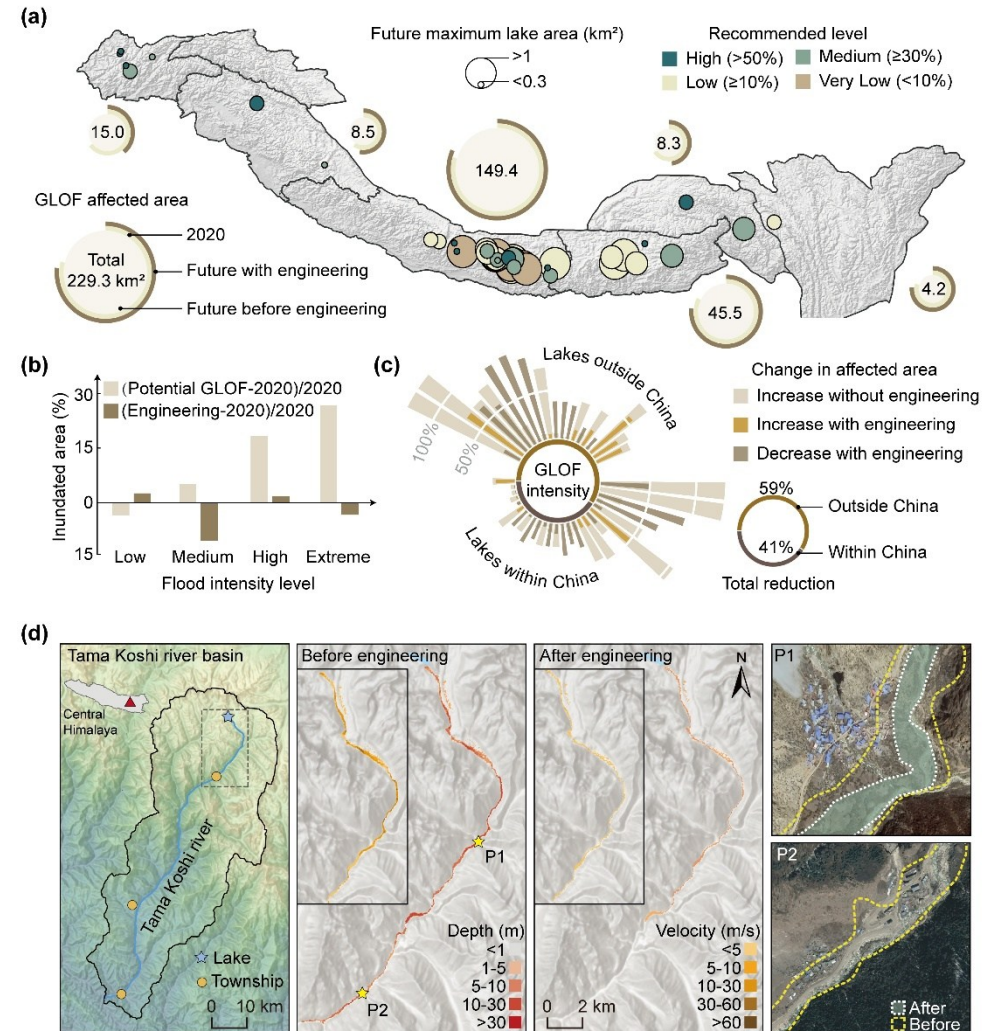
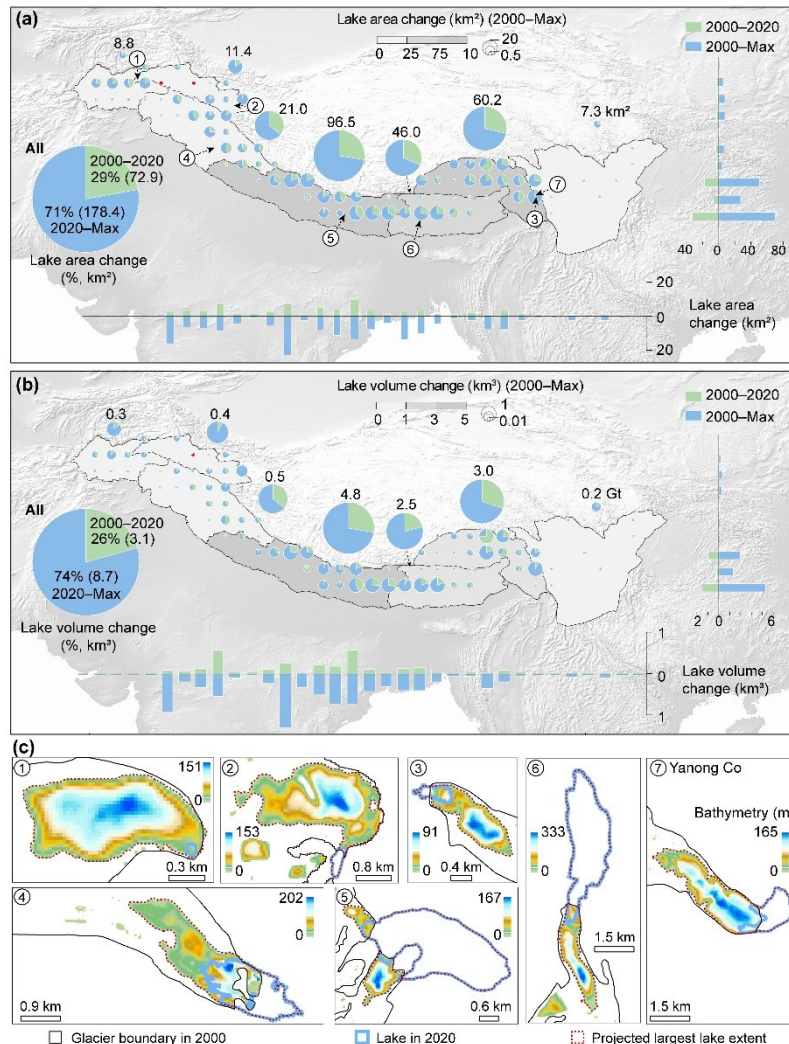


(b) Examples of mitigation measures in China



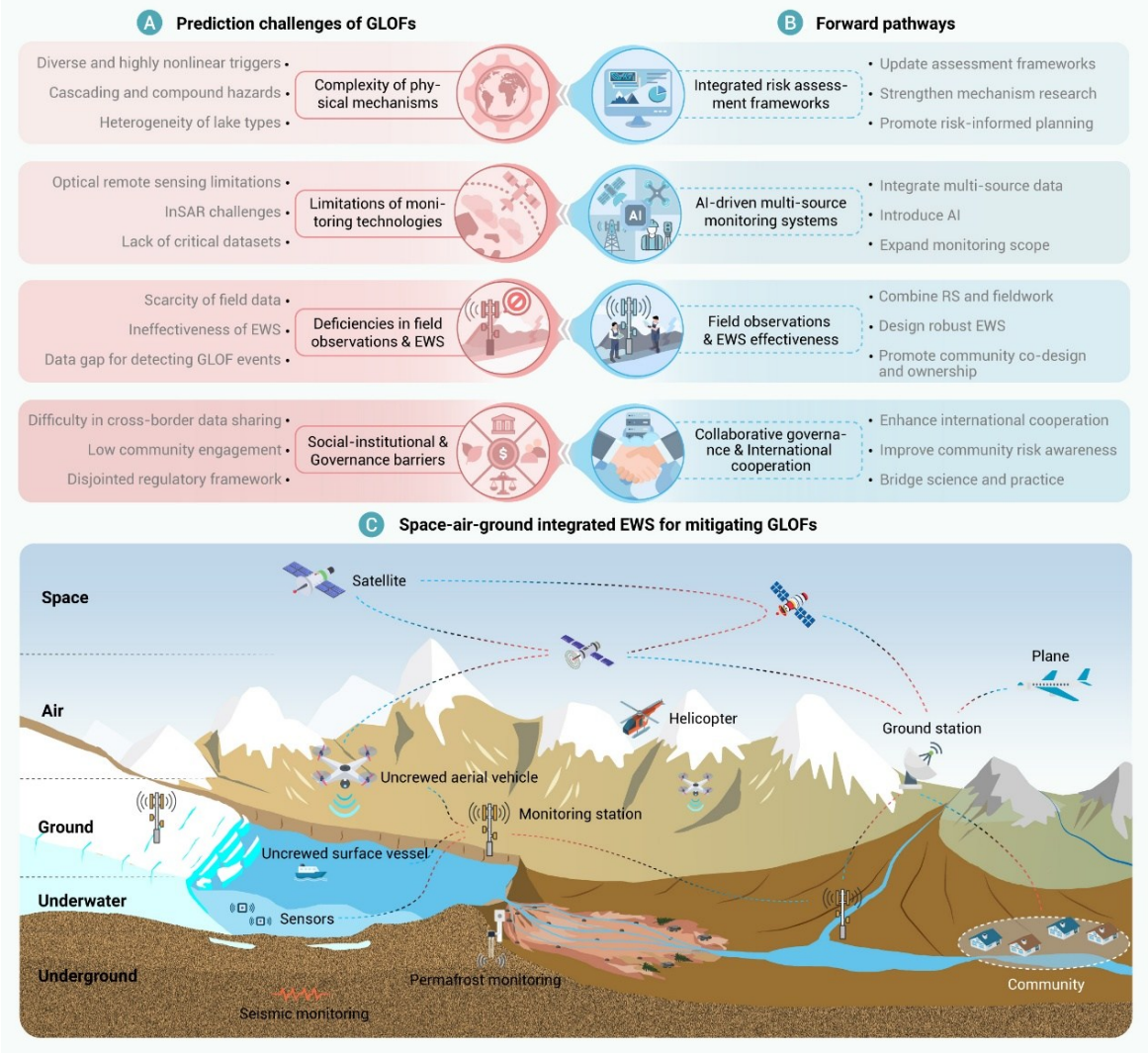
Disaster risk reduction through systematic management

Implementing China's glacial lake risk management measures could reduce future flood intensity by 24%, with reductions of up to 29% in regions outside China.



Challenges in predicting GLOFs and suggested pathways forward

Develop new risk assessment frameworks, establish cascade-process coupling models, develop an integrated space–air–ground observation network, and strengthen transboundary collaboration and community-based co-management mechanisms.



Zhang* et al., 2026, The Innovation

A high-altitude mountain landscape featuring a vibrant turquoise lake nestled in a valley. The surrounding mountains are rugged, with dark rock faces and patches of snow. In the background, majestic snow-capped peaks rise against a clear blue sky. The foreground shows a rocky, brownish slope. The text "Thank you for your attention!" is overlaid in the center in a bold, yellow font.

Thank you for your attention!