TOWARDS DATA-DRIVEN GLOF EARLY WARNING IN INDIA

Shako Cho Lake GLOF Monitoring Station

Seasonal hydrometeorological patterns and risk forecasting from India's first GLOF-dedicated meteorological installation at a glacial lake site





Baidya & Das, 2026

National Disaster Management Authority | Accenture Strategy

Why Shako Cho matters

Himalayan GLOFs are high-consequence, compound hazards

Can release millions of cubic metres of water and sediment within hours
Eastern Himalaya risk is shaped by glacial retreat, monsoon precipitation, steep terrain and moraine fragility
2023 South Lhonak event underscored the real-time monitoring gap

1st
GLOF-dedicated meteorological station at a glacial lake site in India

6
Meteorological variables captured continuously

2023-25
Multi-year observation window used for technical baseline

Conference message

Shako Cho is a proof point for converting high-altitude meteorological data into operational GLOF preparedness, threshold design and a scalable national monitoring template.

Analytical focus

The paper identifies seasonal signatures, anomalous sensor behaviour, the primary hazard window and the sensor upgrades needed to move from observation to early warning.

Study design: one station, six variables, three time lenses

Temperature
snow/glacier melt; ice phenology

Pressure
monsoon trough; synoptic shifts

Precipitation
rainfall/snowfall inflow pulses

Humidity
moisture availability; radiative cooling

Solar radiation
energy-balance driven melt

Wind speed
sensor-health flag; not used quantitatively

Temporal aggregation clarifies different signals

Daily
short-term variability, events, sensor spikes

Weekly
smooths noise; exposes inter-annual thermal contrast

Monthly
cleanest basis for seasonal comparison and model forcing

Data treatment note

2023 and 2024 annual records are broadly complete; 2025 extends to approximately October and is treated as a partial-year dataset. Wind-speed anomalies preclude meaningful monthly aggregation.

Five figures that frame the hazard story

~6-7°C
warmer Jan-Feb 2025 vs 2024

340-365
April radiation maximum

+5°C
July monthly temperature peak

43-48 mm
August monthly precipitation maxima

90-98%
monsoon near-saturation humidity

Apr-May

Pre-monsoon melt

radiation + 0°C crossing

Jun-Aug

Peak monsoon hazard

warmth + humidity + rainfall

Sep-Oct

Secondary risk

residual warmth + radiation recovery

Bottom line

The highest-risk meteorological envelope is June-August, but preparedness should start earlier because April-May radiation primes snowmelt and glacier-surface melt before monsoon rainfall arrives.

Temperature: daily variability and weekly smoothing reveal the melt arc

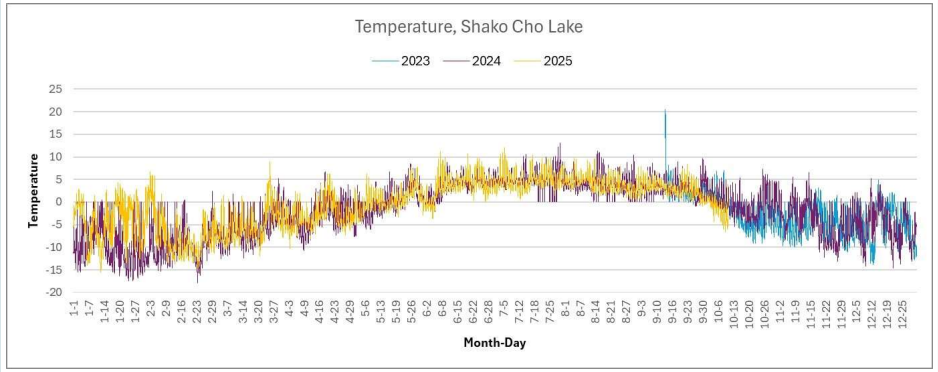


Fig. 1 Daily temperature, 2023-2025

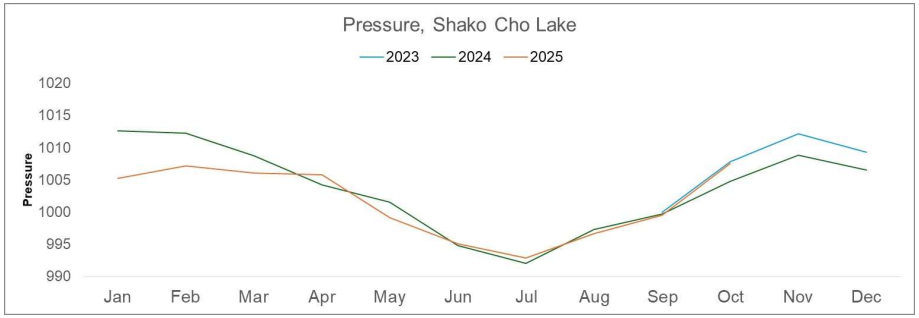


Fig. 2 Weekly average temperature, 2023-2025

Seasonal arc is robust

Records show a winter trough, spring warming ramp, monsoon peak and autumn decline across available years.

2025 starts materially warmer

Weekly smoothing shows January 2025 around 6-7°C warmer than 2024 before convergence in March-April.

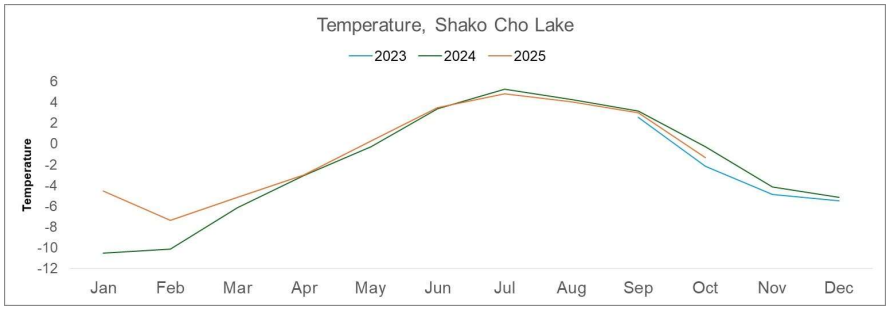
Data quality flag

A ~+20°C mid-September 2023 spike is implausible and should be excluded from quantitative analysis.

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2025 winter was ~6°C warmer, potentially advancing the melt window

Temperature evidence points to extended pre-monsoon system conditioning in 2025



Monthly temperature record: Jan–Feb 2025 is warmer than 2024; both years converge through the melt/monsoon season.

Key observation

Jan 2025 averaged near −4.5°C versus ~−11°C in 2024; this may mean less lake ice formation, earlier snowmelt initiation and a longer effective melt season.

March–April: ENERGY-DRIVEN MELT BEGINS
↑ solar radiation → daytime/surface melt

While the monthly averages of roughly **−6°C in March, −3°C in April and ~0°C in May**, but the **daily record already shows frequent crossings above 0°C during April–May**.
More importantly, air temperature is only one part of the surface energy balance.

−11°C
Jan 2024 trough

−4.5°C
Jan 2025 average

~0°C
May melt transition

~6–7°C interannual winter contrast

Operational interpretation: conditioning pathway

1 Warmer winter baseline

Potentially reduced lake-ice formation and faster warming of snow/ice surfaces.

2 Earlier melt onset

More frequent 0°C crossings can initiate snow and glacier melt before monsoon rainfall.

3 Higher pre-monsoon lake loading

Cumulative meltwater inflow can reduce storage/freeboard buffer before peak monsoon.

Caution: meteorology suggests conditioning only; moraine weakening must be confirmed with lake-level, camera, discharge, seismic or field data.

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Pressure indicates monsoon transition; rainfall onset must be confirmed by humidity + precipitation

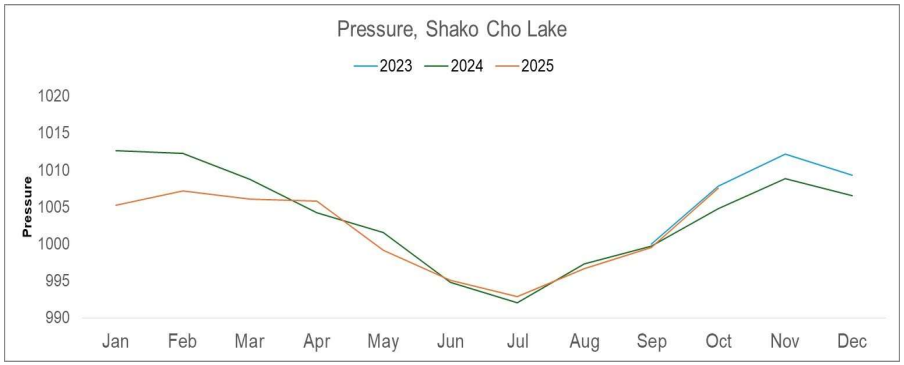
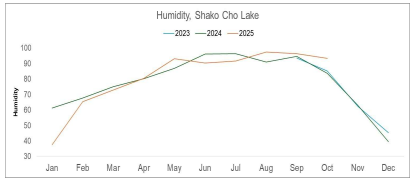
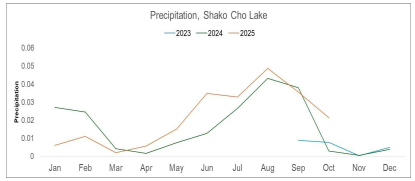


Fig. 5 Monthly pressure: winter high pressure → July monsoon trough → post-monsoon recovery



Humidity rises to near-saturation



Rainfall peaks later in August

992–994 hPa
July monsoon trough

90–98%
Jun–Sep humidity

43–48 mm
Aug rainfall peak

What pressure indicates

The seasonal pressure drop marks establishment of the monsoon circulation.
It is not, by itself, proof of rainfall onset; the rainfall signal must be read with humidity and precipitation.

Operational use for early warning

Rapid 24–48 hour pressure falls can provide lead indication of incoming weather systems, but alert thresholds should combine pressure trend, precipitation intensity and lake-level response.

Pressure falls May–Jul Atmospheric transition → **Humidity rises Jun–Sep** Moisture build-up → **Rainfall peaks Aug** Hydrological loading → **Lake level responds** Actionable GLOF trigger

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Precipitation: Peak rainfall arrives after months of melt-driven lake loading creating the primary GLOF trigger

August precipitation is the immediate hydrological trigger window, but April-July melt and humidity pre-condition the lake.

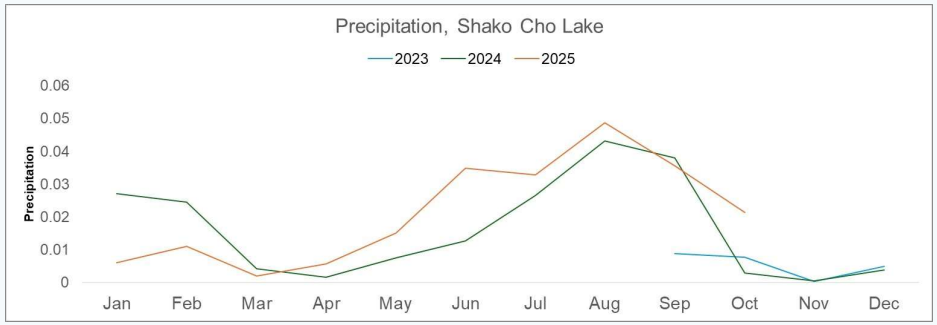


Fig. 6 Monthly precipitation totals (m)

0.048 m
2025 August peak

0.043 m
2024 August peak

+12%
2025 above 2024 in August

43-48 mm
Monsoon peak monthly loading

Apr-May Pre-conditioning
energy-driven melt

Jun-Jul Compound loading
melt + monsoon build-up

Aug Peak rainfall trigger
43-48 mm monthly peak

Why rainfall becomes dangerous

Monthly totals hide short daily bursts. These event-scale pulses can raise lake level rapidly during June-September.

Compound hazard, not rainfall alone

Rainfall is most hazardous when the lake is already loaded by snow/glacier melt and slopes are saturated.

Data-quality watch

Elevated Jan-Feb 2024 precipitation values (~0.025-0.027 m) should be verified against raw gauge records.

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Humidity rises to >90% as the monsoon establishes, and remains near-saturated through the GLOF hazard window

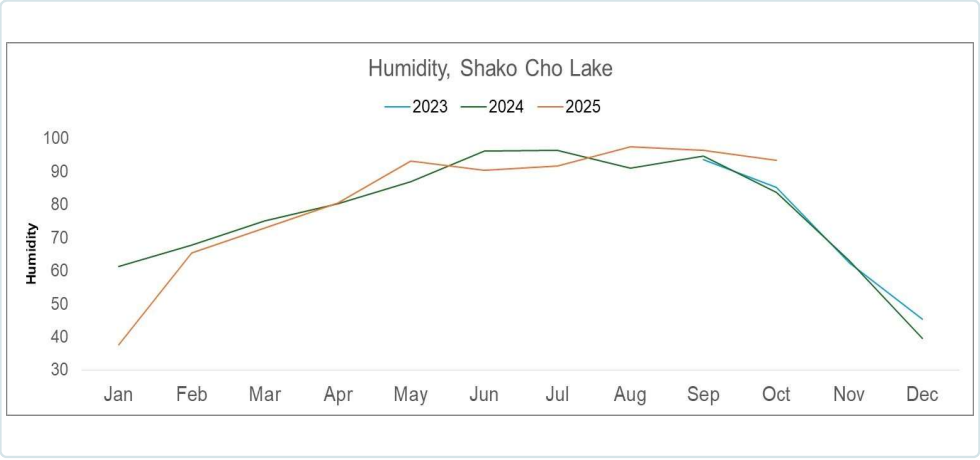


Fig. 7 Monthly relative humidity

~38%
January 2025 humidity

~61%
January 2023/24 humidity

91-98%
June-September near saturation

Why humidity matters

Near-saturation signals a moisture-rich regime; with above-freezing temperatures it extends daily melt windows and supports rainfall-driven inflow.

Preparedness implication

In 2025, humidity remained elevated (~93–94%) into Sep–Oct, indicating that residual post-monsoon susceptibility may persist after peak rainfall.

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Solar radiation peaks before the 0°C threshold starting pre-monsoon melt and shows a bimodal pattern

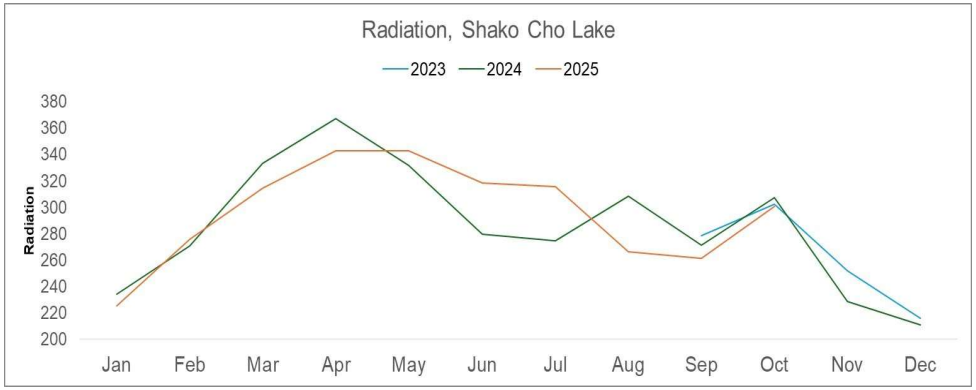


Fig. 8 Monthly solar radiation

340-365

April radiation maximum

~−3°C

April monthly avg still below 0°C

~0°C

May transition to sustained melt

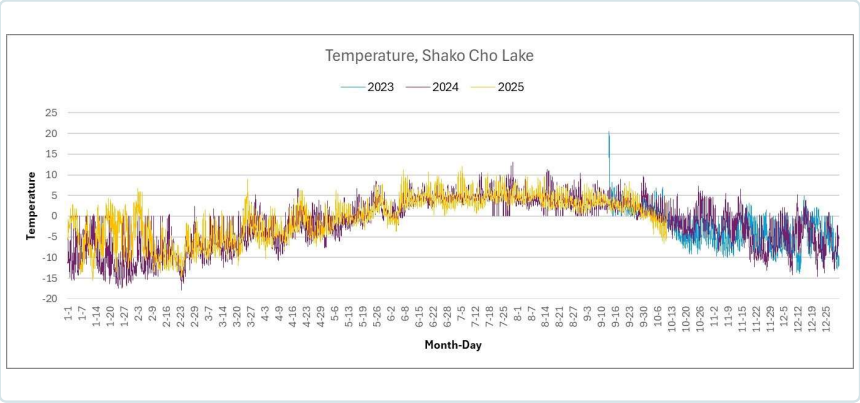
Melt can begin before May

April peak shortwave energy can drive daytime or local surface melt even when the monthly mean air temperature remains below 0°C.

GLOF relevance: pre-monsoon lake loading

Radiation-driven melt starts loading the lake before monsoon rainfall; June-August rainfall can then act on a pre-loaded system.

Data quality is part of early-warning readiness



Temperature QC: 2023 September spike

Wind-speed record: exclude until validated

Extreme spikes reach ~700-900 units against near-zero baseline
Anomalies appear across 2023, 2024 and 2025
Likely persistent hardware, firmware, installation or scaling issue

Physical inspection + calibration

Range and rate-of-change filters

Compare with ERA5 / IMDAA wind fields

Confirm logger unit and scaling

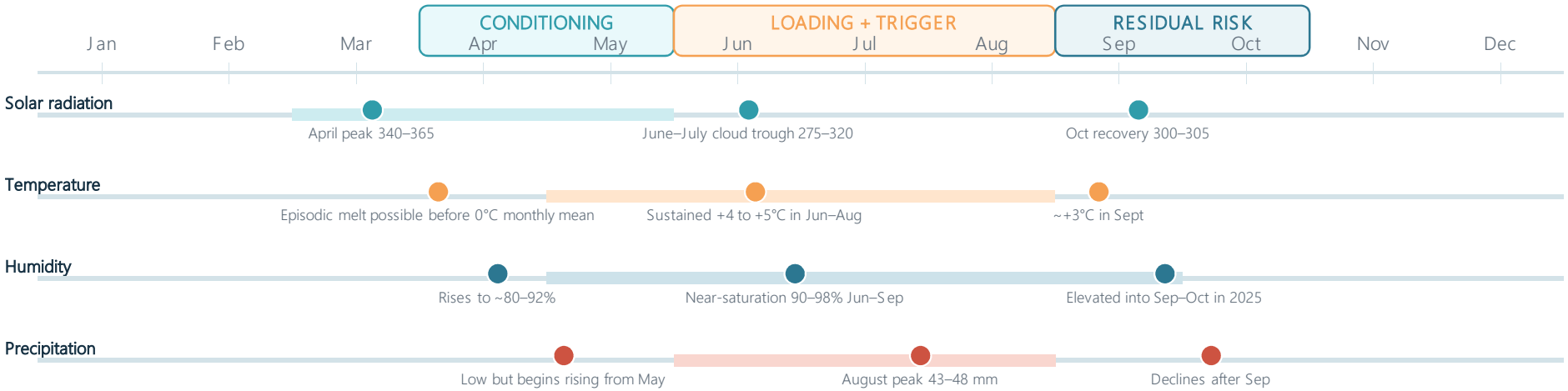
Key message

Early-warning analytics need a formal quality-control protocol. Sensor faults are not merely data problems; they can create false confidence or false alerts.

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Integrated meteorology defines a three-phase GLOF risk season

Risk begins before rainfall: radiation primes melt, monsoon rainfall triggers peak loading, and residual susceptibility persists after the monsoon.



APR–MAY Pre-monsoon conditioning

Peak radiation starts melt before rainfall; lake loading Can begin before the monsoon.

JUN–AUG Primary hazard window

Positive temperature + 90–98% RH + peak rainfall combine to maximize inflow.

SEP–OCT Residual susceptibility

Lake may remain **elevated while humidity and radiation** still support late-season conditions.

Central insight

Conditioning → loading → peak trigger → residual risk: early warning should start before monsoon, intensify in June–August, and remain active through September–October.

Pre-monsoon GLOF window: conditioning before rainfall peaks

APR-MAY | CONDITIONING

April-May: high radiation and 0°C crossings can prime the lake-moraine system before monsoon loading.

Measured parameter	Indicative level	Dominant phenomenon	GLOF occurrence pathway
Temperature	−3°C Apr → 0°C May; >0°C days increase	Snow/glacier melt begins; freeze-thaw; **potential thaw of ice-rich moraine if present**	**Meltwater inflow raises lake level; moraine degradation is plausible** but not directly measured by current sensors
Solar radiation	Annual max ~340-365 units in Apr	Strong **surface energy input**; accelerated snow and exposed glacier-ice melt	Pre-conditions lake filling before rainfall; **underappreciated first melt-inflow** window
Relative humidity	Rises toward 80-92% by May	More atmospheric moisture; **reduced** sublimation and **nocturnal cooling**	**Supports sustained melt** and transition toward wetter regime
Atmospheric pressure	**Declining toward monsoon;** 2025 lower by ~6-7 hPa vs 2024 early-year	Synoptic-state indicator, not a direct dam-weakening mechanism	**Rapid pressure falls may flag incoming weather systems** when fused with rain and lake-level data
Precipitation	Low Mar-Apr; starts increasing in May	Rain-on-snow or early catchment runoff where events occur	Early rainfall or melt pulse can rapidly add inflow to a lake already starting to fill

Premonsoon weather is better described as a **priming mechanism: peak radiation + warming generate meltwater and may condition ice-rich moraine material; a separate lake-level or instability trigger is still needed for breach.**

Peak monsoon GLOF window: maximum compound hydrological loading

JUN-AUG | LOAD + TRIGGER

June-August: sustained warmth, near-saturation humidity and August rainfall peaks create the primary trigger envelope.

Measured parameter	Indicative level	Dominant phenomenon	GLOF occurrence pathway
Temperature	Avg +4 to +5°C; daily maxima +8 to +13°C	Sustained glacier/snow melt; precipitation falls mainly as liquid	**Continuous meltwater keeps the lake highly charged** through the hazard season
Solar radiation	**Cloud-suppressed** ~275-320 units in Jun-Jul	**Solar melt is reduced versus April**, but **positive temperature sustains melt**	Reduced radiation does not remove risk because **rainfall and sensible heat dominate inflow**
Relative humidity	Near-saturation ~90-98%	Persistent monsoon moisture; reduced nocturnal cooling	Supports rainfall generation and extends daily melt window
Atmospheric pressure	**Monsoon trough minimum** ~992-994 hPa in Jul	Large-scale monsoon circulation is established	Useful atmospheric context; **combine pressure trends with rain intensity** and lake level
Precipitation	Monthly maxima ~43-48 mm in Aug; episodic daily events	**Direct lake input, catchment runoff and slope saturation**	**Rapid stage rise, overtopping, piping or slope/ice avalanche** impact can trigger breach

This is the primary GLOF occurrence window: the system shifts from gradual conditioning to active loading, where a rainfall burst or lake-level surge can convert susceptibility into failure.

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Post-monsoon GLOF window: residual risk after peak rainfall

SEP-OCT | RESIDUAL RISK

September-October: direct monsoon loading declines, but elevated lake storage, residual warmth and radiation recovery can sustain susceptibility.

Measured parameter	Indicative level	Dominant phenomenon	GLOF occurrence pathway
Temperature	+3°C in Sep; crosses below 0°C around Oct	Late melt persists before freeze-up	**Continued inflow can act on an already seasonally elevated lake**
Solar radiation	Recovery peak **~300-305 units in Oct**	**Clearer skies revive surface energy input**	Can sustain late-season **surface melt despite cooling air temperatures**
Relative humidity	2025 stayed high ~93-94% Sep-Oct	Moist post-monsoon environment persists	Maintains chance of precipitation and reduces cooling**, extending effective risk season**
Atmospheric pressure	**Recovering** after monsoon trough	Withdrawal of monsoon circulation	**Direct loading declines**, but pressure changes still help identify incoming events
Precipitation	Declines rapidly after Sep; occasional events remain possible	Lower frequency rainfall, but pulses may occur	Late rainfall/melt pulse can stress a lake already filled during monsoon

Residual risk should not be dropped from preparedness calendars: the lake may remain full after the monsoon, while September warmth and October radiation can sustain or renew meltwater inflow.

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From observations to alerts: four-tier meteorological risk classification

Green	Normal	Routine monitoring	Seasonal readings within expected range; no anomalies detected
Yellow	Watch	Heightened surveillance	Sustained above-freezing temperatures plus rising humidity and radiation
Orange	Warning	Operational alert	Heavy precipitation coinciding with above-freezing temperatures for several consecutive days
Red	Critical	Emergency response	Rapid lake-level rise, intense rainfall, visible moraine or slope instability, or seismic disturbance

Calibration note

Threshold values are illustrative until a lake-level sensor empirically links meteorological triggers to observed inflow and stage response.

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Enhancement roadmap: transform a weather station into an early-warning node

1

Lake water-level sensor

highest priority; direct proximity to overtopping or failure

2

Outlet discharge measurement

real-time inflow-to-outflow ratios

3

Time-lapse / near-real-time camera

surface change, moraine dam face and avalanche zones

4

Seismic / vibration sensor

mass movement, ice avalanche and internal erosion signal

5

Telemetry upgrade

near-real-time alerts to disaster authorities

6

Wind repair + QC protocol

calibration and automated filtering

Upgrade logic

Meteorological observations are a strong foundation; early-warning value is transformed when weather signals are fused with lake stage, outlet discharge, imagery, seismic triggers and telemetry.

Closing message: a scalable baseline for Himalayan GLOF readiness

Shako Cho demonstrates how continuous high-altitude observations can shift GLOF management from retrospective assessment to data-driven seasonal preparedness.

Scientific baseline

10-15 years of data can detect warming, monsoon timing shifts and melt-season changes

Operational readiness

May-October planning window aligns field inspections, maintenance and community awareness

National template

Replicable architecture for high-risk lakes across Sikkim, Uttarakhand, Himachal Pradesh and Arunachal Pradesh

Final conference takeaway

The data are imperfect but irreplaceable. Their value grows with every monsoon season and with each step toward multi-sensor, real-time early warning.