The Huaytapallana Glacier.
Image by Daniel Grossman.
Peru, 2011.
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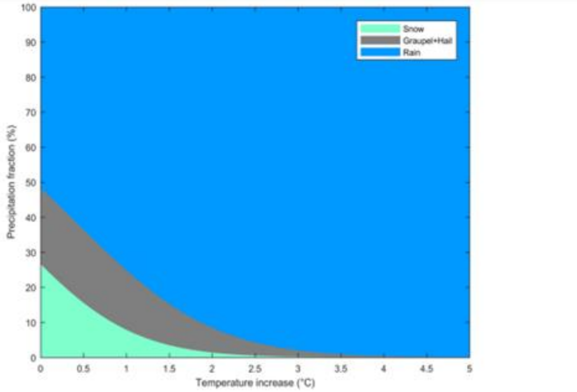


Fig. 8. This is an Extended Data Figure. Model Predictions of Precipitation Type Changes in Relation to Temperature Changes (Eq. 1). This figure provides a predictive view of the shift in precipitation types in response to increasing temperatures. Starting from a baseline condition where approximately 50% of precipitation is in the solid phase, the model illustrates the dramatic reduction in solid precipitation with rising temperatures.

Fig.8 illustrates a dramatic reduction in solid precipitation with rising temperatures.

Analysis of a research paper addressing current and future potential impacts of differentiated precipitation types on the Huaytapallana glacier in the Peruvian Andes.

Target audience: Local environmental managers

Llactayo, V. *et al.,* (2024) ‘Future changes of precipitation types in the Peruvian Andes’, *Scientific Reports*, Volume 14. doi.org/10.1038/s41598-024-71840-2

Overall environmental issue
Warming and glacier retreat

- Adaptation is becoming irreversible loss for Earth's frozen water in ice sheets, sea ice, permafrost, polar oceans, glaciers and snow (International Cryosphere Climate Initiative (2023).
- Advanced models project changes to 215,000 glaciers 2015-2100. At 1.5°C 49% glaciers could disappear by 2100. 50% by 2050. At 4°C 83% could disappear (Rounce *et al.,* 2023).
- Glaciers react quickly to climate change. Contribute a third to observed sea level rise (Davies, 2023).
- Climate change and sustained forcing likely caused by positive feedback processes. World Glacier Monitoring Service (2024) (**Fig.1, Fig. 3**).
- Warming in Himalayas, Swiss Alps, central Andes increases with altitude. Andes glacier volume loss and permafrost thawing likely to continue, causing reductions in river flow and high-magnitude glacial lake outburst floods (Intergovernmental Panel on Climate Change, 2022).

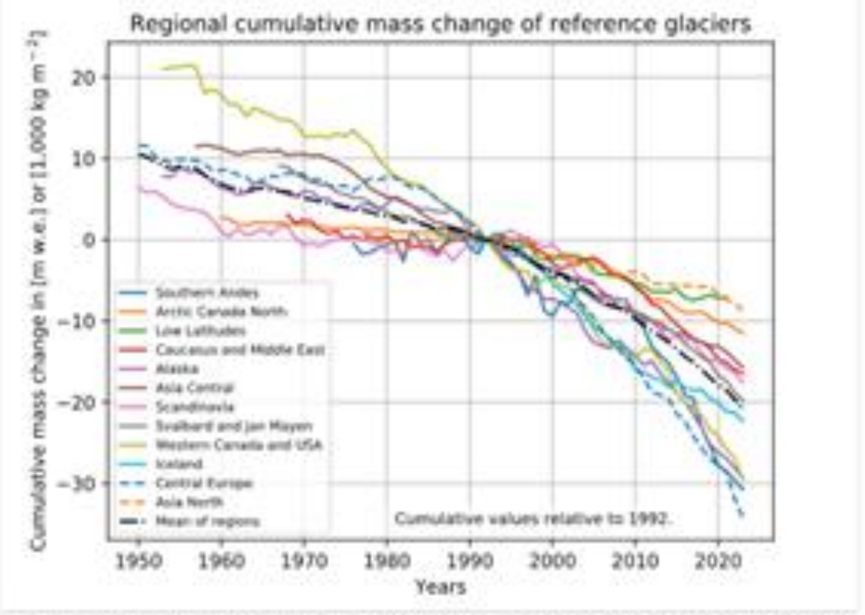


Fig. 3: Cumulative mass change relative to 1992 for regional and global means based on data from reference glaciers. Cumulative values are given on the y-axis in the unit meter water equivalent (m w.e.).

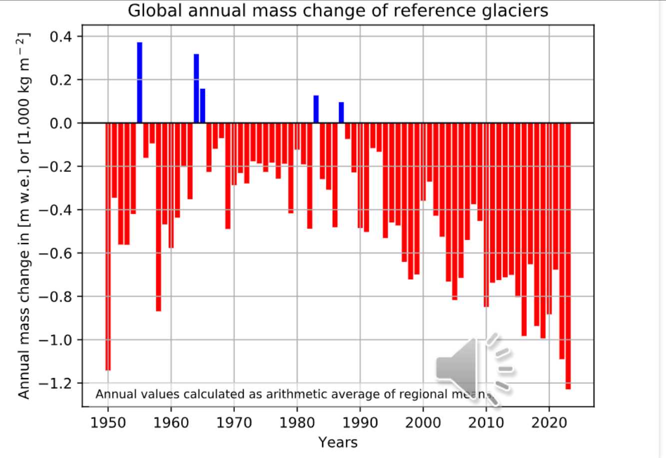
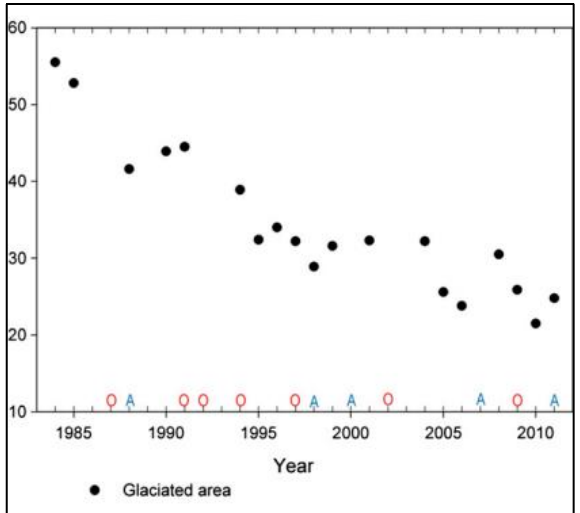


Fig. 1 Annual mass balance of reference glaciers with more than 30 years of ongoing glaciological measurements. Annual mass change values are given on the y-axis in the unit meter water equivalent (m w.e.) which corresponds to tonnes per square meter (1,000 kg m^{-2}). Source: WGMS (2023, updated and earlier reports).

Glacier retreat in Andes is unprecedented since the Little Ice Age

- 99% world's tropical glaciers in Andes. 70% in Peru. (Yarleque *et al*., 2018). Glacier retreat last 30 years unprecedented since mid-17th to early 18th century Little Ice Age (Rabatel *et al*.,2013).
- Retreat endangers agriculture, subsistence farming, fragile ecosystems and 5.8 million populace. Cities rely on glacier melt water supply: 5.3% Quito, Ecuador; 61.1% La Paz, Bolivia; 67.3% Huaraz, Peru. (Buytaert *et al*., 2017).
- First Cordillera Huaytapallana study: 55% decrease surface covered by glaciers over 28 years. Snowline moved up 93 - 157 meters. Glacier retreat higher rate El Niño years than La Niña years. (**Fig. 5**). (López-Moreno *et al*., 2014).
- Huaytapallana glacier (right) main mountain in Cordillera Huaytapallana in Huaytapallana Regional Conservation Area. Peaks 5500 m ASL. Headwater for Mantaro Basin. Records from 2013: Average temperature 3°C with maximum and minimum values 12°C and - 5°C in January and August. Dry season Jun. - Aug. (JJA). Rainy season Dec.- Feb. (DJF) Average annual accumulated rainfall 930 mm 86% during DJF.
- Present day mountain ecosystem essentially connected with solid (cold) precipitation, retaining solid water in glaciers during seasonal precipitation months (Oct.-May). Stored water released during seasonal no-precipitation months (Apr.-Sept.).



Interannual evolution of ice covered area. El Niño and La Niña events are indicate
O" and "A", respectively.

Focus of research paper: 'Future changes of precipitation type in the Peruvian Andes' Llactayo, V. *et al*. (2024)

- Studying precipitation types in high-altitude remote and rugged regions is challenging in extreme weather conditions. Previous researchers hindered by lack of maintained weather stations.
- Distinguishing precipitation types is crucial to understanding glacial melting process. Solid precipitation (snow, graupel, hail) can increase surface albedo and snow accumulation in high mountain regions. Liquid precipitation (drizzle and rain) is associated with runoff and infiltration.
- November 2022 - March 2023 researchers assessed distribution changes three types precipitation: snow, hail-graupel and rain on Huaytapallana glacier using temperature thresholds, diurnal cycles and CMIP6 Socioeconomic Pathway climate scenarios: Scenario 3: Middle of the Road (2.7°C by 2100) SSP2-4.5.and worst case Scenario 5: Avoid at All Costs (4.4°C by 2100) SSP5-8.5. (Intergovernmental Panel on Climate Change (2021).
- Researchers acknowledged Yarleque *et al.,* (2018) Quelccaya Ice Cap study using CMIP6. Seventeen years ago researchers found it had lost 20% area since 1978 (Konkel, L. 2008).
- **Findings: Increased temperatures could lead to significant reductions in solid-phase precipitation with implications for mass balance of Andean glaciers. A 2°C rise could result in less than 10% of solid precipitation transforming regional hydrological processes**.
- This in situ data may enable local environmental managers to plan improved water resource management strategies, focus on further research requirements and address glacier preservation.

Methods: Observational data
Tropical glacier precipitation patterns

- Researchers analysed data collected by the Glacier and Mountain Ecosystem Monitoring Center located 4709 m ASL, 4k west of glacier (Fig. 1) using an optical-laser disdrometer and compact weather station combined with Coupled Model Intercomparison Project Phase 6 (CMIP6) future climate scenarios (CarbonBrief, 2019) to model potential future changes in precipitation types.
- OTT Parsivel² captures size and speed of falling particles. 32 size and velocity classifications. Calculate type, amount, intensity, kinetic energy of precipitation, visibility, equivalent radar reflectivity (Lufft, 2025).
- However, researchers grouped hail and graupel as a single category as OTT Parsivel² did *not* distinguish "graupel" as a separate hydrometeor.
- Temperature observations recorded 1-minute intervals by Lufft WS500-UMBWS500-UMB Smart Weather Sensor that measures temperature, relative humidity, air pressure, wind direction, wind speed (Lufft, 2025).
- Bias correction CMIP6 models (Zekollari, H.*et al.,* 2024) hourly 2013–2023 recorded temperature data from a meteorological station set up by National Weather and Hydrological Services (SENAMHI) - Huaytapallana at 4,760 m (15,617 ft).

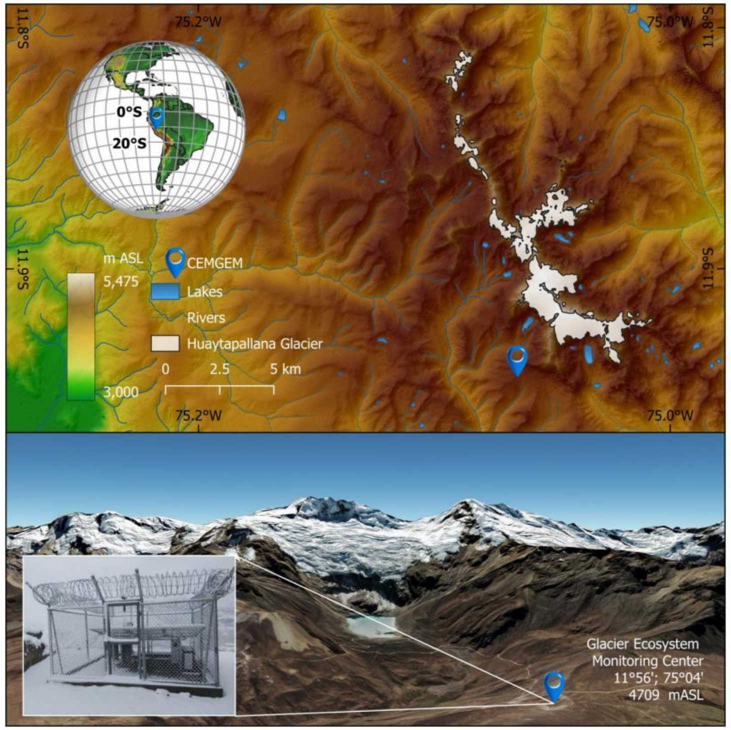
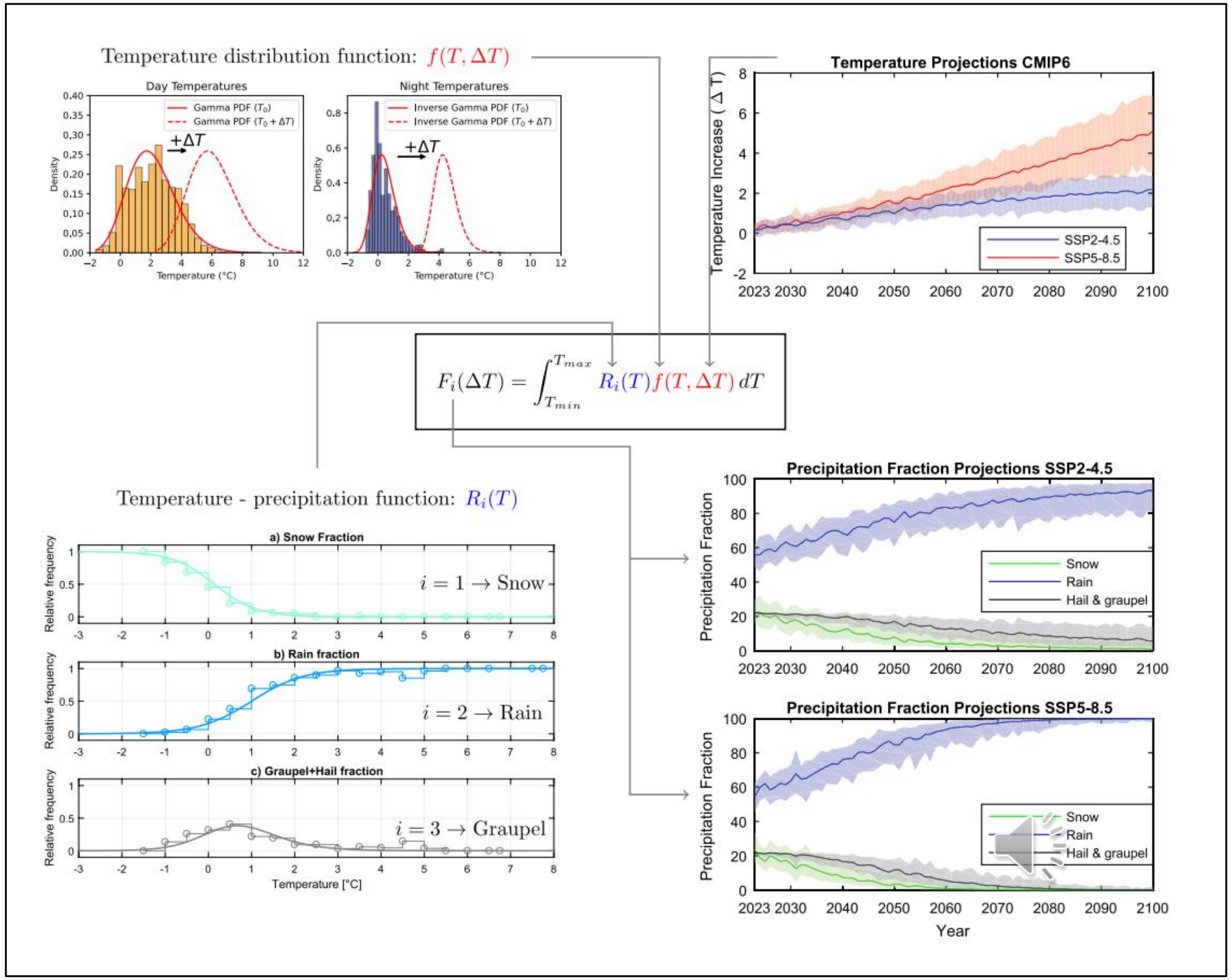


Fig. 1. A comprehensive view of our high mountain glacier study area in the Tropical Andes. The top-left globe shows the broad South American location, with latitudes 0° and 20° South marked for context. The middle frame provides a detailed view of the study area, precisely the Huaytapallana glacier (Junin - Peru). The bottom frame shows a Google Earth image of the glacier, along with the Glacier and Mountain Ecosystem Monitoring Center (CEMGEM) equipment installed in the area, which is indicated by a blue symbol.

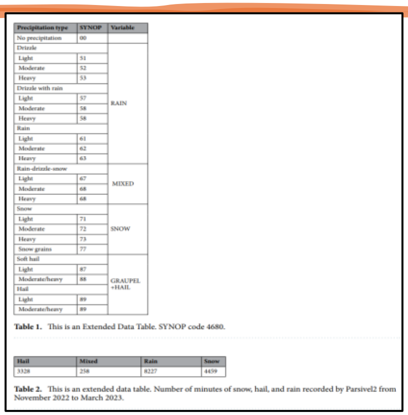
Methods: Modelling precipitation fraction

- Due to limited rainfall data availability over one season and to avoid uncertainties in modeling, researchers developed a mathematical model to understand how precipitation patterns will alter.
- **Fig. 7**. Methodology flow diagram for computing future precipitation types. The diagram includes temperature distribution functions for day and night temperatures, temperature projections under different climate scenarios (SSP2-4.5 and SSP5-8.5), and temperature-precipitation functions for snow, rain, and graupel. Researchers predict the future fractions of different precipitation types under the influence of climate change.



Results: Present day tropical glacier precipitation patterns

- Data from 89 events. 80% annual precipitation according to historical data. “Precipitation event” a rain period separated by 2-h or more rain-free periods in rain-rate time series of OTT Parsivel² and a rain/no-rain threshold set at a minimum of 10 drops and a rain rate of 0.1 mm/hour.
- OTT Parsivel² identified 6 precipitation categories based on SYNOP (surface synoptic observations) numerical code used for reporting weather observations made by staffed and automated weather stations.
- “Rain” recorded either drizzle or rain. Records of rain/drizzle/snow taken as “mixed” precipitation. Researchers did *not* consider mixed precipitation due to capturing only a few minutes of data (**Extended data Table 2**).
- **Table 1**. Extended Data Table. SYNOP code 4680. **Table 2**. Number of minutes of snow, hail, and rain recorded by OTT Parsivel² Nov. 2022 - Mar. 2023.
- **Fig. 4.** (Right) Fractional contributions different precipitation types (rain, graupel-hail, and snow) day and night. Modeled values averaged over evenly distributed day and night periods (50–50%), based on temperature. Observational values derived from in-situ OTT Parsivel² data on actual events.

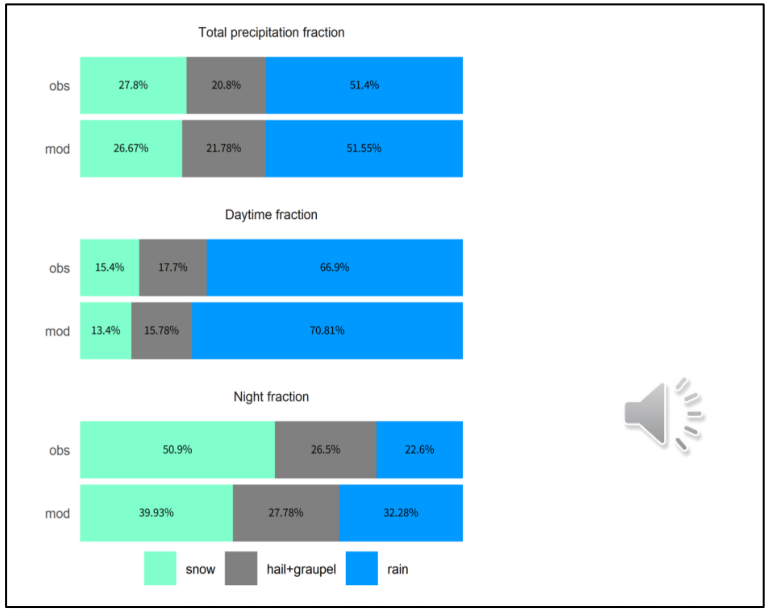


Precipitation type	SYNOP	Variable
No precipitation	00	
Drizzle		RAIN
Light	51	
Moderate	52	
Heavy	53	
Drizzle with rain		
Light	57	
Moderate	58	
Heavy	58	
Rain		
Light	61	
Moderate	62	
Heavy	63	
Rain-drizzle-snow		MIXED
Light	67	
Moderate	68	
Heavy	68	
Snow		SNOW
Light	71	
Moderate	72	
Heavy	73	
Snow grains	77	
Soft hail		GRAUPEL +HAIL
Light	87	
Moderate/heavy	88	
Hail		
Light	89	
Moderate/heavy	89	

Table 1. This is an Extended Data Table. SYNOP code 4680.

Hail	Mixed	Rain	Snow
3328	258	8227	4459

Table 2. This is an extended data table. Number of minutes of snow, hail, and rain recorded by Parsivel2 from November 2022 to March 2023.



Current density distribution and diurnal cycle

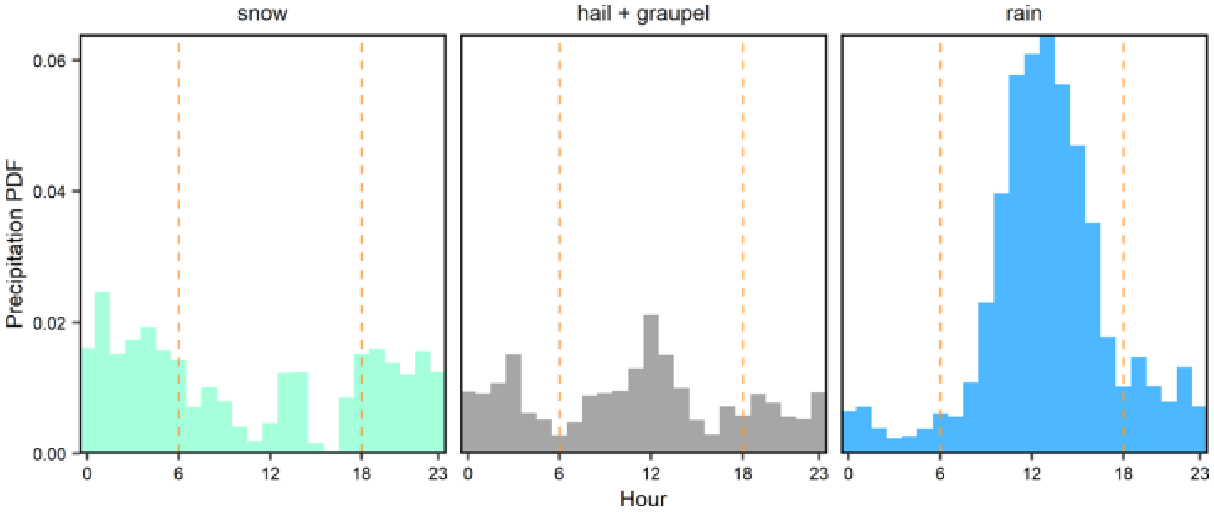


Fig. 3. Diurnal cycle in LST of the probability frequency for snow (light green), hail + graupel (grey), and rain (blue) calculated using observational data from 89 events from late November 2022 to March 2023.

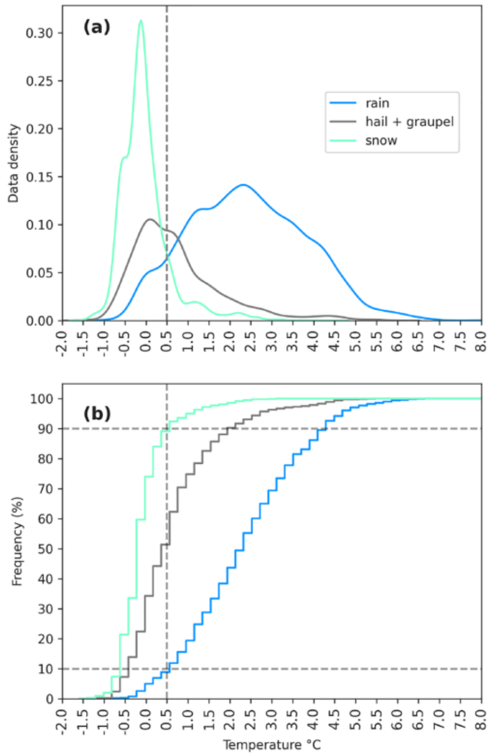


Fig. 2. (a) Density distribution of snow (light green), hail + graupel (grey), and rain (blue) data according to temperature. The dotted line is located at 0.5 °C, below which 90% of the snow records are located and 90% of rain records are located above the same value. **(b)** Cumulative frequency graph expressed in percentages for snow, hail, and rainfall records according to temperature values. The horizontal dotted lines mark the location of 90% (upper line) and 10% (lower line). The vertical line marks the 0.5 °C value.

Further understanding of hail and graupel role in glacier retreat required

- Graupel and hail 43% of solid phase present day yet lack of understanding on whether graupel and hail reach the glacier surface contributing to glacier mass accumulation or promoting runoff in the presence of rainfall. Researchers grouped hail and graupel into a single category as OTT Parsivel² disdrometer did not distinguish "graupel" as a separate type of hydrometeor and underestimated total rainfall by 16% each single event.
- **Fig. 5** **A stark picture of alterations in precipitation types with rising temperatures 2030-2090 in both scenarios. Model indicates significant shift from solid to liquid precipitation with a 2°C increase in temperature, transitioning from present day 50% solid precipitation to under 10%.**
- **SSP2-4.5 scenario suggests 80% future rainfall dominant 2060s–2070s with less than 5% of snowfall**. **Table 4**. In both SSP2-4.5 and SSP5-8.5 scenarios hail and graupel occurrences reduce to less than 5% around 2090s and 2050s. SSP2-4.5 scenario suggests 80% of future rainfall dominant 2060s–2070s.
- **Glacier retreat can be expected across the Huaytapallana glacier due to higher air temperatures increasing heat transfer and inducing a change from snow to rain. Water sustainability will be affected by warmer rainfall contributing to glacier retreat.** Environmental managers will welcome deeper research using effective equipment into precipitation-type discrimination as Fig. 5 highlights graupel-hail as predominant over snow.

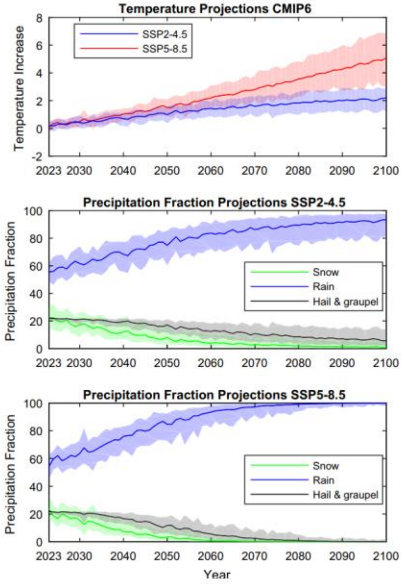


Fig. 5. Future Projections of Precipitation Types with Error Margins and Temperature Increase (ΔT) under SSP2-4.5 and SSP5-8.5 Scenarios. Top panel: CMIP6 model-based temperature increase projections under SSP2-4.5 (blue) and SSP5-8.5 (red) scenarios, with the shaded areas representing the 10th to 90th percentile range of the projections. Middle panel: Projected changes in the occurrence of three types of precipitation - snow (green), rain (blue), and hail & graupel (gray) - from 2023 to 2100 under the SSP2-4.5 scenario, including error margins. Bottom panel: Similar precipitation fraction projections under the SSP5-8.5 scenario, also including error margins.

SSP2-4.5					SSP5-8.5			
	ΔT°	Snow	Rain	H+G	ΔT°	Snow	Rain	H+G
2030	0.6 ± 0.4	14.4 ± 7.2	65.3 ± 9.4	20.3 ± 2.2	0.7 ± 0.5	12.0 ± 7.3	68.6 ± 10.4	19.4 ± 3.1
2040	0.9 ± 0.5	9.4 ± 6.6	72.7 ± 10.4	17.9 ± 3.8	1.3 ± 0.5	5.3 ± 4.9	80.6 ± 10.0	14.1 ± 5.2
2050	1.2 ± 0.5	5.6 ± 5.2	79.7 ± 10.5	14.7 ± 5.2	1.8 ± 0.7	2.2 ± 3.4	88.9 ± 9.5	8.9 ± 6.1
2060	1.5 ± 0.6	3.5 ± 4.2	84.6 ± 10.2	11.8 ± 6.0	2.5 ± 0.9	0.6 ± 1.5	95.4 ± 6.5	4.0 ± 5.0
2070	1.7 ± 0.7	2.4 ± 3.9	87.9 ± 10.4	9.7 ± 6.5	3.1 ± 1.2	0.2 ± 0.7	98.3 ± 4.2	1.6 ± 3.4
2080	1.9 ± 0.8	1.7 ± 3.1	90.6 ± 9.5	7.7 ± 6.4	3.9 ± 1.4	0.0 ± 0.2	99.5 ± 1.8	0.5 ± 1.6
2090	2.1 ± 0.8	1.3 ± 2.8	92.1 ± 9.1	6.6 ± 6.3	4.6 ± 1.7	0.0 ± 0.1	99.8 ± 1.1	0.2 ± 1.0

Table 4. Decadal Projections of Precipitation Types from 2030 to 2090 under the CMIP6 SSP2-4.5 and SSP5-8.5 scenario. The table presents averaged projections of temperature increase (ΔT°) in Celsius Degrees, snow fraction, rain fraction, and hail + graupel (H+G) fraction for each decade. Values are derived from CMIP6 SSP2-4.5 and SSP5-8.5 model outputs. The error margin represents the midpoint between the 10th and 90th percentile projections.

Model Predictions of Precipitation Type Changes in Relation to Temperature Changes

- **Fig. 8**. Model Predictions of Precipitation Type Changes in Relation to Temperature Changes (Eq. 1). Provides a predictive view of the shift in precipitation types in response to increasing temperatures. **Starting from baseline condition where 50% of precipitation is solid phase, the model illustrates dramatic reduction in solid precipitation with rising temperatures.**
- Potential changes in precipitation types with increased frequency of rain events in both SSP2-4.5 and SSP5-8.5. **Glacier retreat at Huaytapallana is linked to temperature change from snow to rain increasing glacier decline.**
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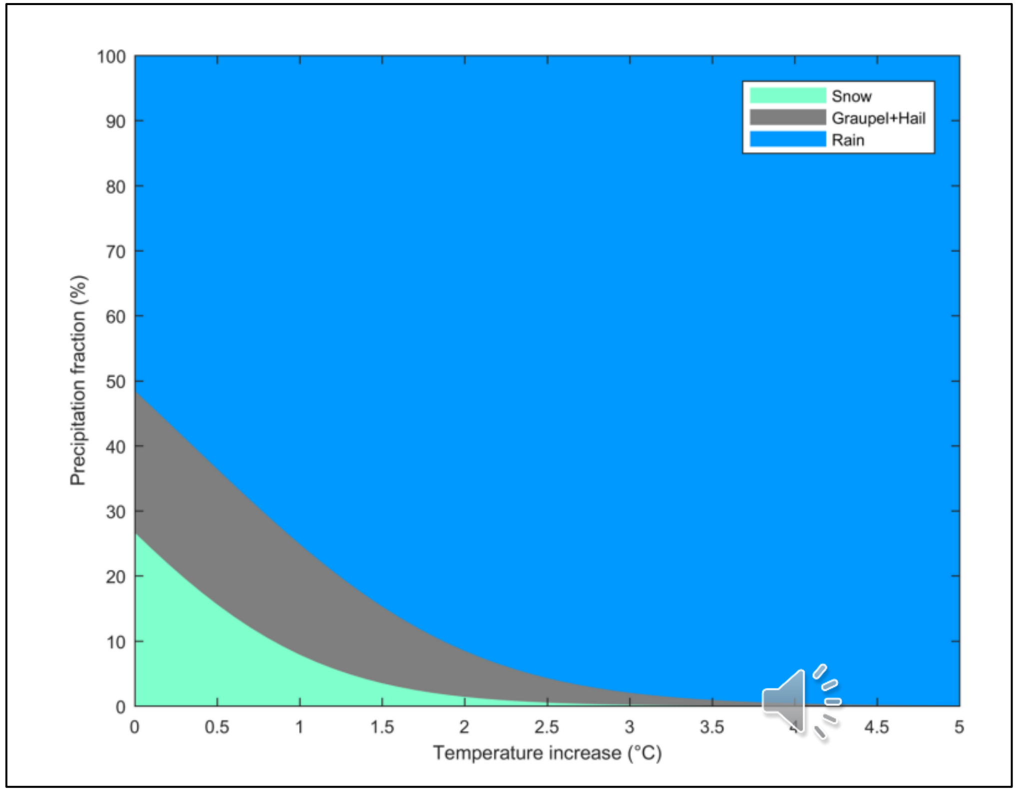

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