Supplement of Nat. Hazards Earth Syst. Sci., 25, 1207–1228, 2025
https://doi.org/10.5194/nhess-25-1207-2025-supplement

Natural Hazards and Earth System Sciences
Open Access

Supplement of

Causes, consequences and implications of the 2023 landslide-induced Lake Rasac glacial lake outburst flood (GLOF), Cordillera Huayhuash, Peru

Adam Emmer et al.

Correspondence to: Adam Emmer (adam.emmer@uni-graz.at, aemmer@seznam.cz)

Supplementary figures:

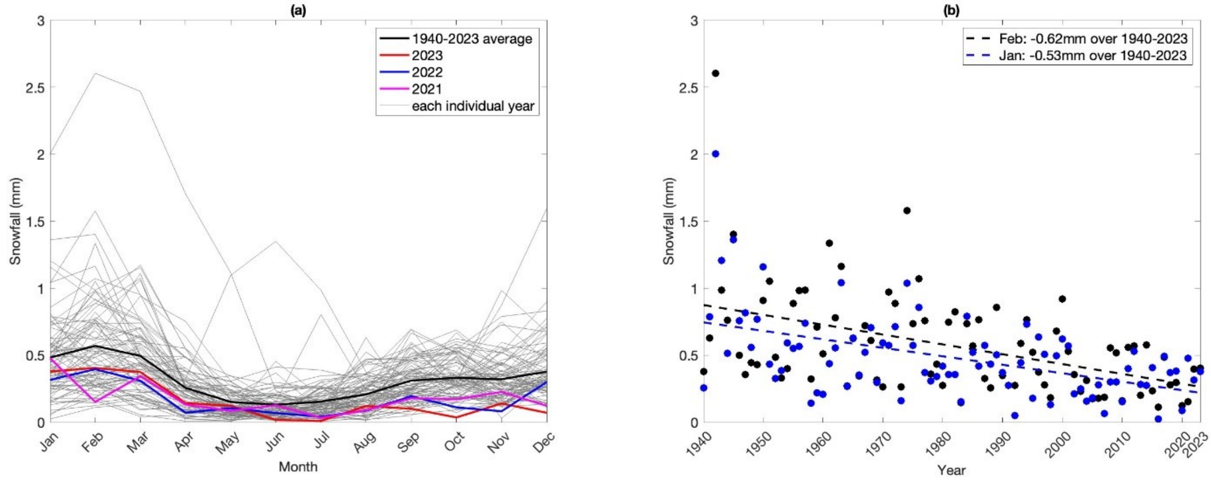

Figure S1. Snowfall averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

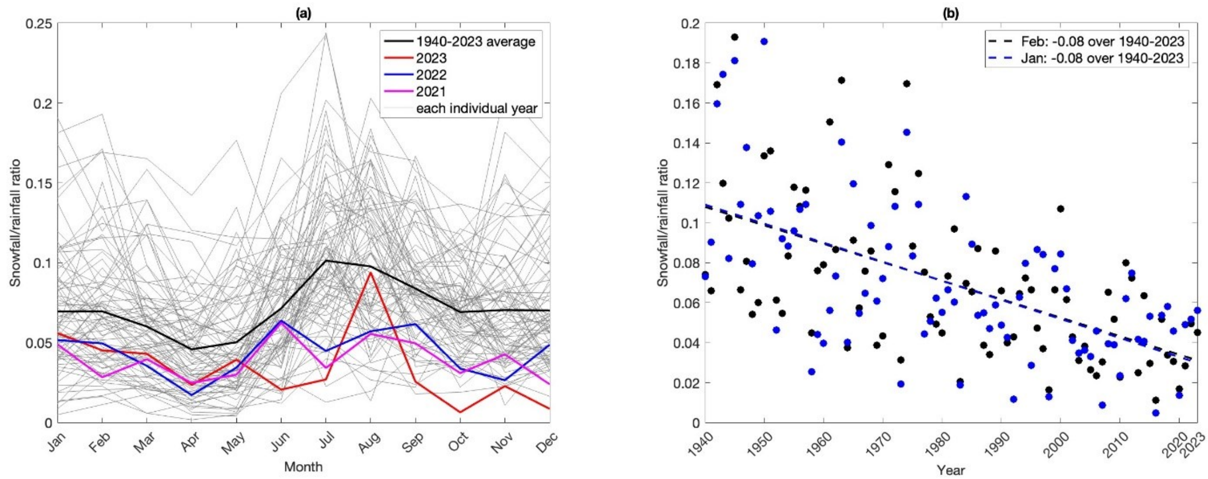

Figure S2. Snowfall to rainfall ratio averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

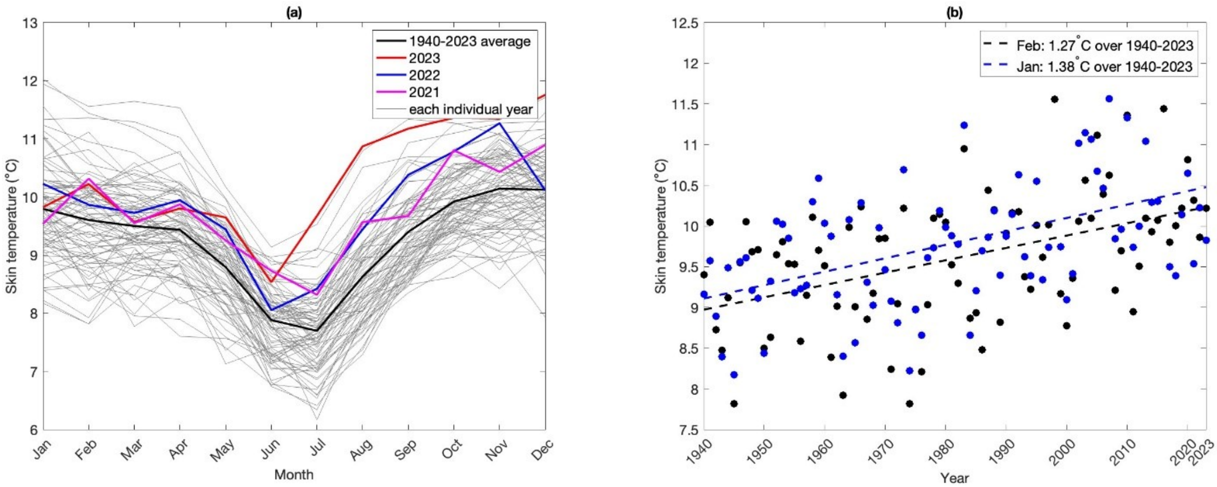

Figure S3. Land surface skin temperature averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

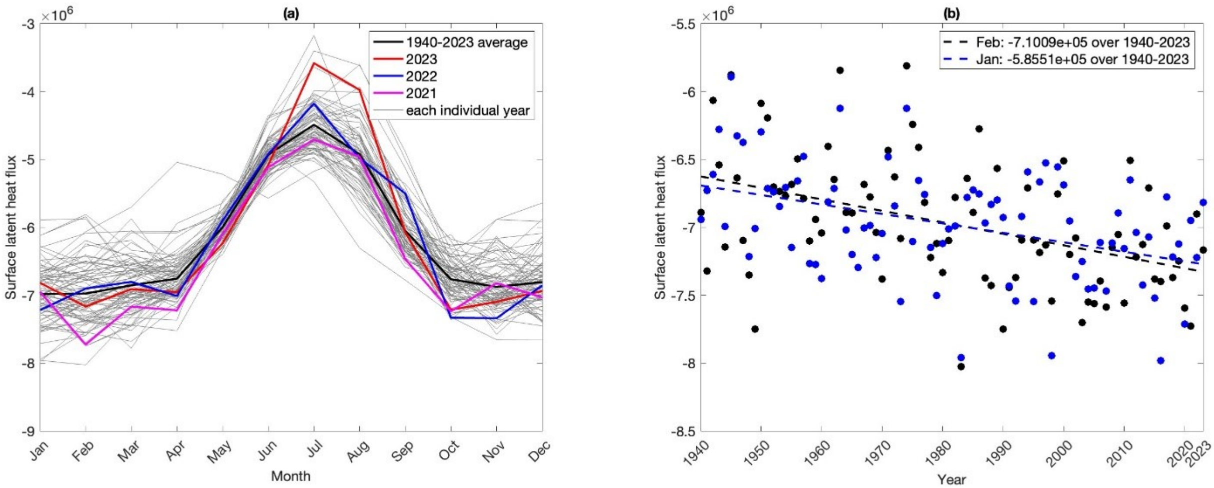

Figure S4. Surface latent heat flux averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

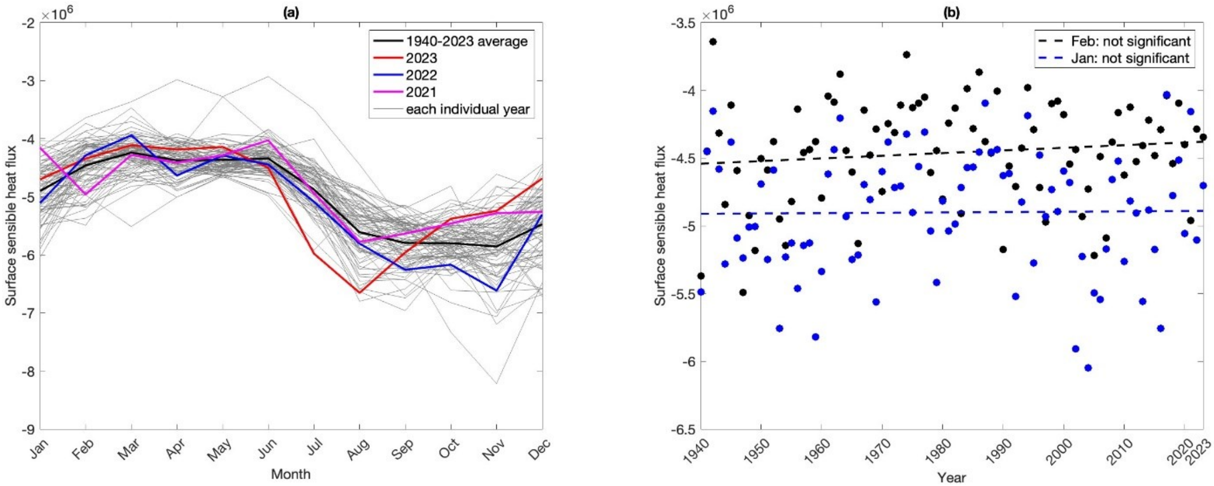

Figure S5. Surface sensible heat flux averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

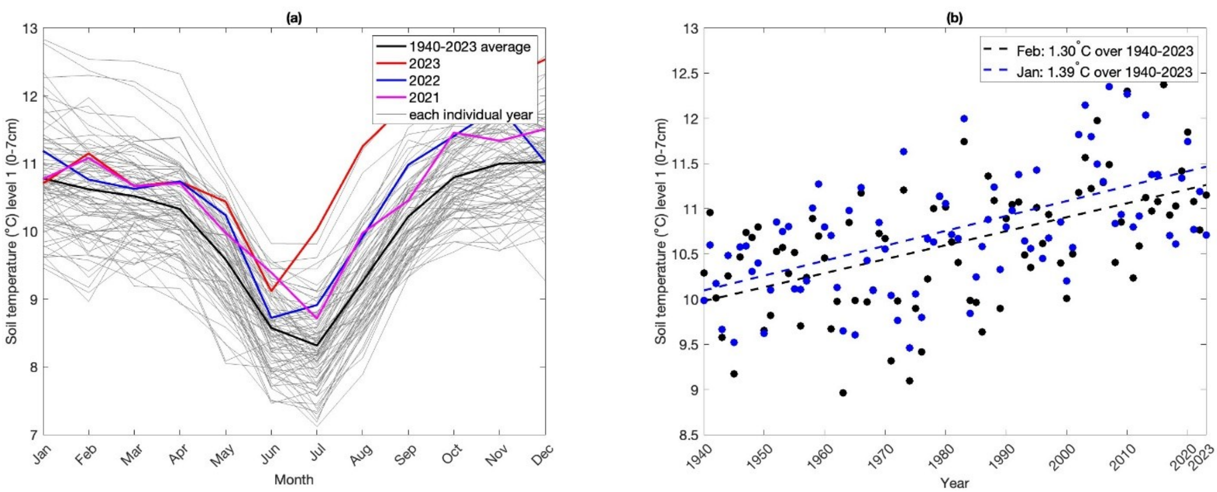

Figure S6. Soil temperature in layer 1 (0-7cm) averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

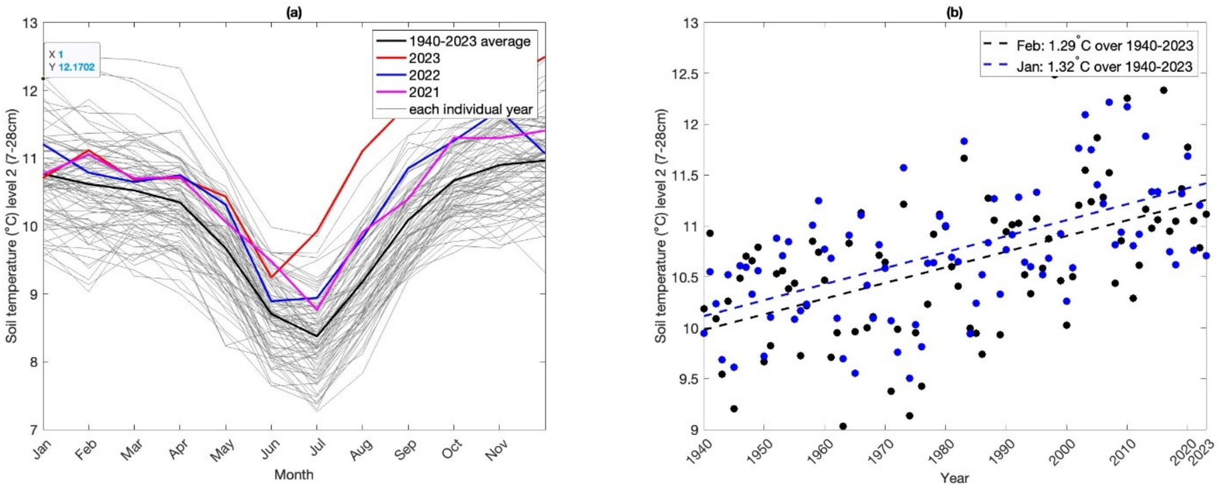

Figure S7. Soil temperature in layer 2 (7-28cm) averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

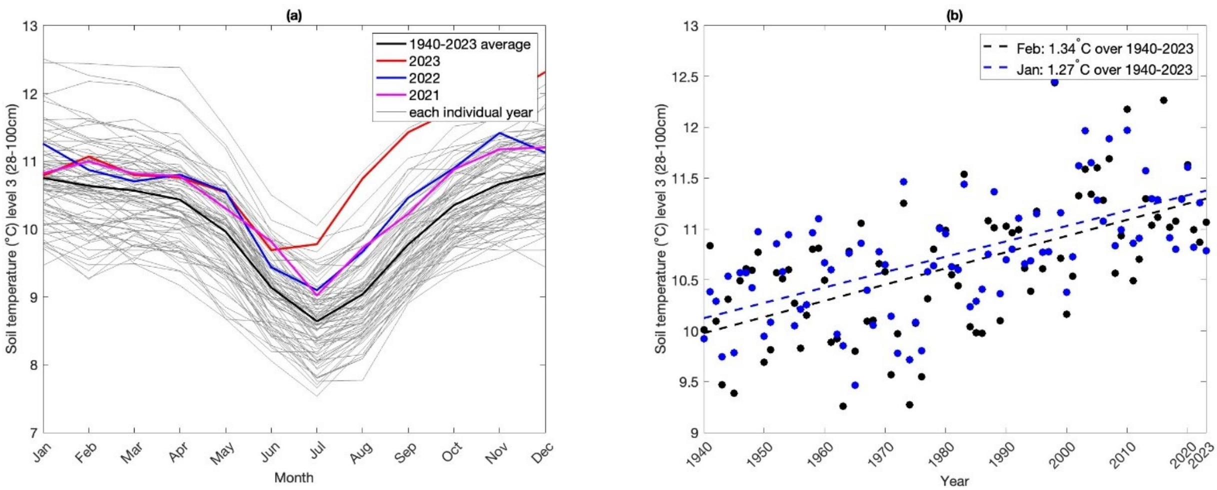

Figure S8. Soil temperature in layer 3 (28-100cm) averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

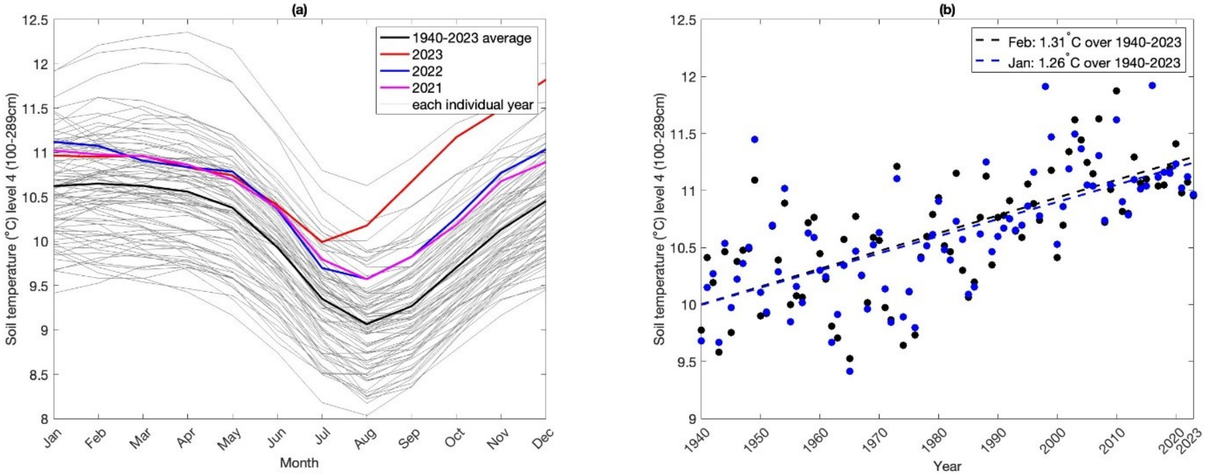

Figure S9. Soil temperature in layer 4 (100-289cm) averaged over the 1° by 1° box [-77.5, -76.5, -10.75, -9.75] covering Rasac, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2023.

We have also performed the same set of analysis for the Aug 2022 Upiscocha GLOF and the Feb 2020 Salkantaycocha GLOF (Table3 of the main text), the same list of climate variables as shown in Table 2 are analysed. We used the average value over 1° by 1° box [-71.75,-70.75,-14.25,-13.25] and [-73.07,-72.07,-13.84,-12.84], covering Upiscocha and Salkantaycocha respectively, representing the meteorological conditions of the two lakes, to investigate 1) the long term trend over the past eight decade over 1940-2022 for lake Upiscohca and over 1940-2020 for lake Salkantaycocha, and 2) the anomalous states (compared with climatological mean averaged over 1981-2010) that occurred in the near-surface atmosphere, land surface, and sub-surface of different soil layers for the time period leading up (up to 2 years) to the event. Monthly products were used to analyse the climate trends and daily products were used to analyse the anomalous conditions prior to the two GLOF events respectively.

Results for Lake Upiscocha:

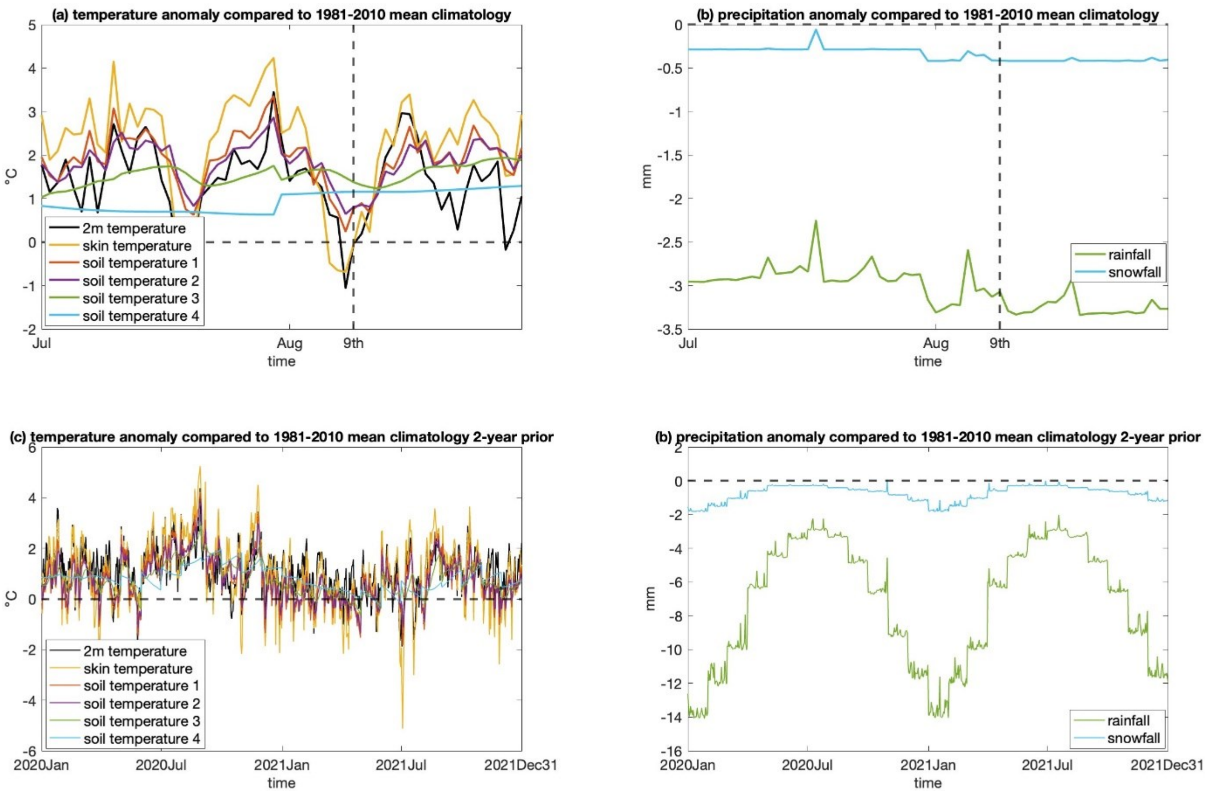

Figure S10. Anomalies in temperature and precipitation compared to the 1981-2010 mean climatology. Panel (a) shows the daily temperature anomalies for July and August of 2022, showing variables across 2m air temperature, surface skin temperature, and soil temperatures at different soil column depths. Panel (b) shows the corresponding precipitation anomalies during the same period. Panel (c) expands the temperature anomalies over two years prior to 2022, and panel (d) shows the corresponding precipitation anomalies over the same two-year period. Dashed vertical line indicates the timing of the Upiscocha GLOF event on the 9th of August 2022.

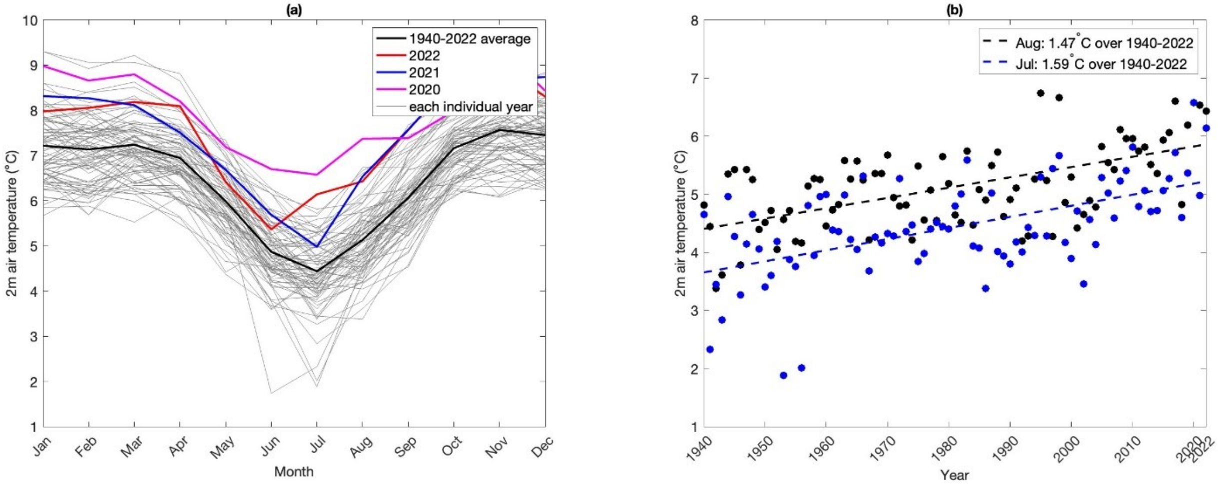

Figure S11. 2m temperature averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

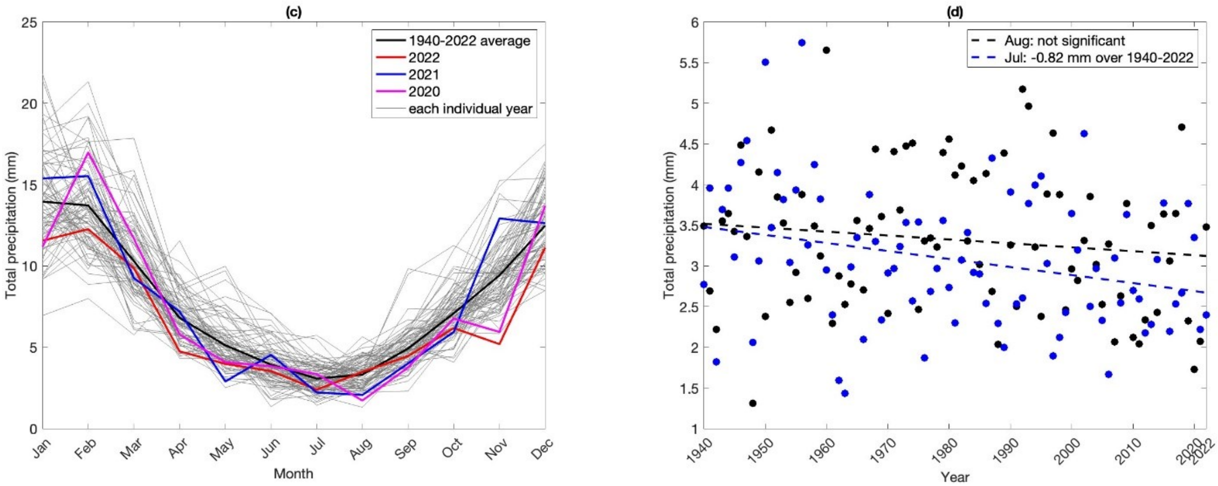

Figure S12. Total precipitation averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

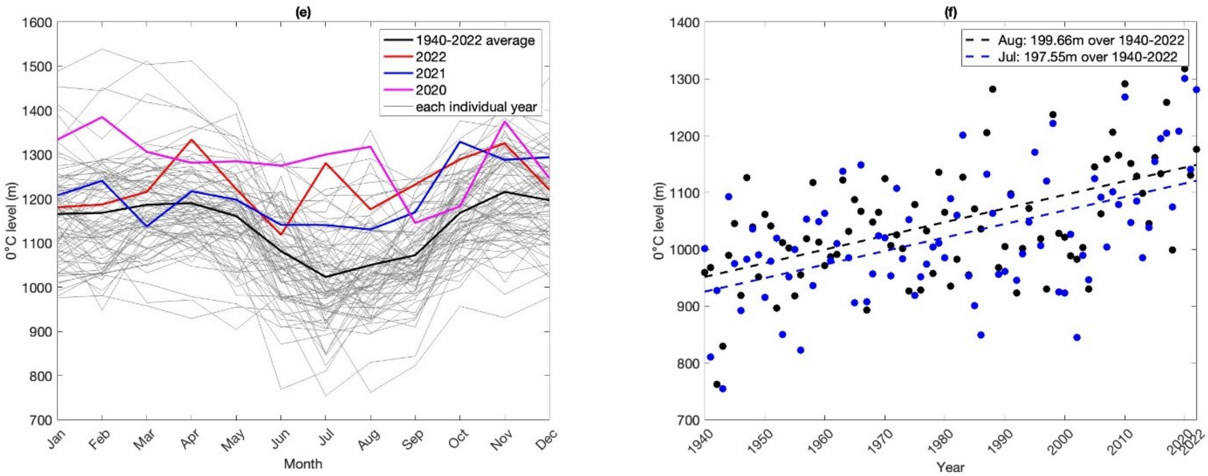

Figure S13. 0°C level (m) averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

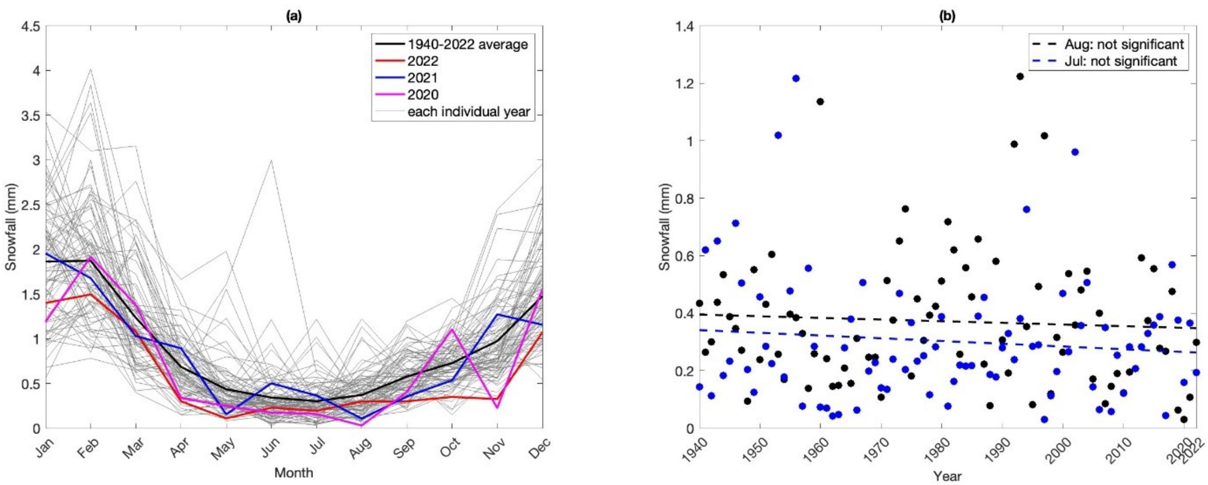

Figure S14. Snowfall averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

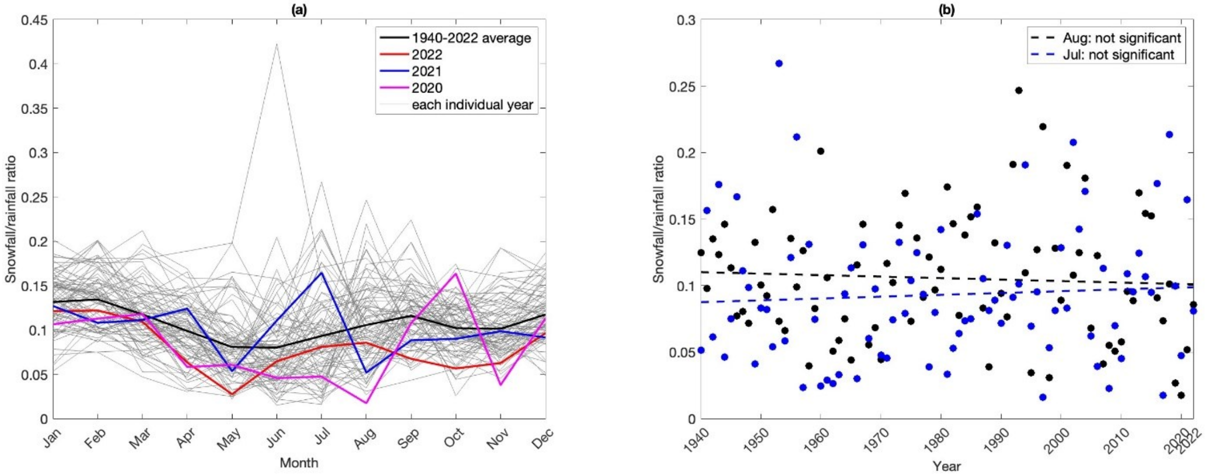

Figure S15. Snowfall to rainfall ratio averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

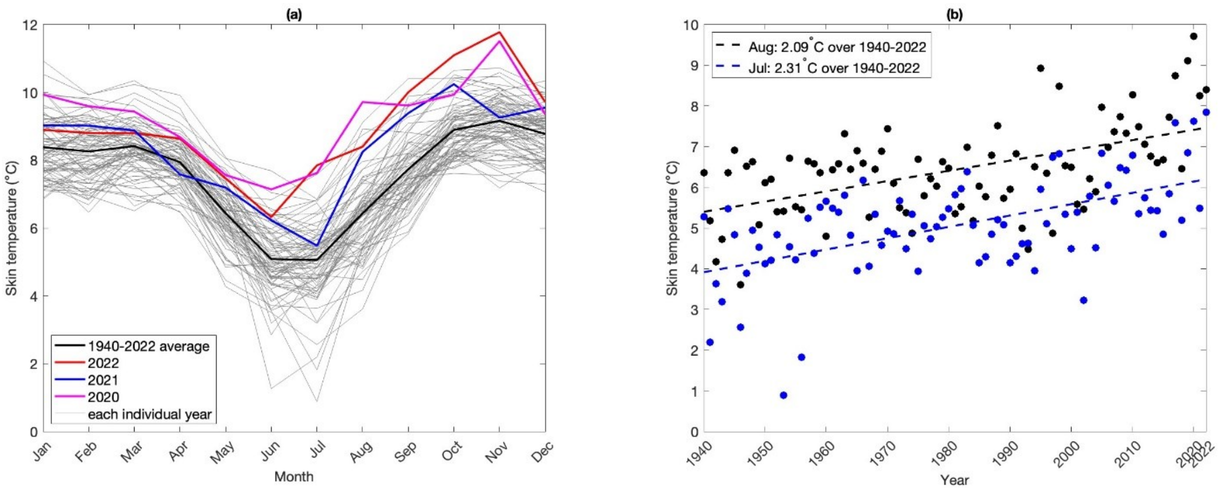

Figure S16. Land surface skin temperature averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

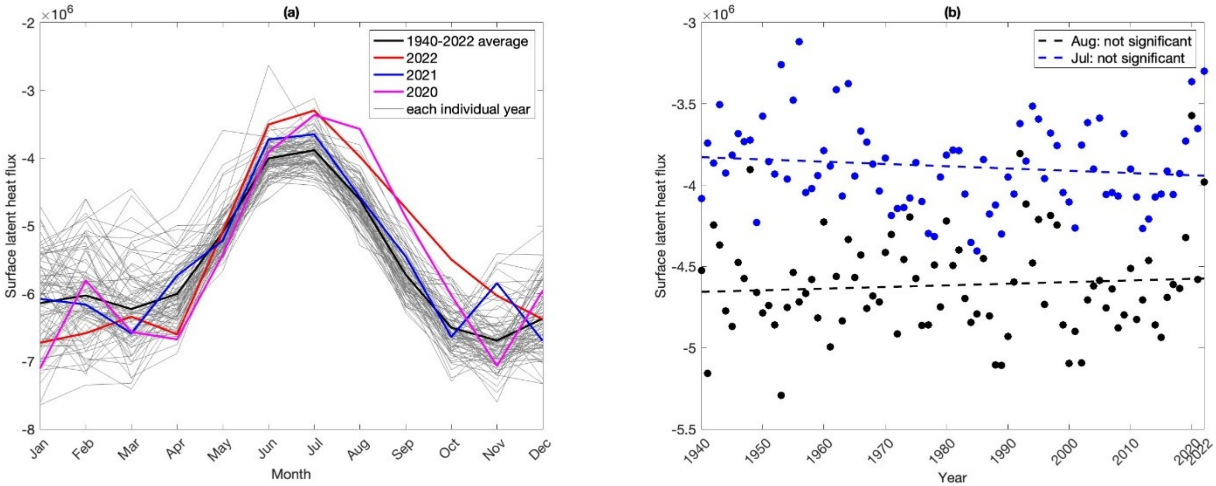

Figure S17. Surface latent heat flux averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

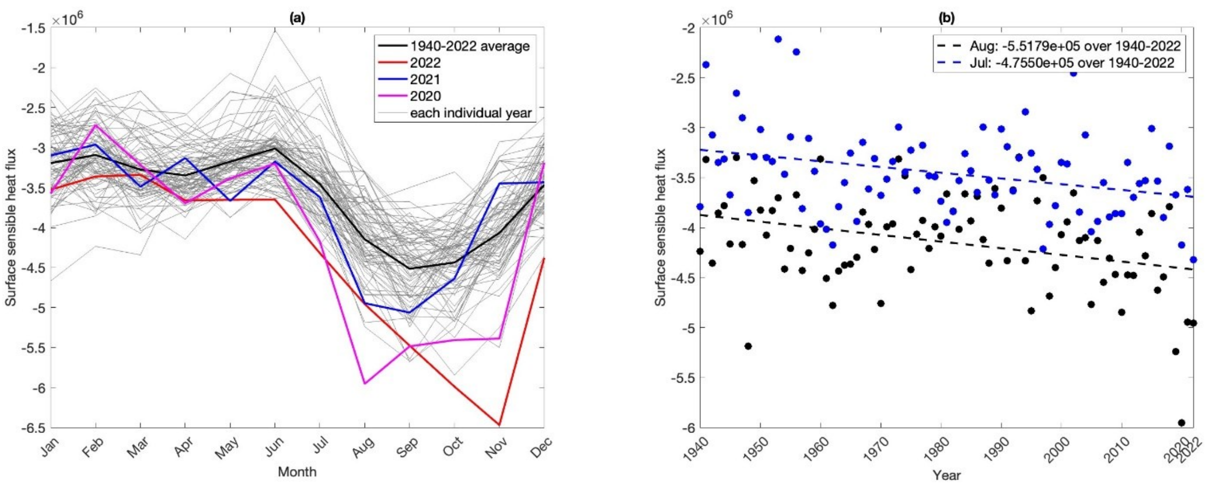

Figure S18. Surface sensible heat flux averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

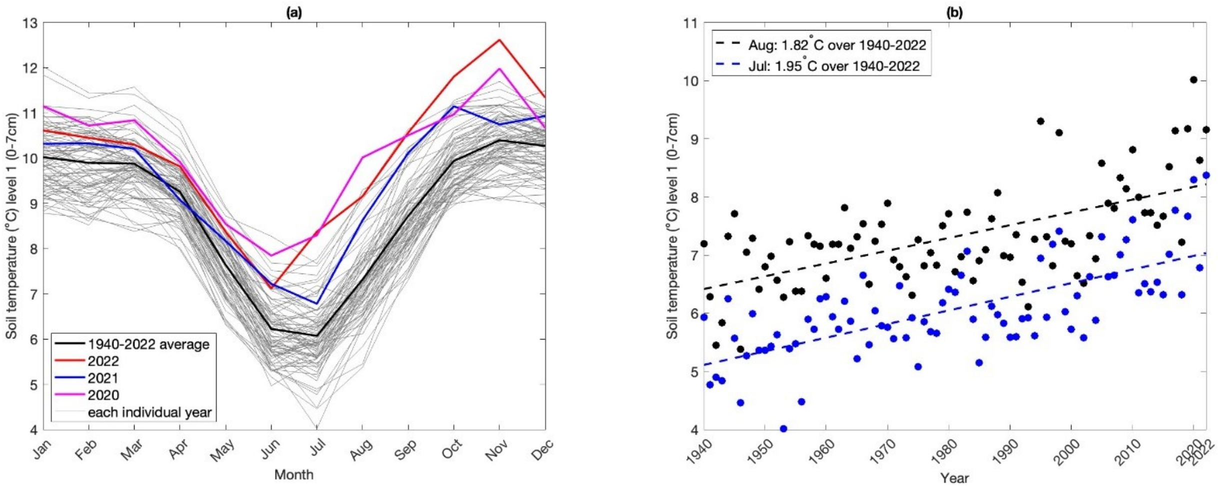

Figure S19. Soil temperature in layer 1 (0-7cm) averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

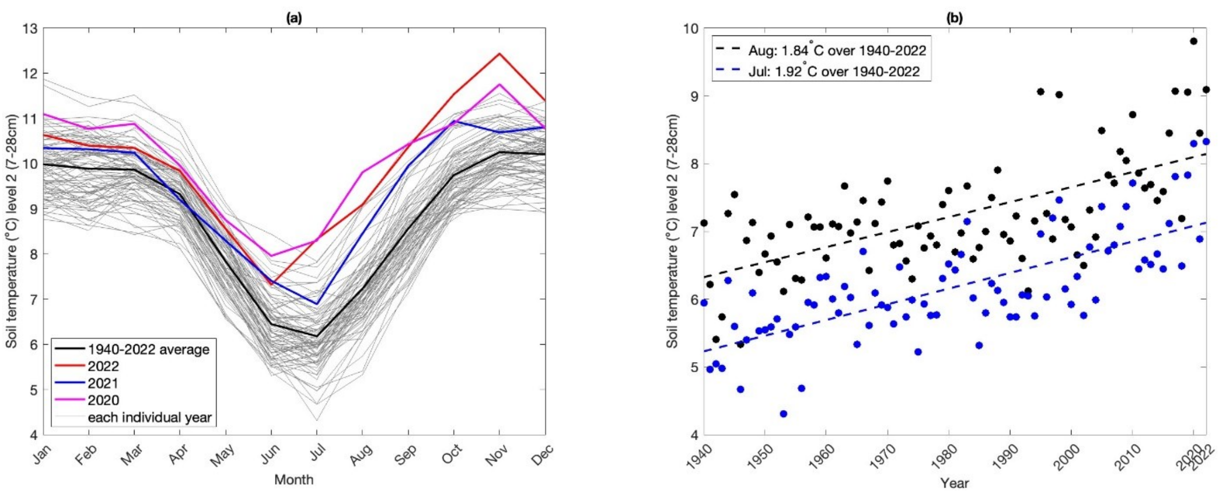

Figure S20. Soil temperature in layer 2 (7-28cm) averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

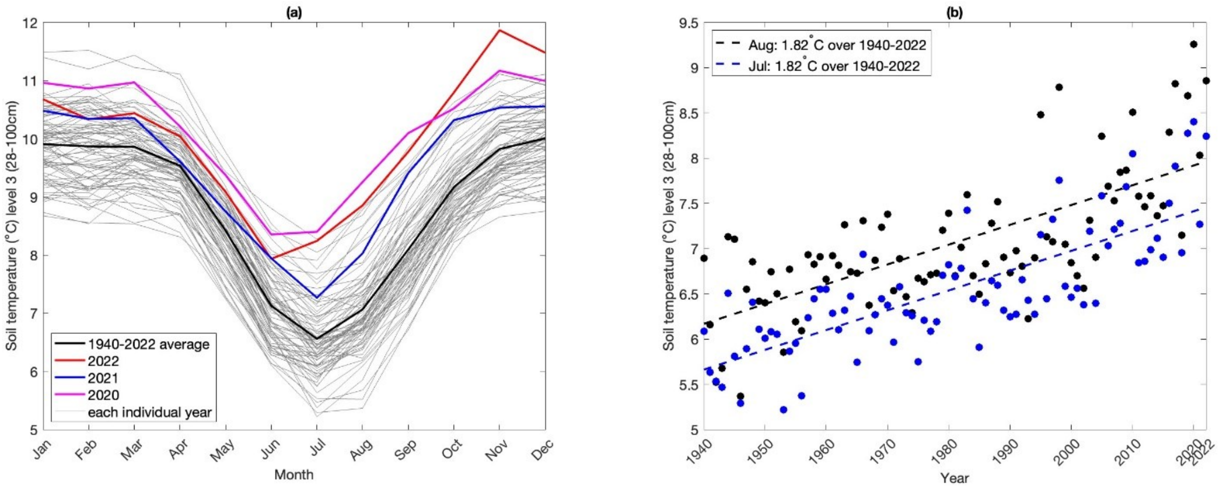

Figure S21. Soil temperature in layer 3 (28-100cm) averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

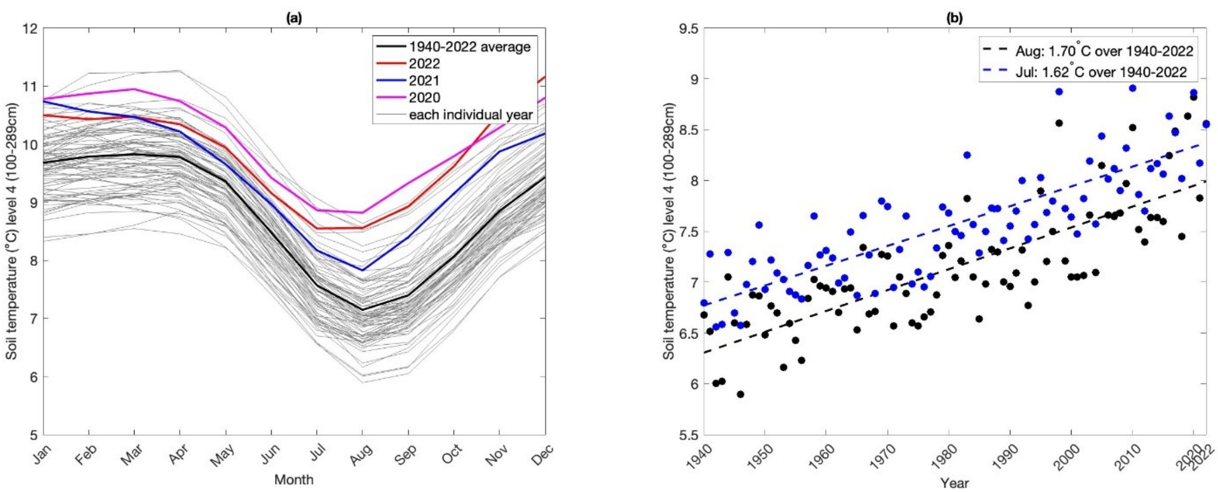

Figure S22. Soil temperature in layer 4 (100-289cm) averaged over the 1° by 1° box [-71.75,-70.75,-14.25,-13.25] covering Upiscocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2022.

Results for Lake Salkantaycocha:

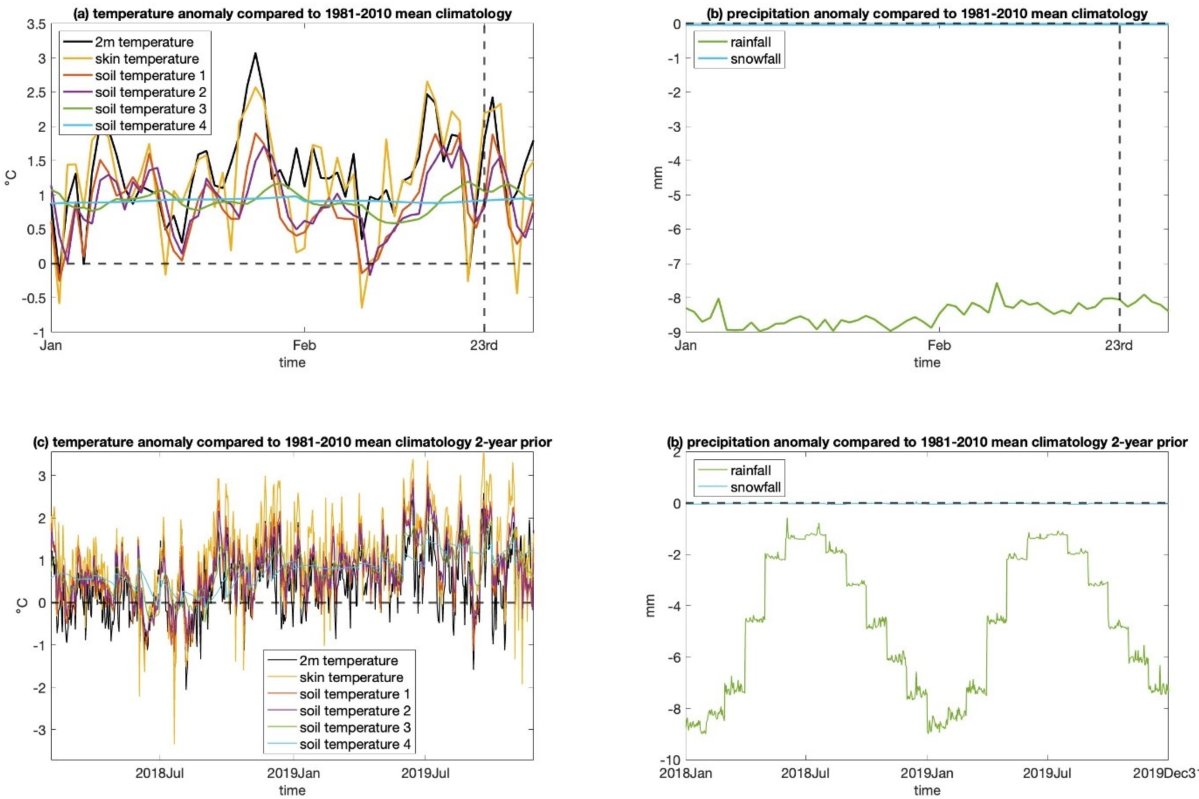

Figure S23. Anomalies in temperature and precipitation compared to the 1981-2010 mean climatology. Panel (a) shows the daily temperature anomalies for July and August of 2020, showing variables across 2m air temperature, surface skin temperature, and soil temperatures at different soil column depths. Panel (b) shows the corresponding precipitation anomalies during the same period. Panel (c) expands the temperature anomalies over two years prior to 2020, and panel (d) shows the corresponding precipitation anomalies over the same two-year period. Dashed vertical line indicates the timing of the Upiscocha GLOF event on the 23rd of February 2020.

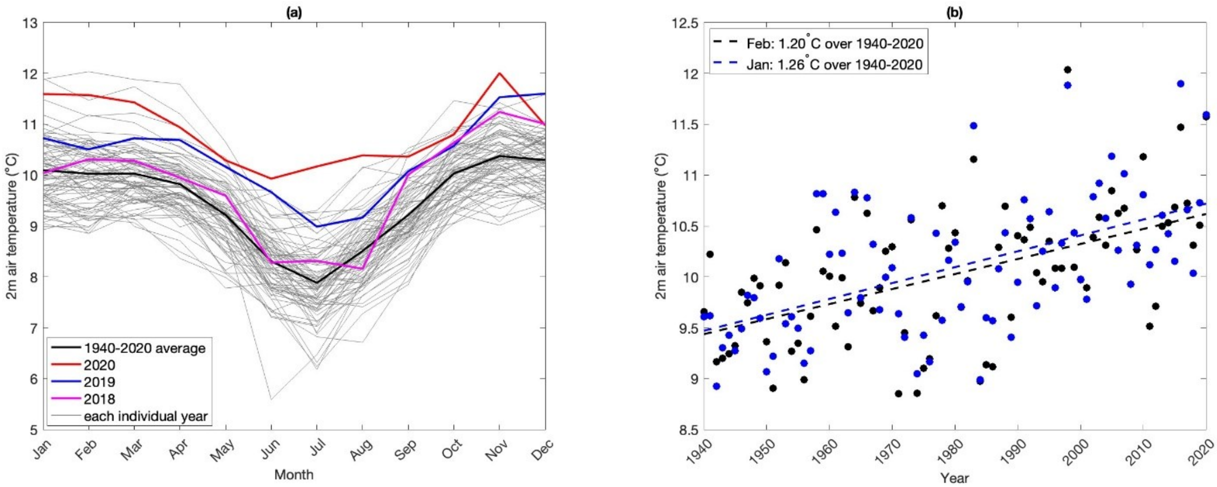

Figure S24. 2m temperature averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

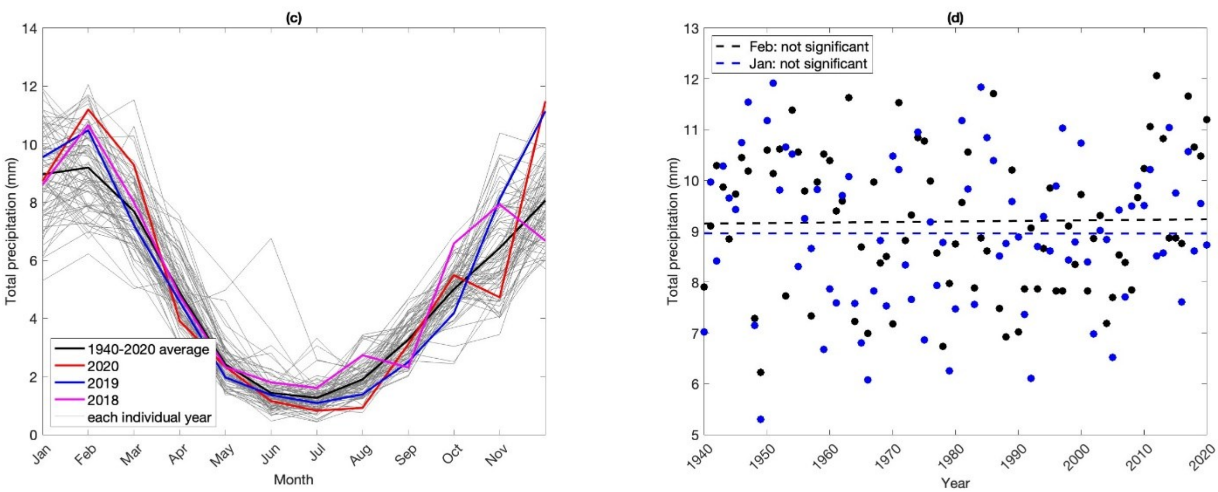

Figure S25. Total precipitation averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

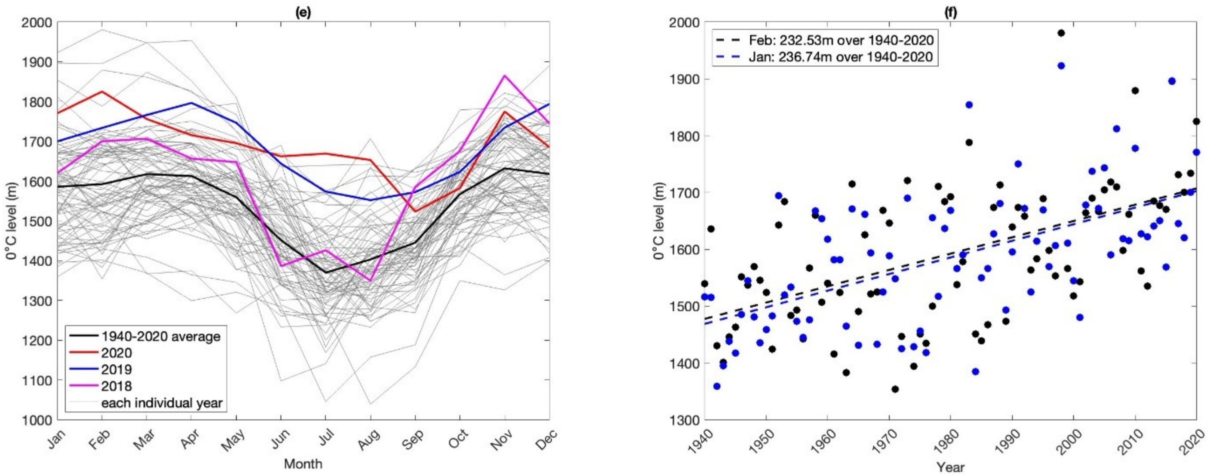

Figure S26. 0°C level (m) averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

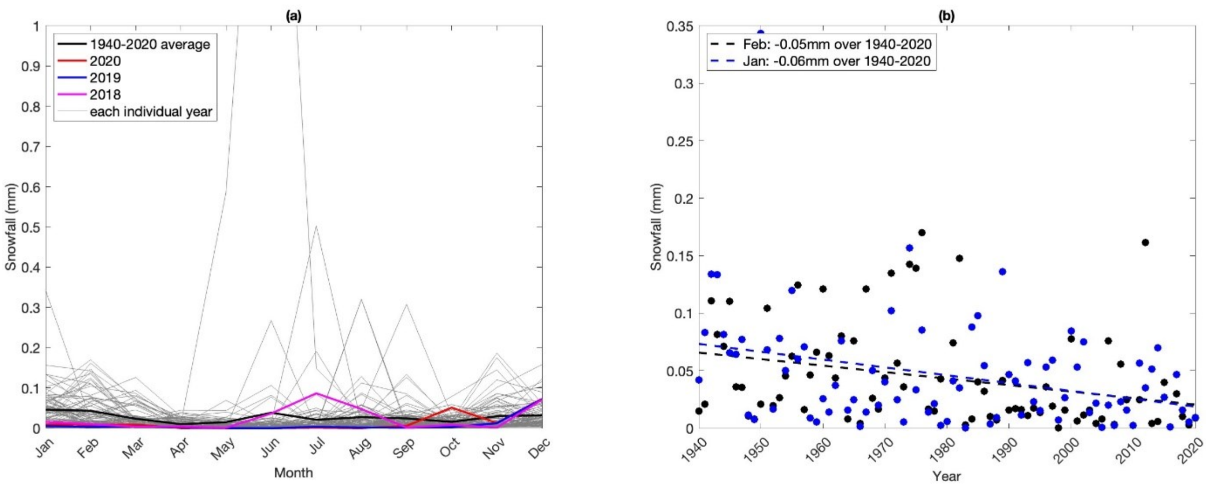

Figure S27. Snowfall averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

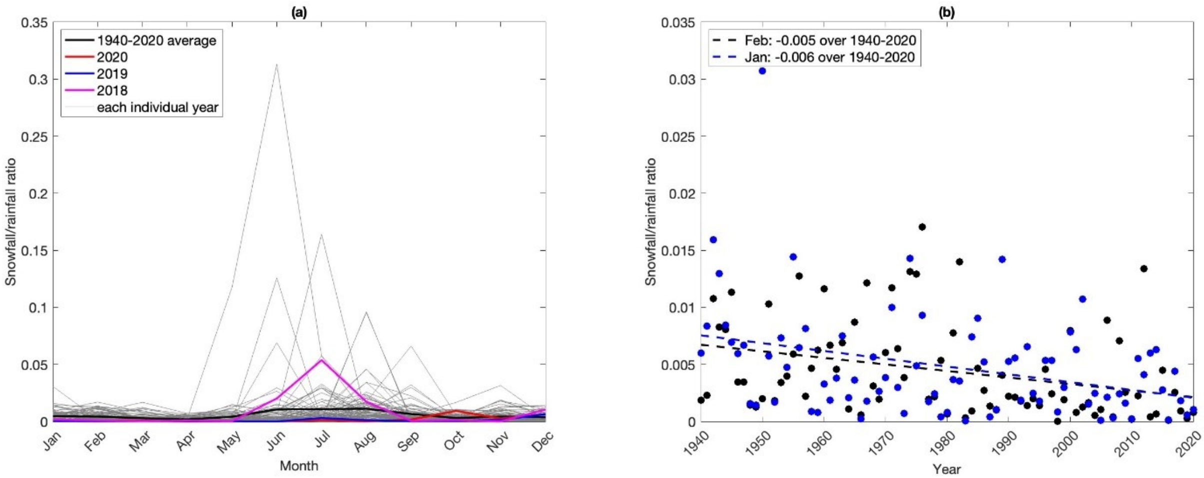

Figure S28. Snowfall to rainfall ratio averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

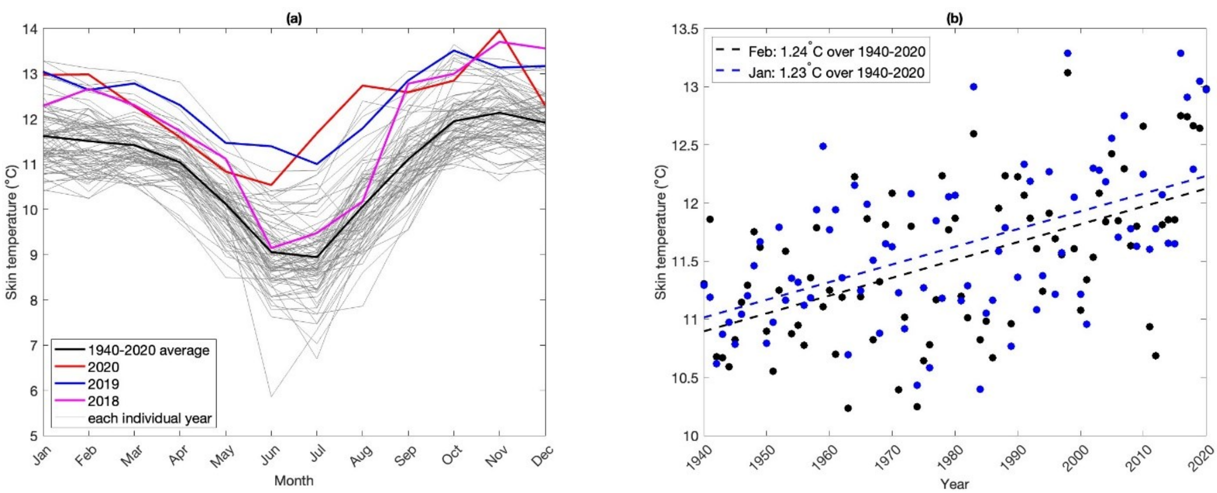

Figure S29. Land surface skin temperature averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

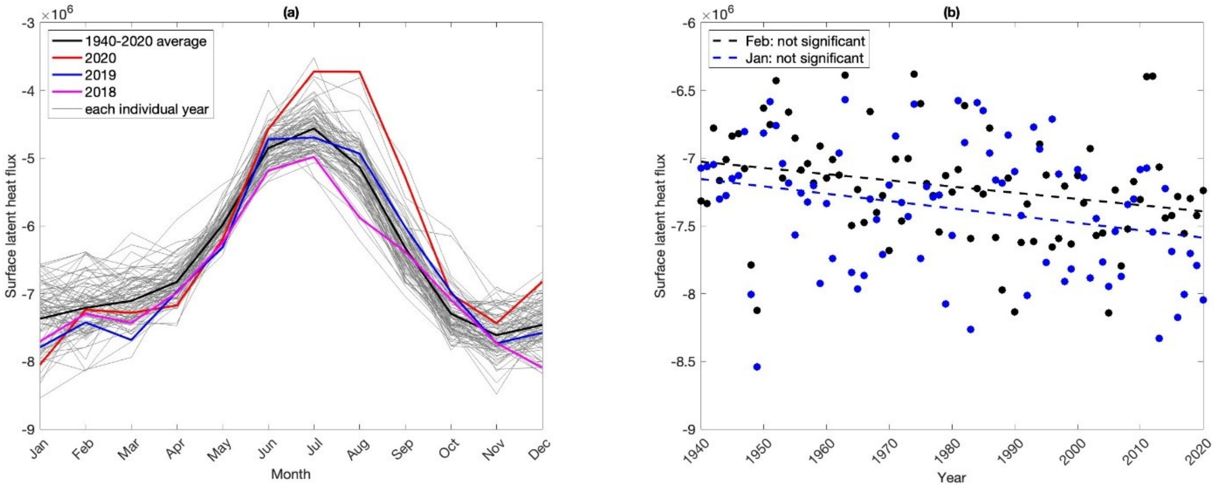

Figure S30. Surface latent heat flux averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

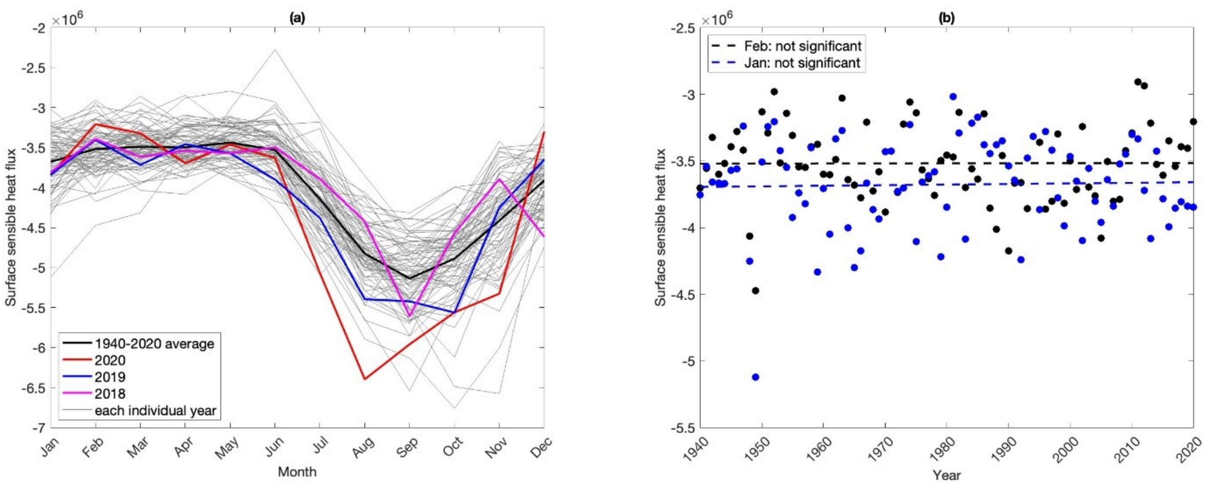

Figure S31. Surface sensible heat flux averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

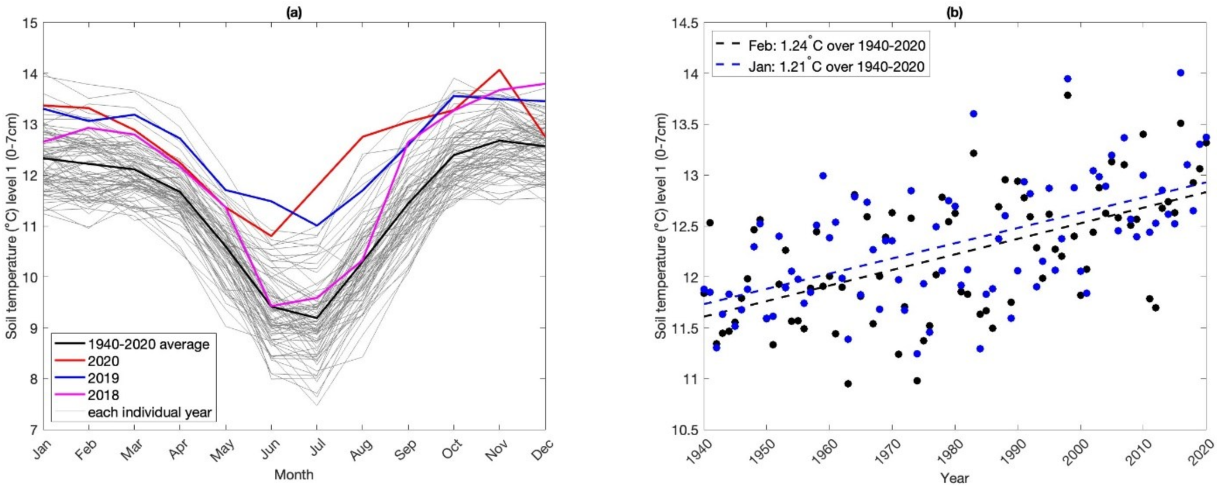

Figure S32. Soil temperature in layer 1 (0-7cm) averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

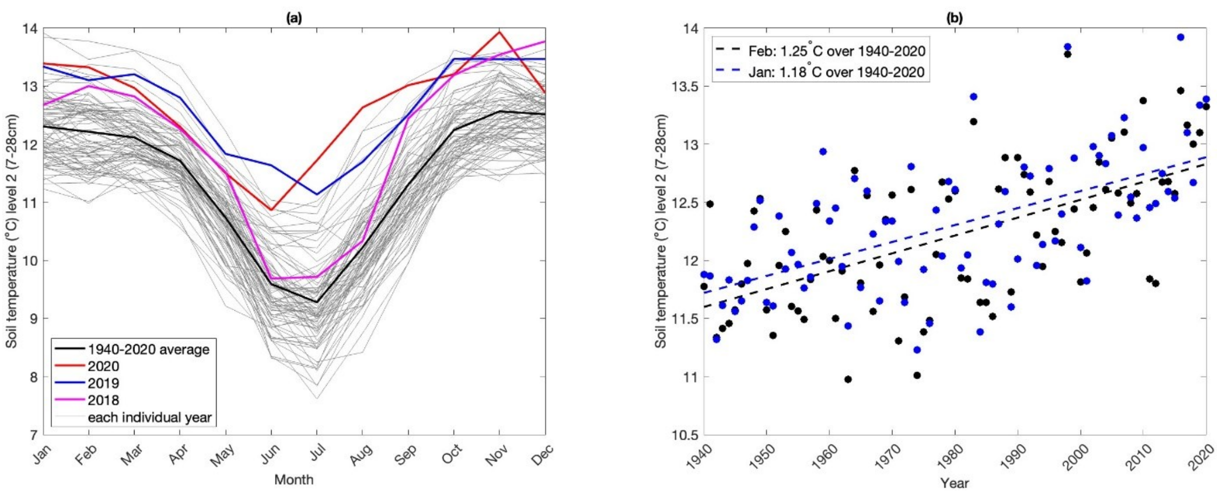

Figure S33. Soil temperature in layer 2 (7-28cm) averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

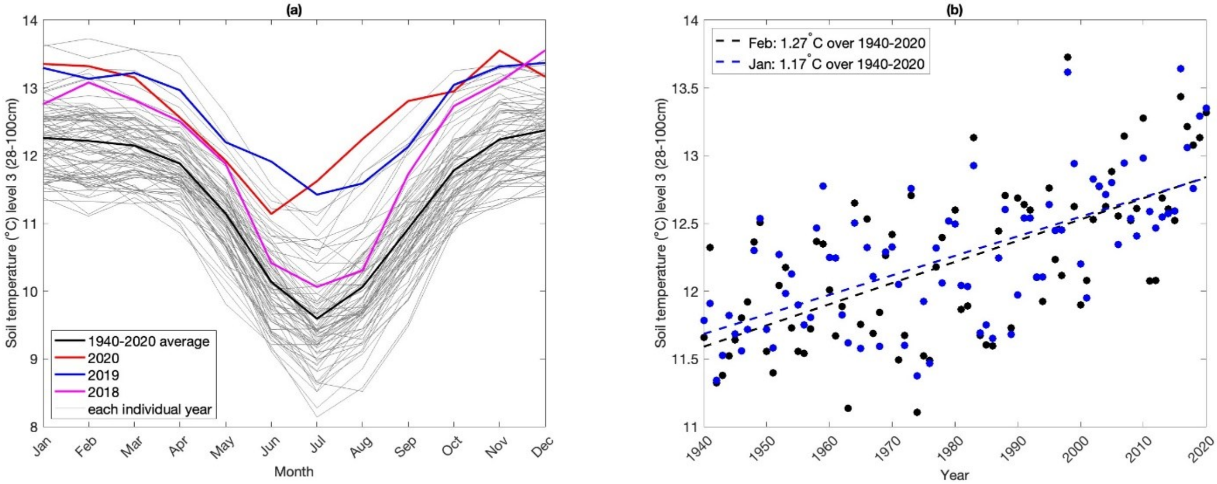

Figure S34. Soil temperature in layer 3 (28-100cm) averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

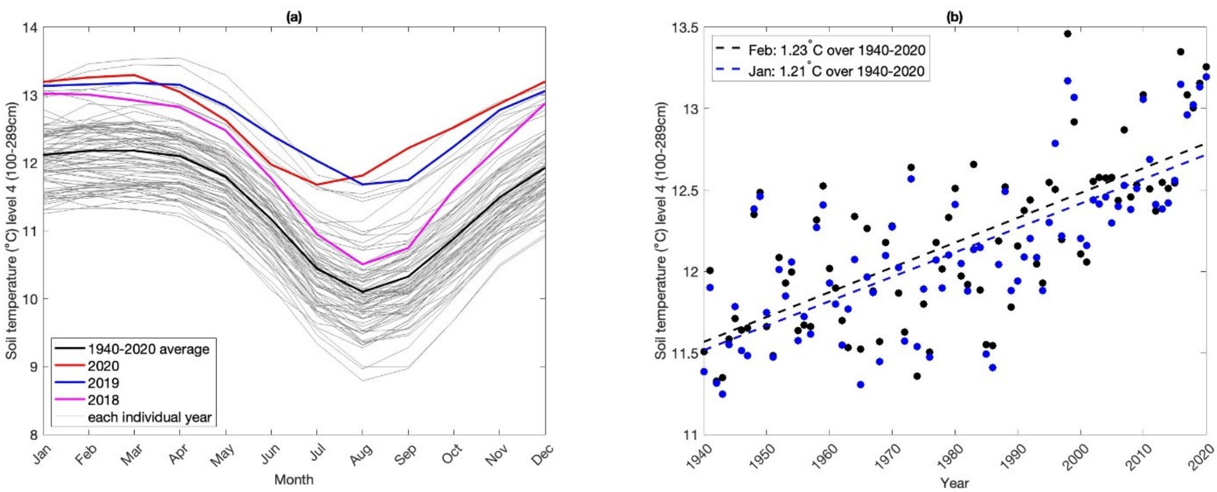

Figure S35. Soil temperature in layer 4 (100-289cm) averaged over the 1° by 1° box [-73.07,-72.07,-13.84,-12.84] covering Salkantaycocha, showing their seasonal cycles (panel a) and historical trends (panel b) over 1940-2020.

As mentioned in the main text, there was no clear peaks in temperature anomalies right before the GLOF. In the case of 2022 Upiscocha, the positive temperature anomalies peaked in July then dropped continuously to even negative anomalies right before the 9th of August. With any meteorological signal, it's not clear to derive key contributing meteorological metrics to perform attribution analysis in the 'traditional way'. However, for the same of illustrative purposes, here we chose the 1-day maximum 2m temperature during the month when the event occurred, to conduct an initial attribution analysis (results shown in Figure S*. below). The results show that for the Upiscocha case, the event has a return period of 7 years under the current climate of 2022, but the event would have a return period of ~80 years under the preindustrial climate, yielding a probability ratio of ~12. For the Salkantaycocha case, the event has a return period of 9 years under the current climate of 2020, but the event would have a return period of ~25399 years, yielding a probability ration of ~2718. But we stress again, this is just for illustrative purposes, given that there is no clearly definable meteorological signal directly linking these two GLOFs to meteorological anomalies either concurrent with the events nor preceding the events.

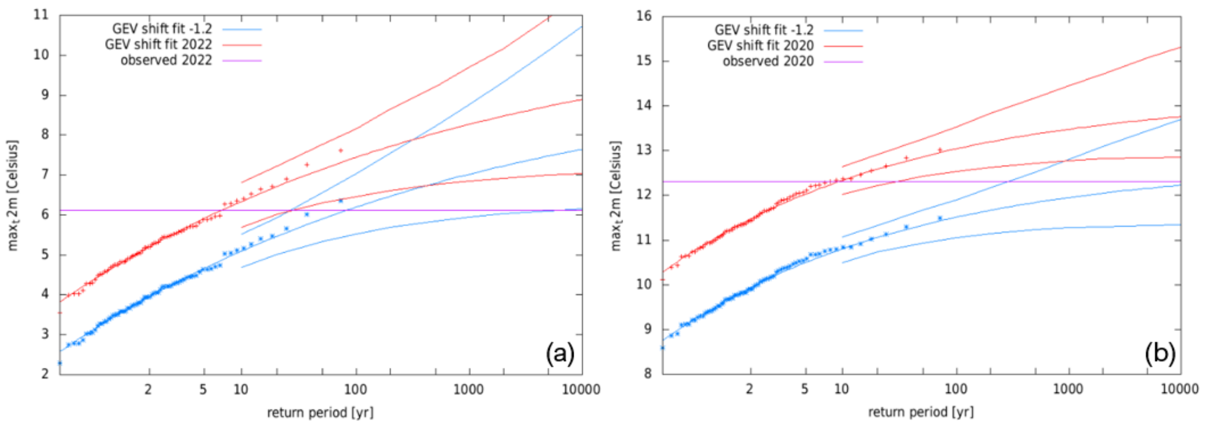

Figure S36. The Generalized Extreme Value (GEV) fit to the data at two levels of the covariate global mean sea surface temperature: in 2022/2020 (red line) for lake Upiscocha (a) and Salkantaycocha (b), and in a 1.2 degrees cooler climate (pre-industrial, blue line). The purple line shows the magnitude of the Aug 2022 Upiscocha event (panel a) and the Feb 2020 Salkantaycocha event (panel b).