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Recent ground thermo-hydrological changes in a Tibetan endorheic catchment and implications for lake level changes

Léo C.P. Martin¹, Sebastian Westermann^{2,3}, Michele Magni¹, Fanny Brun^{1,4}, Joel Fiddes⁵, Yanbin Lei^{6,7}, Philip Kraaijenbrink¹, Tamara Mathys⁸, Moritz Langer^{9,10}, Simon Allen¹¹ and Walter W. Immerzeel¹

1. Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands
2. Department of Geosciences, University of Oslo, Blindern, 0316 Oslo, Norway
3. Center for Biogeochemistry in the Anthropocene, Oslo, Norway
4. Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France
5. WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
6. Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
7. CAS Center for Excellence in Tibetan Plateau Earth System Sciences, Beijing 100101, China
8. Department of Geosciences, University of Fribourg, Fribourg, Switzerland
9. Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, 14473 Potsdam, Germany
10. Department of Geography, Humboldt Universität zu Berlin, 12489 Berlin, Germany
11. Department of Geography, University of Zurich, Zürich, Switzerland

Correspondence to: Léo Martin (leo.doug.martin@gmail.com)
Walter Immerzeel (w.w.immerzeel@uu.nl)

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Appendices: 515 words, 5 figures, 1 table



1 **Abstract**

2 Climate change modifies the water and energy fluxes between the atmosphere and the surface in
3 mountainous regions. This is particularly true over the Qinghai-Tibet Plateau (QTP), a major headwater
4 region of the world, which has shown substantial hydrological changes over the last decades. Among
5 them, the rapid lake level variations observed throughout the plateau remain puzzling and much is still
6 to be understood regarding the spatial distribution of lake level trends (increase/decrease) and paces.
7 The ground across the QTP hosts either permafrost or seasonally frozen ground and both are affected
8 by climate change. In this environment, the ground thermal regime influences liquid water availability,
9 evaporation and runoff. Therefore, climate-driven modifications of the ground thermal regime may
10 contribute to lake level variations. For now, this hypothesis has been overlooked by modelers because
11 of the scarcity of field data and the difficulty to account for the spatial variability of the climate and its
12 influence on the ground thermo-hydrological regime in a numerical framework.

13 This study focuses on the cryo-hydrology of the catchment of Lake Paiku (Southern Tibet) for the
14 1980-2019 period. We use TopoSCALE and TopoSUB to downscale ERA5 data and capture the spatial
15 variability of the climate in our forcing data. We use a distributed setup of the CryoGrid community
16 model (version 1.0) to quantify thermo-hydrological changes in the ground during the period. Forcing
17 data and simulation outputs are validated with weather station data, surface temperature logger data and
18 the lake level variations. We show that both seasonal frozen ground and permafrost have warmed (1.7
19 °C per century 2 m deep), increasing the availability of liquid water in the ground and the duration of
20 seasonal thaw. Both phenomena promote evaporation and runoff but ground warming drives a strong
21 increase in subsurface runoff, so that the runoff/(evaporation + runoff) ratio increases over time.
22 Summer evaporation is an important energy sink and we find active layer deepening only where
23 evaporation is limited. The presence of permafrost is found to promote evaporation at the expense of
24 runoff, consistent with recent studies. Yet, this relationship seems to be climate dependent and we show
25 that a colder and wetter climate produces the opposite effect. This ambivalent influence of permafrost
26 may help to understand the contrasting lake level variations observed between the south and north of
27 the QTP, opening new perspectives for future investigations.



28 **Main text**

29 **1. Introduction**

30 Climate change is amplified in mountainous environments, with major consequences for
31 ecosystems, landscapes, hydrology, human communities and infrastructure (IPCC, 2019). Station
32 observations show that global warming is elevation dependent, the strongest warming rates being
33 observed at high elevation (Pepin et al., 2015; Wang et al., 2014). Over the Qinghai-Tibet Plateau
34 (QTP), a significant increase in surface air temperatures has been recorded since the 1980s (in particular
35 in the North of the plateau, Zhang et al., 2022 and references therein). It is accompanied by a decrease
36 in wind speed, a humidification of the air, and a general increase in precipitation, but with a strong
37 spatial variability (Yang et al., 2014a). Altogether, these changes have affected the surface energy
38 balance of the plateau through a shift of the Bowen ratio towards more latent heat fluxes, limiting the
39 sensible surface warming (Bibi et al., 2018; Yang et al., 2014 and references therein).

40 These changes in water and energy fluxes between the atmosphere and the surface have the potential
41 to alter the hydrological cycle of the QTP, which is the headwater region for major Asian rivers. As
42 such, increasing trends of evaporation over land have been measured (3.8 mm per decade since the
43 1960s) with strong spatial variability both in absolute values and increase rates (Wang et al., 2020b).
44 Changes in the seasonality of river discharge (Cao et al., 2006) and groundwater discharge (Niu et al.,
45 2011) were reported for the same period. Overall glacier shrinkage is also observed since the 1960s
46 with a persistent increase in glacier mass loss rates (Bhattacharya et al., 2021).

47 The QTP also features more than 1,000 lakes larger than 1 km² (Zhang et al., 2017), most of them
48 located in endorheic catchments. Lake volume changes are therefore attributable to climatic and
49 hydrological changes occurring within the lake catchment, such as glacier melt, ground ice melt,
50 precipitation, evaporation or runoff patterns. A majority of these lakes have experienced a pronounced
51 increase in water levels since the 1990s (Lei et al., 2013, 2014), a trend that was suggested to be mainly
52 driven by changes in precipitation and evaporation patterns (Yao et al., 2018) rather than by an increase
53 in glacier mass loss (Brun et al., 2020). Nevertheless, lake level variations are not uniform across the



54 QTP and exhibit important spatial variability. Whereas the northern and central QTP have recorded lake
55 expansion, the southern parts of the plateau have experienced lake shrinkage (Qiao et al., 2019; Zhang
56 et al., 2020, 2021a). Such a complex pattern challenges our understanding of the hydrological changes
57 occurring in these high Asian watersheds.

58 In this regard, new insights on hydroclimatic changes over the QTP can emerge from the
59 investigation of the coupled energy and water fluxes between the ground surface/subsurface and the
60 atmospheric boundary layer. These fluxes are driven by the climate and have a major impact on cold-
61 region hydrology (Bring et al., 2016; Gao et al., 2021; Pomeroy et al., 2007). Indeed, hydrological
62 variables (precipitation, evaporation, runoff) affect the soil water content, which changes its thermal
63 properties, the distribution between latent and sensible fluxes and thus substantially influences the
64 ground thermal regime (Bring et al., 2016; Koren et al., 1999; Martin et al., 2019). In turn, the ground
65 thermal regime modifies the relative proportion of frozen and liquid subsurface water, influencing
66 infiltration possibilities and the amount of water available for evaporation and surface/subsurface runoff
67 (Carey and Woo, 2001; Yi et al., 2006). So far, climate induced thermo-hydrological changes over the
68 QTP have received limited attention. Large-scale modeling studies reported changes in the seasonal
69 ground freezing cycles characterized by a reduction of the frost depth and duration of the frozen period
70 since the 1960s (Qin et al., 2018; Wang et al., 2020a) and notable ground warming trends in summer
71 and winter (Qin et al., 2021). Additionally, ground warming over the QTP was reported to promote
72 evaporation and to decrease runoff (Qin et al., 2017; Wang et al., 2020b).

73 Complementary to seasonally frozen ground, permafrost is also a distinctive feature of climate-
74 surface interactions in cold regions. Large-scale permafrost modeling suggests that it covers a
75 significant part of the QTP, mainly as continuous permafrost in the north of the plateau and as
76 discontinuous or sporadic in the south (Obu et al., 2019). Permafrost on the QTP has usually a low ice
77 content due to limited precipitation and strong evaporation (Wu et al., 2005; Yang et al., 2010).
78 Borehole temperature measurements show that it is a relatively warm type of permafrost (Biskaborn et
79 al., 2019; Wu and Zhang, 2008) and its exposure to high solar radiations makes it sensitive to changes
80 in surface conditions and climate change (Yang et al., 2010). Since the 1960s, climate change has driven
81 the warming of permafrost across the plateau (Ran et al., 2018; Shaoling et al., 2000). Ran et al. (2018)



82 reports that most of the plateau exhibit a warming trend of the ground comprised between 2.6 and 7.4
83 °C per century and half of the plateau warms at a rate higher than 5 °C per century. This warming is
84 accompanied by upward migration (of around 100 m between the 1960s and 2000s) and shrinkage of
85 permafrost covered areas (24% of permafrost extent lost between the 1960s and 2000s, Ran et al., 2018).

86 Permafrost grounds are characterized by a strong interplay between the ground thermal regime and
87 the land hydrology. Seasonal thawing and freezing of the active layer is driven by the surface energy
88 balance and in return, influences surface and subsurface runoff (Kurylyk et al., 2014; Sjöberg et al.,
89 2021; Walvoord and Kurylyk, 2016) and evaporation (Gao et al., 2021). In this regard, both large scale
90 and regional modeling indicates that thawing permafrost enhances evapotranspiration (Qin et al., 2017;
91 Wang et al., 2020b). Qin et al. (2017) also reports that the increase in evaporation is logically
92 concomitant with a decrease in runoff. Additionally, permafrost stores water as ground ice and its
93 thawing can trigger the release of liquid water in the watershed, contributing up to 15% of the yearly
94 river streamflow (Cheng and Jin, 2013; Yang et al., 2019).

95 The aforementioned hydrological changes are tied to various interdependent climate-driven
96 physical processes happening at the ground surface and subsurface (e.g. surface energy balance,
97 infiltration, water phase change, heat conduction...). Because these processes exhibit a strong spatial
98 variability in high mountain environments, they are challenging to represent accurately together on
99 large spatial scales. Therefore, a deeper understanding of the impact of ground thermo-hydrological
100 changes on the High Asia water cycle can be gained through small-scale physical modeling of these
101 processes. Yet, for now, physics-based approaches at the catchment scale aiming to connect the ground
102 thermo-hydrological regime and the observed hydrological changes on the QTP (such as lake level
103 changes) remain scarce. They are however a powerful approach to tackle the question: how much
104 climate-driven ground thermal changes might affect the water cycle in high mountain headwater
105 regions? In this study, we use physical land surface modeling to quantify the ground thermo-
106 hydrological changes of an endorheic Tibetan catchment over the last 40 years as a response to climate
107 change. We show the interplay in the water and energy fluxes occurring between the atmosphere, the
108 surface and the subsurface and discuss their impact on the hydrology of the catchment and their
109 implication regarding lake level variations.



110 2. Study area: the Paiku catchment

111 The Paiku catchment is located in south-western Tibet, China, close to the border with Nepal
112 (28.8°N - 85.6°E, Fig. 1). Its southern edge lies 7 km from the Shishapangma peak (8027 masl). The
113 catchment is endorheic and spans over 78 km from North to South, 66 km from East to West and covers
114 2 400 km². The median elevation of the catchment is 4872 masl, ranging from 7272 masl to its lowest
115 point, the lake Paiku at 4580 masl. Geologically, the catchment is mainly located in the Tethys
116 Himalayan, and thus, an important part of the formations underlying the catchment are metamorphized
117 sedimentary series. The southern part of the catchment crosses the Southern Tibetan Detachment, and
118 thus, the southern ridges of the massif belong to the High Himalayan metamorphic formations in the
119 west and to the High Himalayan leucogranites of the Shishapangma massif on the east. The north and
120 north-east ridges are formed by granite intrusions surrounded by metamorphic domes. The inner part of
121 the catchment presents Plio-Quaternary formations such as alluvial fans close to the ridges and inclined
122 alluvial plains in its inner parts (Fig. B of the appendices, Aoya et al., 2005; Searle et al., 1997;
123 Wünnemann et al., 2015).

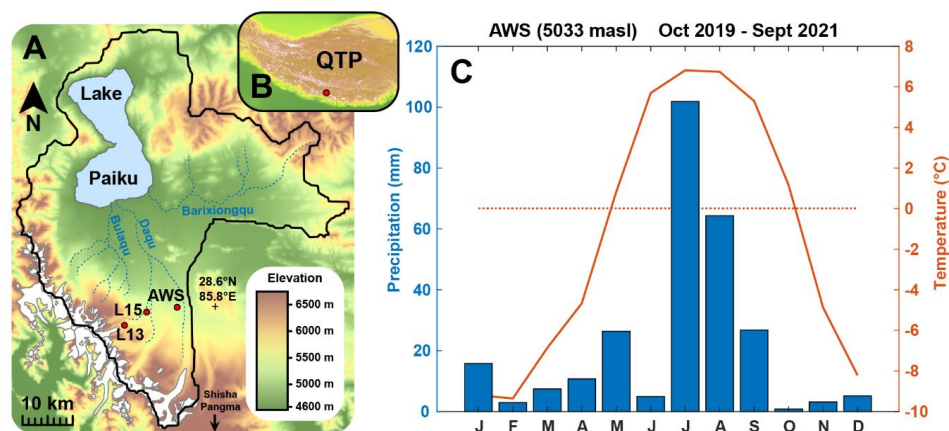
124 Automatic Weather Station (AWS) observations (5033 masl, Oct 2019 – Sept 2021, Fig. 1) show
125 that the climate in the catchment is characterized by a relatively small temperature amplitude during the
126 year (around 20 °C, JJA being the warmest months and DJF the coldest) and significant daily amplitude
127 (up to 10 °C during the warm season). The mean annual temperature is -1.5 °C at the AWS, where night
128 freezing can occur until the beginning of June and restart at the beginning of October. The catchment
129 is dry (~ 200 mm year⁻¹) and precipitation mostly fall as rain during the monsoon (JJAS).

130 Around 5% of the catchment is covered by glaciers (RGI Consortium, 2017), which are
131 concentrated in its southwestern part. They feed several proglacial lakes that can reach up to 6 km in
132 length. Geodetic glacier mass budgets show that, similar to other glaciers in the region, glaciers of the
133 Paiku catchment have undergone sustained mass loss at least since the 1970s, with an average mass
134 balance of -0.3 m w.e.a⁻¹ until the beginning of the 2000s and around -0.4 m w.e.a⁻¹ afterwards
135 (Bhattacharya et al., 2021). There are more than 10 rivers that drain the catchment towards the lake and
136 most of them only exhibit a seasonal activity during the monsoon months. The three main ones are (Fig.



137 1), Daqu (glacier-fed, 450 km²), Bulaqu (glacier-fed, 325 km²) and Barixiongqu (non-glacier-fed, 703
138 km²) (Lei et al., 2018).

139 In the north-west of the catchment, Lake Paiku covers approx. 280 km² (11.5% of the catchment
140 surface area) and spans over 27 km from north to south. It has a mean water depth of 41 m, with a
141 maximum water depth of 73 m (Lei et al., 2018). It receives water from direct precipitation and from
142 land and glacier runoff which can be routed at the surface via the river systems or the subsurface via
143 the alluvial formations. Because it is hydrologically closed, the lake mainly loses water through
144 evaporation. Previous studies reported lake level fluctuations over different time scales. It reached 4665
145 masl (85 m higher than present level) prior to 25 ka BP and at the onset of the Holocene (11.9-9.5 ka
146 BP). Afterwards, the lake shrank gradually (Wünnemann et al., 2015). More recently, the lake level
147 decreased by 3.7 m between 1972 and 2015, losing 4.2% of its surface and 8.5% of its volume (Fig. 2,
148 Lei et al., 2018). At the seasonal scale, the lake level cycle has an amplitude of ~ 0.4 m. It is marked by
149 a strong increase during the monsoon period (JJAS) supported by direct precipitation, glacier melt and
150 land runoff. From October and until the next monsoon period, evaporation dominates the lake mass
151 budget and the level decreases rapidly until January and at a slower rate afterwards (Lei et al., 2021).



152
153 *Figure 1. The Paiku Catchment. A: Topographic and hydrologic map of the catchment with the glaciers*
154 *in white, the ephemeral rivers in dark blue and the lake in light blue. AWS: Automatic Weather Station.*
155 *L13 and L15 are surface temperature loggers (Sect. 3.1). B: Localization of the catchment over the*
156 *QTP. C: Monthly temperature and precipitation recorded at the AWS between October 2019 and*
157 *September 2021.*
158



159 **3. Material and methods**

160 **3.1. Field measurements**

161 An AWS was set up in October 2019 in the South of the catchment at an elevation of 5033 masl
162 (Fig. 1). It is equipped with various sensors which record air temperature, pressure, relative humidity,
163 wind speed, incoming and outgoing long and short wave radiations and precipitation every 15 minutes.
164 The meteorological record extends to September 2021 and covers a period of nearly 2 years. We used
165 it to evaluate and correct the distributed downscaled climatic forcing we used in our modeling
166 framework (Sect. 3.2.5.).

167 Two temperature loggers recorded the surface temperature in the vicinity of the AWS location.
168 Logger 15 (L15) is located at 5055 masl, 6 km west from the AWS. Logger 13 (L13) is located at 5356
169 masl, 12 km west from the AWS (Fig. 1). Both loggers were buried 10 to 15 cm below the surface to
170 avoid direct solar radiation on the sensors and recorded surface temperature at a 20 minutes time step
171 from October 2017 to October 2018. These surface temperature records were used to evaluate the
172 simulations (Sect. 3.2.5.).

173 **3.2. Catchment thermo-hydrological modeling**

174 *3.2.1. Conceptual hydrological model for the catchment*

175 In order to understand the level variations of lake Paiku over the last 40 years (1980-2019 period),
176 we develop an approach at the catchment scale. Because the catchment is hydrologically closed, the
177 lake receives water input via direct precipitation, land surface and subsurface runoff and glacier runoff.
178 Conversely, it only loses mass via evaporation. As such, the present study requires quantification of all
179 these terms of the hydrological balance. The production of forcing data for the catchment (including
180 precipitation) is detailed in Sect. 3.2.2. The land hydrology processes are quantified using the CryoGrid
181 community model (version 1.0) (Westermann et al., 2022) as described in section 3.2.3. Distributed 1D
182 simulations are used to quantify land evaporation and runoff. The routing of water in the catchment is
183 not represented and the runoff computed for a given simulation is directly accounted as a water input
184 for the lake. The evaporation from the lake is simulated using the CryoGrid3-Flake model (Langer et



185 al., 2016) as described in Section 3.2.4. Glacier melt is not modeled, but estimated for the study period
186 (1980-2019) from remote sensing observations. From these observations, glaciers yield is calculated as
187 described in Sect. 3.2.6. Our catchment-scale approach to represent the hydrological balance of the lake
188 is summarized in Fig. 2.

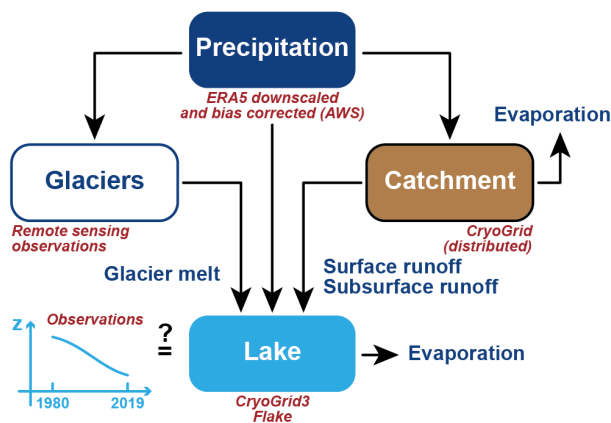


Figure 2. Conceptual hydrological framework for the study.

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190
191
192

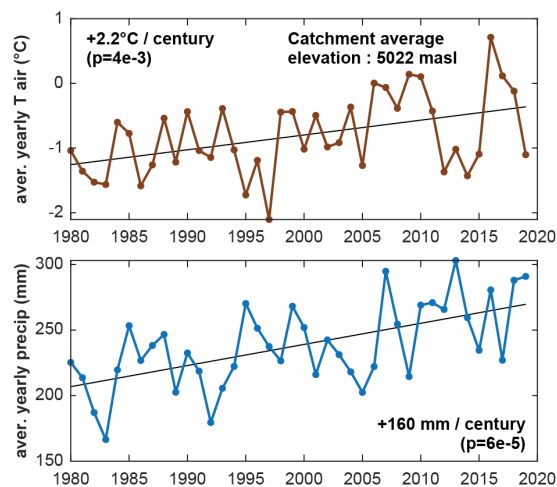
3.2.2. Forcing data production and validation

193 In high mountain environments, topography creates strong spatial variability of temperature and
194 incoming radiation, which impact the surface energy balance (Klok and Oerlemans, 2002) and the
195 ground thermo-hydrological regime (Magnin et al., 2017). Our approach requires forcing data that (i)
196 captures this variability, (ii) includes numerous variables such as air temperature, incoming long and
197 short wave radiations, wind speed, specific humidity, rain and snowfall and (iii) cover the 40 years
198 study period at a sub-daily timestep. The TopoSCALE approach (Fiddes and Gruber, 2014) was
199 developed for this purpose and allows to downscale reanalysis products like ERA5 (Hersbach et al.,
200 2020) at high resolution (here $\sim 100 \times 100$ m). Additionally, because working at a 10^{-2} km² spatial
201 resolution over a 2400 km² catchment would require more than 200,000 forcing files and simulations,
202 we rely on the TopoSUB method (Fiddes and Gruber, 2012) to reduce computational costs. This method
203 uses a SRTM30 Digital Elevation Model to explore redundancies in physiographic parameters of the
204 study area such as elevation, aspect, slope and sky-view factor and identify groups of high resolution
205 pixels (100 x 100 m) sharing similar values for these parameters. From there, all the high resolution
206 pixels belonging to such a group are only described as a single TopoSUB point for which climatic



207 variables can be downscaled to create one single dataset of climatic timeseries. The degree of similarity
208 required by TopoSUB to identify groups of high resolution pixels with redundant physiographic
209 parameters can be adjusted by choosing the final number of TopoSUB points (and thus climate datasets)
210 that should be used to cover the area corresponding to one ERA5 pixel. The Paiku catchment intersects
211 8 ERA5 pixels at 30 km resolution and we chose to use 50 TopoSUB points within each ERA5 pixels
212 to cover the spatial variability created by the topography on small-scale climate. Ultimately, 368
213 TopoSUB points are used to cover the catchment. The average level of redundancy (i.e. the average
214 number of high resolution pixels represented by a single TopoSUB point) is 723 ± 745 (1σ , median:
215 506, min: 1, max: 4347). Fig. C shows the distribution of the TopoSUB points and a reconstruction of
216 the topography of the catchment based on this approach. The period covered by the forcing datasets
217 starts on 1st January 1980 and ends on 31st August 2020 (40 years and 8 months).

218 In the TopoSCALE statistical downscaling approach, we do not rely on the AWS data and thus the
219 downscaled ERA5 data can be biased, as is often the case over Asia (Jiang et al., 2020, 2021; Jiao et
220 al., 2021; Orsolini et al., 2019). Comparison against the available AWS observations (Fig. D) indeed
221 highlights notable differences in variables such as air temperature and precipitation. From these
222 differences we derived monthly bias correction factors that we apply systematically to all of the 368
223 climate forcing datasets. The catchment-averages for precipitation and air temperatures are shown in
224 Fig. 3.



225
226 *Figure 3. Climate forcing data for the land and lake modeling. Yearly catchment-average air*
227 *temperature (2 m above ground) and total precipitation for the study period. Note that the model is also*
228 *forced by incoming short and long wave radiations, humidity, windspeed and air pressure. Details*
229 *about the spatial and temporal resolution of the distributed forcing data are presented in Sect. 3.2.2.*
230

231 3.2.3. The CryoGrid community model (version 1.0)

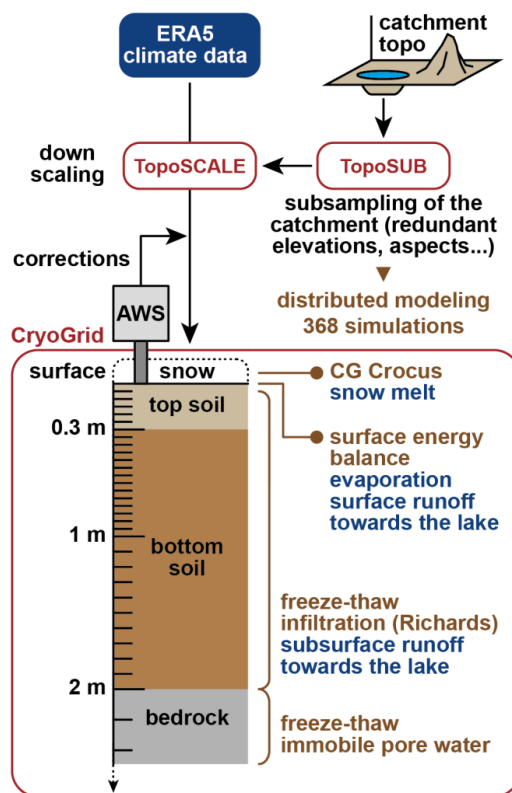
232 To simulate the ground thermo-hydrological regime, we use the CryoGrid community model
233 (Westermann et al., 2022). The CryoGrid community model (CG) is a land surface model designed for
234 applications in cold regions where seasonal frozen ground or permafrost may occur. The model
235 implements heat transfer in a 1D soil column, accounting for freeze-thaw processes of soil water using
236 effective heat capacity (Nakano and Brown, 1972). To do so, soil freezing curves are based on
237 Dall’Amico et al. (2011) as detailed in Westermann et al. (2013). Vertical water movement in the soil
238 column is based on Richards equation (Richards, 1931; Richardson, 1922). The soil matric potential
239 and hydraulic conductivity follow van Genuchten (1980) and Mualem (1976). The model features the
240 snowpack module called *CG Crocus* described in Zweigel et al. (2021) that adapts the snow physics
241 parameterizations from the CROCUS scheme (Vionnet et al., 2012) to the native snow module of
242 CryoGrid3 (Westermann et al., 2016). At the surface, the model uses a surface energy balance module
243 to calculate the ground surface temperature and water content. The turbulent fluxes of sensible and
244 latent heat are calculated using a Monin–Obukhov approach (Monin and Obukhov, 1954). Evaporation
245 is adjusted to the available water in the soil and the water loss is distributed vertically to decrease
246 exponentially with depth.



247 3.2.4. *Model setup and validation*

248 The setup of the CryoGrid community model for land is presented in Fig. 4. To capture the high
249 spatial variability of mountainous climate, our approach relies on the 368 climate forcing datasets to
250 cover the catchment (see section 3.2.3). This approach enables us to perform spatially distributed
251 modeling. All of the 368 simulations are independent and use the same parameterization. In absence of
252 direct observation of the soil stratigraphy within the catchment, the soil column was designed to agree
253 with field observations in the region (Hu et al., 2020; Luo et al., 2020; Wang et al., 2008, 2009; Yang
254 et al., 2014b; Yuan et al., 2020), to be consistent with similar modeling approaches across Tibet (Chen
255 et al., 2018; Song et al., 2020) and to be consistent with input datasets (Shangguan et al., 2013, 2017).
256 Thus, the soil stratigraphy is divided in 3 units: a top soil (0.3 m thick), a bottom soil (1.7 m thick) and
257 a bedrock unit (extending beyond the depth of interest of the study). An overview of the parameters for
258 each unit, their source and the way they are calculated is presented in Table A. Regarding the processes
259 implemented in the model (Sect. 3.2.3), infiltration according to Richards equation only occurs in the
260 top and bottom soil units. The bedrock unit has a static water content. Additionally, to simulate
261 subsurface runoff towards the lake, the two soil units are hydrologically connected to a reservoir at the
262 elevation of the lake. This reservoir drains excess water of the soil column when its water content
263 exceeds field capacity. This drainage is quantified using Darcy's law and relies on a hydraulic slope
264 taken as the mean slope of the catchment.

265 Because we do not have knowledge of the distributed thermal state with depth over the catchment
266 at the beginning of the simulations, we assume temperature profiles were in equilibrium with the climate
267 of the 5 first years of modeling (1980-1984). To do so, we start our simulations with a 60 years spin-up
268 of these first 5 years (12 repetitions), which is sufficient to establish a stable temperature profile in the
269 hydrologically active part of the ground (the first 2 meters).



270
271 *Figure 4. Modeling framework for the land hydrology. ERA5 data are downscaled using the TopoSUB*
272 *and TopoSCALE approaches (Fiddes and Gruber, 2012, 2014). The downscaled data are bias-*
273 *corrected based on the AWS observations. Distributed 1D simulations are performed using the*
274 *CryoGrid community model (Westermann et al., 2022). The vertical resolution is indicated with the tick*
275 *marks on the depth axis.*
276

277 To validate model simulations, the simulated ground surface temperatures (GST) are compared to
278 the two temperature logger time series acquired in the vicinity of the AWS (Sect. 3.1). We used this
279 comparison to calibrate the surface roughness used for the surface energy balance calculations in the
280 model.

281 3.2.5. Lake modeling

282 The lake thermo-hydrological response to the climatic forcing data is simulated using the
283 CryoGrid3-Flake model (Langer et al., 2016). The two models were coupled by Langer et al. (2016) to
284 simulate the thermal regime of thermokarst lakes (including surficial water freezing and melting) and
285 underlying ground. Here we use the coupled models mainly to quantify evaporation at the lake surface.
286 In the coupled model, the native surface energy balance module of CryoGrid3 (Westermann et al., 2016)



287 was amended to account for processes tied to free water surface energy balance: (i) the dependance of
288 the albedo of a water surface to solar angle (and thus time of the day) and wind speed (and wave
289 formation), (ii) the dependance of the surface roughness length to wind speed (and wave formation) and
290 (iii) the exponential decay of incoming radiation with depth in the water column. Similarly to the land
291 simulations, the lake simulations were forced by the downscaled ERA5 data, with the corrections
292 derived from the AWS data (Sect. 3.2.2). The simulations were initiated with a 20 years spin-up of the
293 1980-1984 climate.

294 3.2.6. *Quantification of glacier mass change*

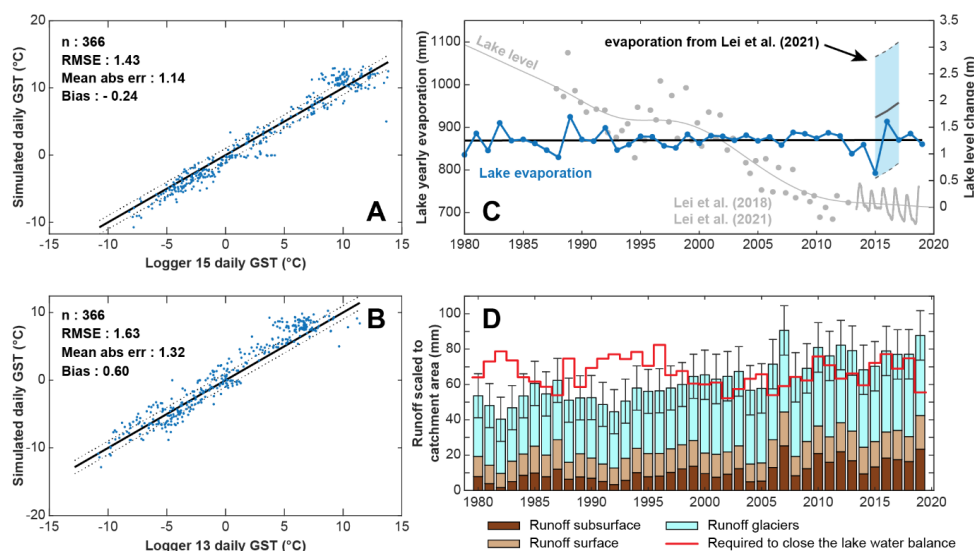
295 Multiple studies quantified the volume change of the glaciers located within Paiku catchment in
296 the recent past (1970s to 2020). There are no field based measurements of glacier mass balance available
297 in this catchment to our knowledge. As a consequence, we rely solely on the geodetic mass balance
298 studies (Brun et al., 2017; Hugonnet et al., 2021; King et al., 2019; Maurer et al., 2019; Shean et al.,
299 2020). All these studies estimated glacier volume changes over periods of 20-30 years from satellite
300 derived DEMs. As a consequence, we can only estimate the average annual glacier mass balance, and
301 not the year to year variability. Glaciers occupy approximately 113 km² in the Paiku catchment. They
302 have shrunk for the past fifty years at a rate of 0.44 % y⁻¹, from an area of 132 km² in 1975 to 122 km²
303 around 2000 and to their current extent (Bolch et al., 2019; King et al., 2019). The average mass
304 balances for the period 1975-2000 and 2000-2020 are $-3.9 \pm 2.1 \times 10^{10}$ kg y⁻¹ and $-5.4 \pm 2.4 \times 10^{10}$ kg y⁻¹,
305 respectively ($-4.6 \pm 2.5 \cdot 10^7$ m³ and $-6.4 \pm 2.8 \cdot 10^7$ m³ with a 850 kg m⁻³ density). These mass balances
306 correspond to specific mass balances of -0.31 ± 0.17 m of water equivalent per year (w.e. y⁻¹) and -0.47
307 ± 0.21 m w.e. y⁻¹, respectively.



308 4. Results

309 4.1. Model validation and lake evaporation

310 Model validation results are presented in Fig. 5. Simulated daily ground surface temperatures are
311 in good agreement with the observed ones with a bias of $-0.2\text{ }^{\circ}\text{C}$ and $0.6\text{ }^{\circ}\text{C}$ and a RMSE of $1.4\text{ }^{\circ}\text{C}$ and
312 $1.6\text{ }^{\circ}\text{C}$ for loggers 15 and 13 respectively (Fig. 5A and 5B). Most of this RMSE is explained by a
313 mismatch between model and observations in the tails of the temperature distribution, whereas
314 intermediate temperatures exhibit the best agreement with observations.



315 *Figure 5. Model validation. A and B: modeled mean daily ground surface temperatures compared to*
316 *measured ground surface temperatures for logger 15 and logger 13 (location on Fig. 1). C: modeled*
317 *yearly lake evaporation (blue curve) and comparison with values calculated by Lei et al. (2021) in the*
318 *light blue zone. The grey curve shows the smoothed lake level variations based on observations from*
319 *Lei et al. (2018) (grey points) and Lei et al. (2021) (grey oscillating line). D: Comparison between the*
320 *runoffs required to reproduce the observed lake variations (red curve, derived from lake level, lake*
321 *area, forcing data and lake evaporation) and the sum of the glacier and land runoff we derive from*
322 *remote sensing observations and modeling respectively (Sect. 3.2). Error bars are associated to the*
323 *glacier values and come from the geodetic results. Runoff values are expressed as heights scaled to the*
324 *land surface of the Paiku catchment.*
325

326
327 Yearly lake evaporation mainly ranges between 800 and 900 mm per year, with a mean value of
328 $870 \pm 23\text{ mm}$ (1σ). Lake evaporation does not exhibit a linear trend of increase or decrease and is mostly
329 dominated by year to year variability. Though slightly lower, our evaporation results are in agreement
330 with the values from Lei et al. (2021), which are derived from local and regional meteorological



331 observation and lake budget calculation (Fig. 5, C). We used the simulated evaporation together with
332 the lake level data and lake area data from Lei et al. (2018) and Lei et al. (2021) and the precipitation
333 forcing datasets (3.2.2) to derive the total runoff (land + glacier) required as an input to the lake budget
334 to reproduce the lake variations. This required runoff corresponds to the red line of Fig. 5D. The
335 required runoff volumes are scaled to the land area of the catchment to be comparable with the other
336 variables. The fact that these values are substantially higher than 0 mm per year highlights the
337 importance of the land and glacier contribution to the lake budget.

338 Fig. 5D also presents the runoff values derived from the land cryo-hydrological modeling and from
339 the glacier remote sensing investigations. Annual volumes are expressed as mm over the land part of
340 the catchment (excluding the lake). Based on the characteristics of remotely sensed observations, glacier
341 mass balance values are considered constant for the 1980-2000 period and 2000-2019 period and
342 respectively equal to $-4.6 \pm 2.5 \cdot 10^7$ and $-6.4 \pm 2.8 \cdot 10^7$ m³ per year. The addition of yearly precipitation
343 to these values to quantify the total glacier runoff introduces year to year variability to the glacier runoff.
344 At the catchment scale, the average glacier runoff over the 40 years is 39 ± 13 mm per year.

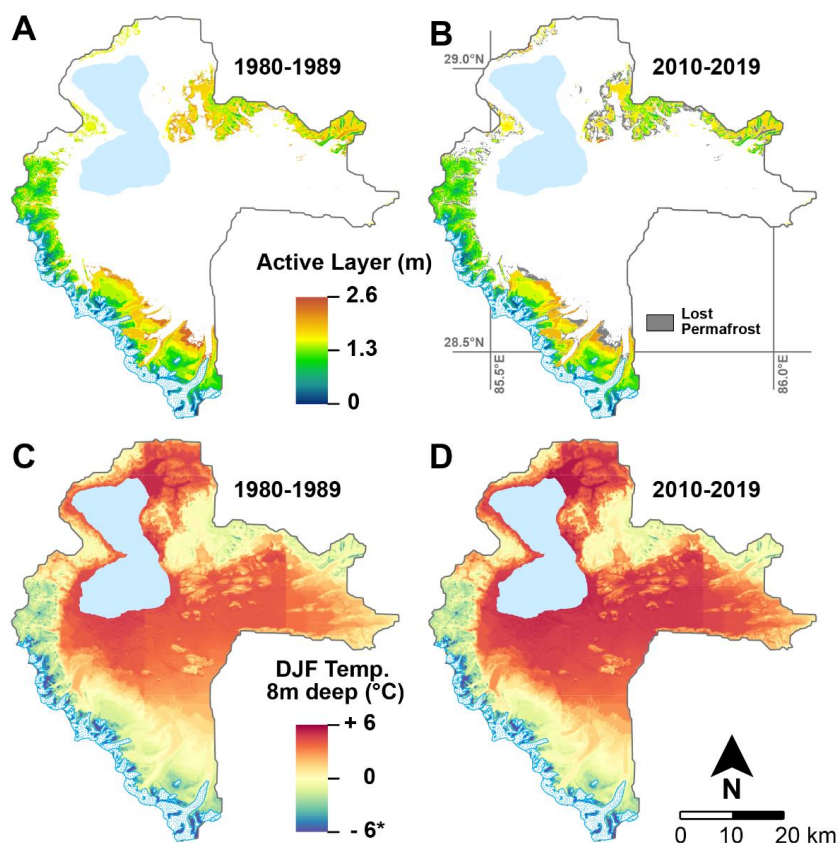
345 Over the 40 years, the average yearly land runoff value (surface + subsurface) we model is 24 ± 8
346 mm. Summed together, the land and glacier runoff find a partial agreement with the runoff that is
347 required to close the lake water balance. Yearly values are compatible within error bars for 28 out of
348 the 40 years of simulations. The glacier and land runoff are slightly too small to close the lake water
349 balance during the first 20 years, and slightly too large for the last 20 years of simulation. Over the
350 whole period, the sum of the glaciers + land runoff produces 95% of the required runoff. Land runoff
351 is further described in Sect. 4.3.



352 4.2. Ground thermal results

353 Thermal results are summarized in Fig. 6, Tab. 1 and the Fig. 7. The maps A and B of Fig. 6 show
354 the active layer thicknesses throughout the catchment, averaged for the 1980-1989 and 2010-2019
355 periods. If there is an active layer present in map A but not in map B, the permafrost disappeared during
356 the simulation (represented in grey in Fig. 6B). From 1980 to 1989, permafrost covers 27% of the
357 catchment and the mean active layer thickness is 1.36 ± 0.51 m (1σ , minimum: 0.11 m and maximum:
358 2.37 m). From 2010 to 2019, permafrost covers 22% of the catchment. At the scale of the initial
359 permafrost area, this change corresponds to a loss of 19%. The mean active layer thickness is $1.29 \pm$
360 0.49 m (1σ , minimum: 0.11 m and maximum: 2.55 m) for this period. Permafrost disappearance mainly
361 happens for low-lying permafrost of the south and the center of the catchment. It occurs for the most
362 part on the outer slopes of the permafrost regions and at the bottom of steep glacial valleys.

363 Maps C and D present 8 m depth temperatures fields for the months of December, January and
364 February averaged for the same two decades. While the mean temperature for the first decade of the
365 simulation is 1.83 °C, it is 2.37 °C for the last decade. This deep warming is associated with a migration
366 of the 0 °C isotherm from 5260 masl to 5320 masl (+60 m). The warming trend is not spatially uniform
367 and varies with elevation. The mean ΔT_{8m} (difference between the 2010-2019 and the 1980-1989
368 period) is the strongest at the bottom of the catchment where it reaches $+0.68 \pm 0.23$ °C for the 4500-
369 5000 masl elevation range and decreases linearly with elevation until $+0.09 \pm 0.14$ °C beyond 6000
370 masl.



371
372 *Figure 6. Thermal result maps. A: Average active layer depth over the 1980-1989 period. B: Average*
373 *active layer depth over the 2010-2019 period. Only locations presenting permafrost at the end of the*
374 *simulation are assigned a color on the map. Locations which underwent permafrost disappearance*
375 *appear in grey on B. C: Average 8m-deep ground temperature for December, January and February*
376 *for the 1980-1989 period. D: Average 8m-deep ground temperature for December, January and*
377 *February for the 2010-2019 period.*
378

379 Based on the active layer results, we define four categories of ground thermal regimes. *Cold*
380 *permafrost* are the areas of the catchment for which the deepest thaw depth did not exceed 1 m over the
381 40 years of simulation. For cold permafrost, frozen conditions dominate the first meters of the ground
382 most of the year and surficial thawing during summer is limited and does not give rise to a distinct
383 active layer season. *Warm permafrost* are the areas of the catchment presenting permafrost for the whole
384 duration of the simulation and which are not part of the *cold permafrost*. These areas are characterized
385 by a distinct seasonal pattern of frozen ground in winter and active layer in summer. *Disappearing*
386 *permafrost* are the areas of the catchment presenting permafrost at the beginning of the simulation and



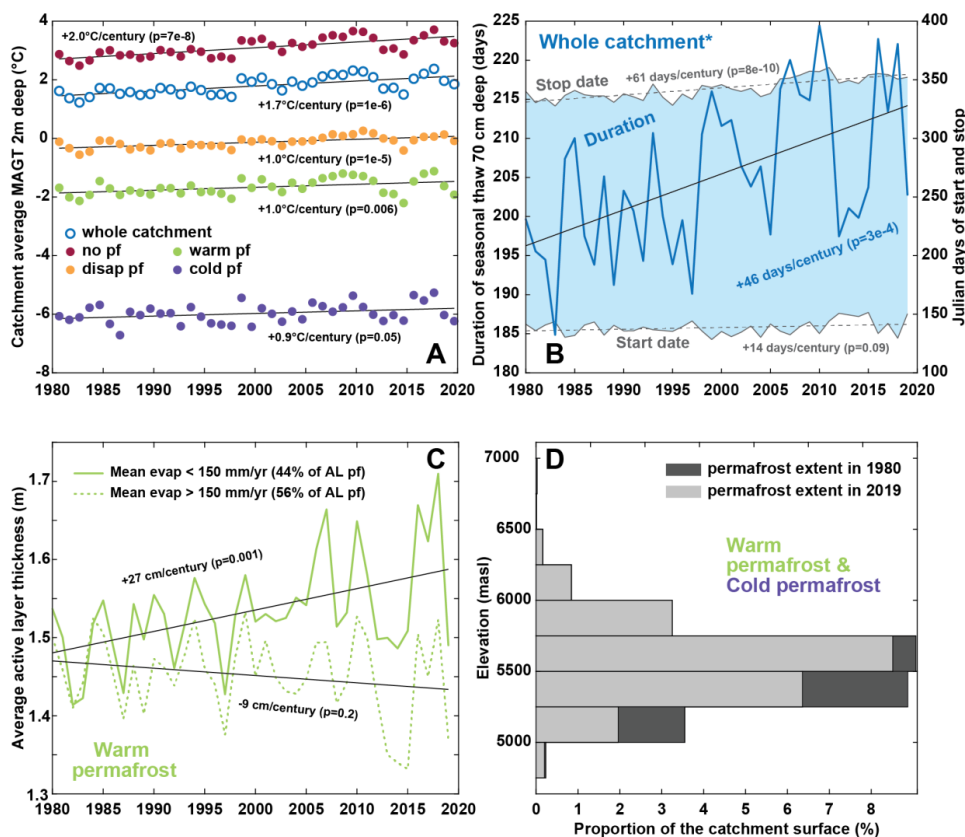
387 not at the end. *No permafrost* are the areas without permafrost at the onset of the simulation. The
 388 geographical characteristics of each ground category is presented in Tab. 1, their distribution throughout
 389 the catchment is shown on Fig. F of the appendices. These different ground categories are subsequently
 390 used to compare their cryo-hydrological behaviors during the simulation (consistent color code).

391 *Table 1. Cryological classification of the catchment based on the modeled ground temperatures*

Name	Characteristics	% of the catchment area	Elevation mean (masl)	Elevation range (masl)	Slope mean (°)
Cold permafrost	Max thaw depth over the 40 years < 1m	3%	6068	6946 5213	35±13
Warm Permafrost	Max thaw depth > 1 m and permafrost present over the 40 years	19%	5480	5921 4877	20±9
Disappearing permafrost	Permafrost present in 1980 but disappears during the simulation	5%	5274	5552 4882	18±9
No permafrost	No permafrost from 1980 to 2019	73%	4900	5463 4580	10±8

392 Fig. 7A shows the yearly temperature at a 2 m depth averaged for the whole catchment and for
 393 each cryological state of the ground. At the catchment scale, the 2 m depth temperature shows a
 394 pronounced warming trend of 1.7 °C per century ($p=1\times 10^{-6}$). This trend is mainly supported by the *no*
 395 *permafrost* areas, which underwent a slightly stronger warming trend of 2.0 °C per century ($p=7\times 10^{-8}$).
 396 Areas with disappearing permafrost, warm permafrost and cold permafrost exhibit smaller trends
 397 around 1 °C per century with decreasing p-values (respectively 0.00001, 0.006 and 0.05).

398 Fig. 7B shows the average duration of seasonal thawing at a depth of 70 cm averaged over the
 399 catchment. Because at this depth some areas might present two (or more) consecutive years without
 400 thawing (highest locations) or without freezing (lowest locations), these areas were excluded from the
 401 averaging. In the end, the averaged results account for 89% of the catchment land area (i.e. excluding
 402 glaciers and lake). The results show an increasing trend in the duration of the seasonal thaw of +46 days
 403 per century ($p=3\times 10^{-4}$). When looking at the average start and stop days of the seasonal thaw in the
 404 Julian calendar (day 150 is the 30th of May and day 300 is the 27th of October), we note that this increase
 405 is mainly caused by a later ending date of the thaw season (*Stop date* on Fig. 7, +61 days per century,
 406 $p=8\times 10^{-10}$) and not by an earlier starting date (+14 days per century, $p=0.09$).



407
 408 *Figure 7. Ground thermal results. A: Yearly 2 m deep ground temperature averaged for the whole*
 409 *catchment and for the different cryological states of the ground (see Tab. 1). B: duration of seasonal*
 410 *thaw 70cm deep averaged over the catchment. The asterisk indicates that the presented curves average*
 411 *89% of the surface of the catchment (Sect. 4.2). The grey curves and the light blue area are associated*
 412 *with the right axis and indicate the average start and stop day of the seasonal thaw in the Julian*
 413 *calendar. Values higher than 365 indicates that freezing conditions came back after the 31st of*
 414 *December. C: active layer thickness (ALT) evolution for warm permafrost. The solid line shows the*
 415 *ALT for simulations experiencing a yearly evaporation lower than 150 mm when averaged over the 40*
 416 *years. The dashed line shows the ALT for simulations with yearly evaporation higher than 150 mm. D:*
 417 *Altitudinal distribution of permafrost in 1980 and 2019. This distribution includes both cold and warm*
 418 *permafrost.*

419
 420 Fig. 7C shows active layer thickness trends for *warm permafrost*. Within *warm permafrost*, AL
 421 thickness is presented for locations experiencing an average evaporation lower or higher than 150 mm
 422 per year during the simulations. Whereas location with average evaporation below 150 mm per year
 423 record an active layer deepening trend of 27 cm per century ($p=0.001$), it is not the case for locations
 424 with an average evaporation higher than 150 mm per year ($p=0.2$, non-significative trend).



425 Fig. 7D compares permafrost spatial distribution between 1980 and 2019. These results show that
426 permafrost distribution above 5750 masl has not been modified during the simulation. Permafrost
427 disappearance has mainly occurred between 5000 and 5750 masl, with the largest loss reaching 2.5%
428 of the catchment area between 5250 and 5500 masl.

429 In the permafrost-free areas of the catchment, seasonal frozen ground reaches a depth of 1.43 ± 0.15
430 m on average and shows a decreasing trend of -68 cm per century ($p=6 \times 10^{-4}$, Fig. E). At a 70 cm depth,
431 the average duration of seasonal frozen ground is 136 ± 12 days with a decreasing trend of -53 days per
432 century ($p=4 \times 10^{-4}$). These values average 88% of the no permafrost areas since locations showing
433 persistent thawed conditions from one year to another were excluded.

434 4.3. Hydrological results

435 Hydrological results are summarized on Fig. 8. Fig. 8A shows the yearly evaporation averaged
436 over the whole catchment (land area only). The mean yearly evaporation over the simulation time is
437 180 ± 19 mm (1σ). Evaporation shows an increasing trend over the 40 years of $+101$ mm per century
438 ($p=3 \times 10^{-7}$). Average total runoff over the 40 years is 24 ± 8 mm per year and exhibits an increasing trend
439 of $+48$ mm per century ($p=8 \times 10^{-7}$). Similarly, surface runoff (13 ± 3 mm per year) and subsurface runoff
440 (11 ± 6 mm per year) show increasing trends of $+13$ and $+35$ mm per century ($p=6 \times 10^{-5}$ and 3×10^{-7})
441 respectively. The surface runoff presented on Fig. 8 includes the snow melt that did not infiltrate the
442 ground.

443 Fig. 8C presents the catchment average of the $runoff / (runoff + evaporation)$ ratio, which is
444 equivalent to $runoff / (rain + snow - snow\ sublimation)$ given the negligible contribution of soil
445 storage variations. Hence it is the proportion of the water input to the ground surface that is converted
446 into runoff. This proportion is $11 \pm 2\%$ over the simulation time and shows an increasing trend of $+13\%$
447 per century ($p=2 \times 10^{-7}$). The graph also shows the average theoretical ratio to maintain a steady lake
448 level of 17.6%. This ratio was obtained under the following hypothesis:

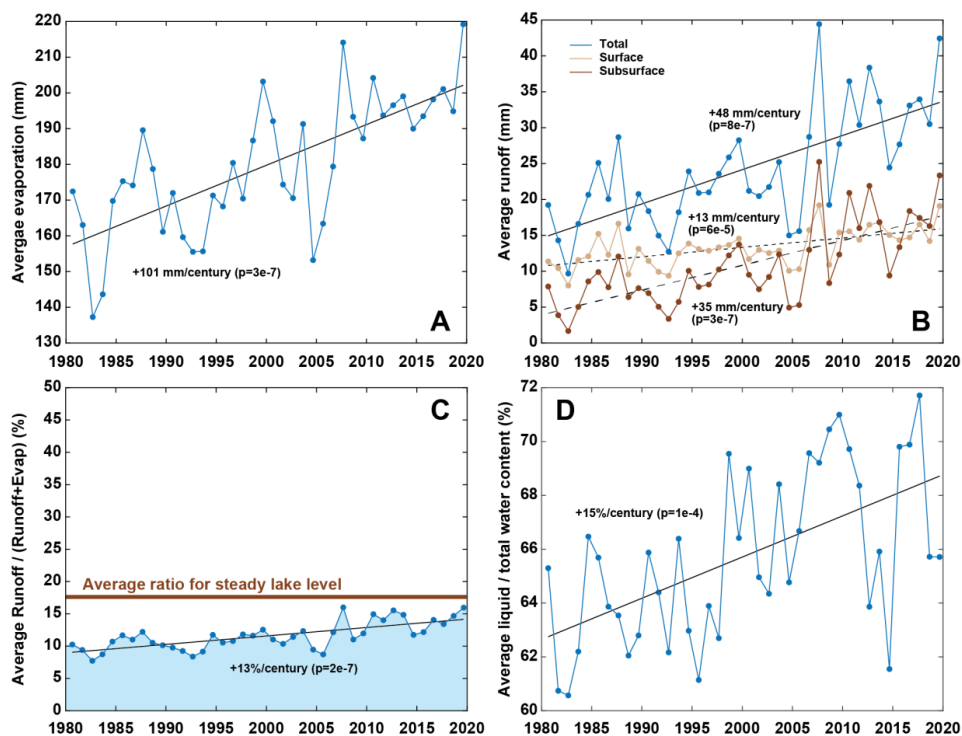


- 449 • Same climate forcing data, hence same lake evaporation
- 450 • The glacier contribution is (i) considered the same for the historical simulation and this
- 451 scenario and (ii) taken as the difference between the total land surface runoff and the red
- 452 curve of *required runoff* on figure 5, therefore independent of remotely sensed estimates.
- 453 • Under these conditions, the runoff increase needed to maintain the lake level is only
- 454 supplied by land runoff (surface and subsurface) by shifting the *runoff / (runoff +*
- 455 *evaporation)* ratio.

456 The graph shows that the ratio from the historical simulation starts significantly below the

457 theoretical steady lake ratio ($10.2\% < 17.6\%$) and increases progressively to 16.0% in 2019. This

458 evolution is consistent with observations that show a progressive stabilization of the lake level (Fig. 5).



459 Figure 8. Hydrological results. A: yearly evaporation averaged over the whole catchment. B: yearly

460 runoff averaged over the whole catchment. The blue curve sums the surface and subsurface runoff. C:

461 Ratio between runoff and (evaporation + runoff) averaged over the whole catchment. The brown line

462 indicates the theoretical average ratio needed to maintain a steady lake level when considering an

463 identical glacier contribution to runoff (details in Sect. 4.3). D: Yearly mean of the (liquid water)/(liquid

464 water + frozen water) ratio over the first 2 meters of ground, averaged over the whole catchment.

465



466 Finally, Fig. 8D shows the yearly proportion of *liquid* / (*liquid* + *frozen*) water averaged for the
467 whole catchment. The value was computed based on the daily water content (liquid and frozen) of the
468 first 2 m of the soil column (the hydrologically active part of the column, Sect. 3.2.4) from which yearly
469 averages were derived and used to compute a catchment scale average. The graph indicates that the
470 proportion of liquid water in the total water content increases at around +15% per century ($p=1\times 10^{-4}$),
471 indicating an increasing availability of liquid water in the ground with time.

472 4.4. Thermo-hydrological couplings

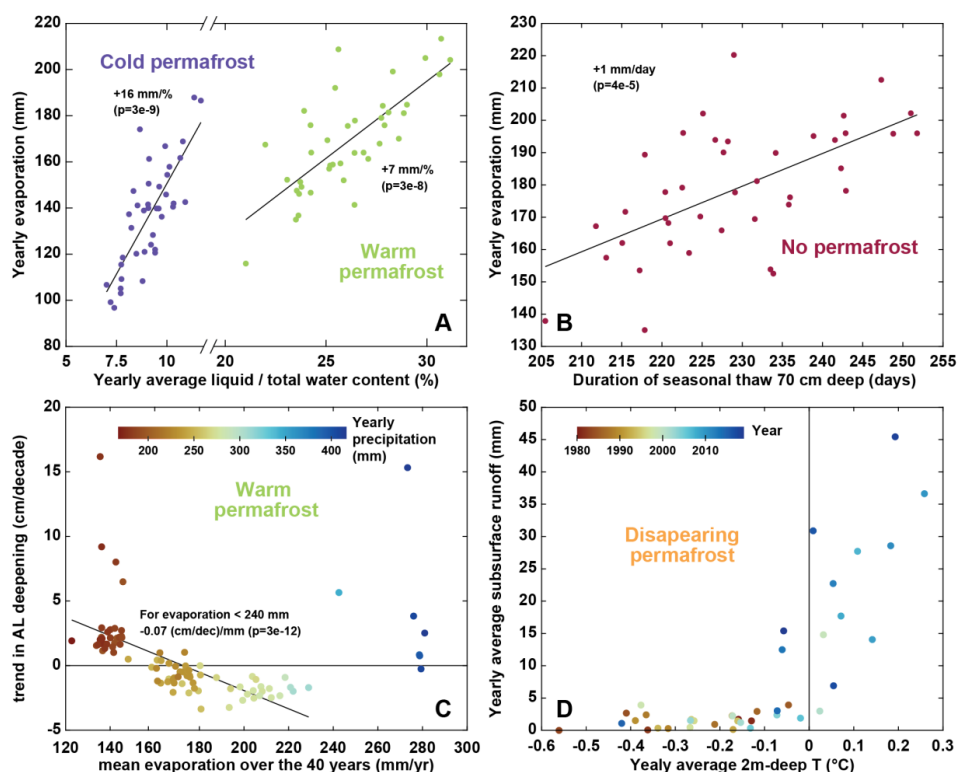
473 Fig. 9 presents simulation results highlighting the interplay between the fluxes of energy and water
474 at the surface and the subsurface and relating the ground temperature to the water content. Fig. 9A
475 shows the correlation between the yearly *liquid* / (*liquid* + *frozen*) water ratio in the first 2 m of the
476 ground and the yearly evaporation for *cold permafrost* and *warm permafrost*. The graph highlights that
477 higher evaporation is observed during the years with higher availability of liquid water in the ground.
478 Fig. 9B shows the correlation between the duration of the seasonal thaw and the yearly evaporation for
479 *no permafrost* areas of the catchment. It shows that years with longer seasonal thaw tend to be associated
480 with higher yearly evaporation.

481 Fig. 9C tests the relationship between the linear trend of active layer deepening and the mean
482 evaporation (over the 40 years of simulation) for *warm permafrost* areas. Thus, this graph does not
483 present yearly values and one point corresponds to one of the 92 simulations classified as *warm*
484 *permafrost* (values based on the 40 years). The graph highlights that simulations showing an AL
485 deepening trend are associated with low evaporation. From there, simulations with stronger evaporation
486 show no deepening trend or even a shrinkage of the AL. This relationship is contradicted for the highest
487 level of evaporation observed for *warm permafrost*, for which AL deepening is observed again (dark
488 blue points of the graph). These simulations with the highest levels of evaporation also correspond to
489 those receiving the largest amount of precipitation.

490 Finally, Fig. 9D displays the yearly values of subsurface runoff against the yearly average 2 m-
491 deep temperature for disappearing permafrost. The color scale of the points indicates the time of the



492 simulation. Consistent with the substantial warming trend observed for disappearing permafrost (Fig.
 493 7A) and the increase of subsurface runoff at the catchment scale (Fig. 8B), subsurface runoff shows
 494 higher values during the year that record a positive 2 m-deep mean annual temperature. The average
 495 annual runoff when the 2 m-deep temperature is positive is 23 ± 13 mm whereas it is 2 ± 3 mm for
 496 negative 2 m-deep temperature (mean annual value).



497
 498 *Figure 9. Thermo-hydrological couplings. A: yearly evaporation vs. yearly mean of the*
 499 *liquid / (liquid+frozen) water ratio over the first 2 meters of ground, averaged for simulations*
 500 *corresponding to cold permafrost and warm permafrost (one dot per year for each permafrost*
 501 *category). B: yearly evaporation vs. duration of seasonal thaw at a 70 cm depth averaged for*
 502 *simulations corresponding to locations without permafrost (one dot per year). C: Active layer*
 503 *deepening trend vs. mean evaporation over the 40 years for each simulation corresponding to warm*
 504 *permafrost (here one dot corresponds to one 40-years-long simulation). The color of the dots shows the*
 505 *precipitations averaged over the 40 years for each simulation. The linear regression excludes*
 506 *simulations exhibiting yearly evaporation higher than 240 mm. D: Yearly subsurface runoff vs Yearly*
 507 *2 m-deep temperature averaged for simulations corresponding to locations with disappearing*
 508 *permafrost (one dot per year). The color of the dot indicates the year of the simulation.*



509 **5. Discussion**

510 **5.1. Limitation and potential of the approach**

511 *5.1.1. Data scarcity*

512 The approach we develop in the present study to quantify the thermo-hydrological regime of the
513 Paiku catchment presents both advantages and limitations that can frame discussions on the presented
514 results. Regarding the limitations, we identify two main points. The first limitation is related to the
515 limited amount of available field observations required to provide robust model parameterizing, climate
516 forcing and in-depth validation of the simulations. Regarding the ground stratigraphy and parameters,
517 in the absence of direct observations, we made use of large-scale data sets (Schaaf and Wang, 2015;
518 Shanguan et al., 2013, 2017; Simons et al., 2020). Even though these datasets are intended to inform
519 numerical modeling, field observation would bring additional confidence in the values we use.
520 Regarding climatic forcing data, our AWS measurement offers sound observations to evaluate and
521 adjust the ERA5 data processed with TopoSUB and downscaled with TopoSCALE. Yet a period of
522 observations longer than 2 years would have brought more robust corrections and could have allowed
523 to perform quantile mapping. Regarding the simulated temperature fields, the comparison with the
524 loggers bring confidence that the model captures both the surface temperature mean values and seasonal
525 patterns, but the validation exercise would benefit from additional loggers located throughout the
526 catchment and ideally also temperature profiles from boreholes. Similarly, even though the lake
527 evaporation values we compute finds a good agreement with those from Lei et al. (2021), a longer
528 comparison would have brought a higher level of confidence in the values.

529 Finally, the lake level variations are the only hydrological observations available to evaluate the
530 robustness of the runoff we compute. We combine lake level observations with our precipitation forcing
531 data and lake evaporation quantifications in a simple mass conservation calculation to derive the land
532 runoff to the lake required to reproduce the level variations (red curve on Fig. 5). The sum of the glacier
533 and land runoff we derive over the 40 years correspond to 95% of the required runoff to the lake,
534 indicating that the magnitude of our reconstruction is correct. Year to year comparison is less accurate
535 and we suggest that this is the consequence of the aforementioned limitations regarding data scarcity



536 (including the simplifications of glacier runoff to 2 constant values over the 1980-2000 and 2000-2019
537 periods) and also of our modeling strategy as detailed below.

538 *5.1.2. Modeling strategy*

539 An important limitation in the modeling strategy we implement is the absence of water routing
540 throughout the catchment. First, water routing could highlight physical processes that our
541 implementation cannot represent such as the evaporation of water during its transport towards the lake,
542 or downstream soil water content increase due to upstream runoff. In this regard, the best our approach
543 can provide is to average these processes over time by closing the catchment water budget on the long
544 run. We suggest that our simulations reach this goal, considering it produces 95% of the required runoff
545 over the 40 years we study.

546 Second, by giving access to the timing of water transport across the catchment, water routing would
547 allow to investigate temporal hydrological patterns at a monthly or seasonal scale. Because we work at
548 yearly and decadal time scales, this limitation has limited consequences on our results. The main
549 consequence is to ignore potential storage effects on the land that would delay the arrival of runoff to
550 the lake. We suggest that this limitation contributes to explaining the limited match between computed
551 and required runoff at a yearly time scale. Yet our subdivision of the catchment based on the different
552 cryological states of the ground allows us to work with hydrological units that are smaller than the
553 catchment and thus present shorter hydrological response time to precipitation.

554 Conversely, our approach also conveys several important advantages regarding our goal to
555 describe and quantify the ground thermo-hydrological regime of the catchment. The use of TopoSUB
556 enables us to produce results at a resolution of 100 x 100 m over an area of nearly 2400 km² with
557 calculation costs 700 times lower than if each 100 x 100 m pixel was treated individually. Yet, thanks
558 to the clustering method used to produce the forcing dataset (Sect. 3.2.2), the strong spatial variability
559 of the physiography and its impact on the climate and incoming radiations is significant in the forcing
560 data and has a major influence on the ground thermo-hydrological results, as exemplified by the strong
561 spatial variability of ground temperatures (Fig. 6). Beyond elevation, other physiographic parameters
562 such as aspect also influence the results. The mean values of 2 m-deep temperature and evaporation



563 over the 40 years for north-facing areas (averaged over the whole catchment and over the 40 years) are
564 of 1.3 °C and 163 mm while they reach 2.9 °C and 197 mm for the south-facing ones. This strong
565 dependance of modeled results on physiography highlight the necessity to take it into account when
566 modeling the thermo-hydrological regime of the ground in high mountainous environments. Finally,
567 our approach allows us to couple the physical processes governing both energy and water fluxes at the
568 surface and subsurface and highlight their interplay, as developed in the following section.

569 5.1.3. *The interdependence of thermal and hydrological variables*

570 Results presented in Sect. 4.4 highlight how water and energy fluxes at the surface and subsurface
571 are coupled. For permafrost areas (*cold permafrost* and *warm permafrost*), evaporation shows a strong
572 connection with the seasonal distribution between liquid and frozen water, similarly to previous
573 modeling works for the region (Cuo et al., 2015). As such, the intensity of seasonal ground thaw plays
574 a major role in enabling higher or lower evaporative fluxes because cold surface temperatures strongly
575 reduce water loss from the surface and because moisture delivery to the surface is inhibited when the
576 ground is frozen. We suggest that this dependance is particularly important in the Paiku Catchment
577 because evaporation is strong (88% of the precipitation input to the surface evaporates on average) and
578 because frozen water is the dominant form of water in the ground in permafrost areas (Fig. 9B, the
579 calculation includes the first 2 meters below the surface).

580 Similarly, evaporation in *no permafrost* areas shows a connection with the duration of the seasonal
581 thaw. Because frozen ground limits the evaporative fluxes, years during which the subsurface seasonal
582 thaw is shorter are associated with reduced evaporative fluxes (Fig.9B). Runoff also shows a strong
583 connection with the ground thermal regime and Fig. 9D highlights how changes in the ground thermal
584 regime correspond to modifications in the hydrological pathways for *disappearing permafrost*. At the
585 beginning of the simulation, years with 2 m-deep frozen conditions are associated with limited
586 subsurface runoff (< 5 mm per year). Over the years, as the ground warms up and permafrost disappears,
587 subsurface runoff increases and can reach 20 to 45 mm per year. This result is consistent with increased
588 subsurface connectivity expected when permafrost thaws (Gao et al., 2021; Kurylyk et al., 2014) that



589 has been both observed (Chiasson-Poirier et al., 2020; Niu et al., 2016) and modeled (Gao et al., 2018;
590 Huang et al., 2020; Lamontagne-Hallé et al., 2018).

591 Altogether, these results highlight the dependance of key variables quantifying the catchment
592 hydrological balance (evaporation, runoff) to the seasonal characteristics and interannual trends of the
593 ground thermal regime (temperature, liquid vs frozen water content). Similarly to previous studies
594 (Ding et al., 2020; Wang and Gao, 2022), these results advocate for the necessity to couple thermal and
595 hydrological modeling to improve our ability to understand and quantify changes in the hydrological
596 balance of high mountain catchments. To our best knowledge, our study represents to date the most
597 complete effort to include the variety of coupled climatological, surface and subsurface processes
598 characterizing the climate, hydrology and ground thermal regime of high-mountain catchments in Tibet
599 at a small scale with a high spatial resolution.

600 5.2. Cryo-hydrological trends in the catchment and across the QTP

601 5.2.1. Permafrost and ground temperature changes

602 Our results indicate that permafrost coverage in the Paiku catchment evolves from 27 to 22% of
603 the land area during the simulated period. Such a coverage corresponds to sporadic permafrost (10-50%
604 of the area) and is consistent with recent large-scale estimates of permafrost in the northern Hemisphere
605 (Obu et al., 2019) and across the QTP (Ran et al., 2018; Zou et al., 2017). This decrease corresponds to
606 a 19% shrinkage of the 1980 permafrost area, which is more important than the 9% reported by Gao et
607 al. (2018), determined by catchment scale numerical modeling in the upper Heihe catchment
608 (northeastern QTP) over a similar period. It is also slightly higher than the 13% decrease modeled from
609 1971 to 2015 for the Qinghai Lake catchment with a similar approach by Wang and Gao (2022). Yet it
610 is smaller than the 34% loss modeled by Qin et al. (2017) from 1981 to 2015 for the Yellow River
611 Source Region (YRSR, North Eastern QTP).

612 Active layer (AL) evolution is contrasted throughout the catchment and a deepening signal is only
613 visible for the locations with limited evaporation (<150 mm per year). Given the strong drive of summer
614 climate on Active Layer Thickness (ALT), this overall lack of a deepening trend highlights how
615 evaporation can act as an energy intake at the surface, limiting the subsurface heat fluxes and thus AL



616 deepening (Yang et al., 2014a). In this regard, our results fall in line with the conclusions of Fisher et
617 al. (2016) when observing evapotranspiration and ALTs in boreal forests and also confirm the modeling
618 experiments of Zhang et al. (2021b) on permafrost wetting in arid regions of the QTP. Besides, the lack
619 of overall deepening trend is consistent with observations from Luo et al. (2018) in the YRSR over the
620 last decade and with the modeled AL from Zhang et al. (2019) at the scale of the QTP for the last 40
621 years. Where evaporation is limited we report an AL deepening trend of 2.7 cm per decade that is
622 smaller than the 4.8 cm per decade trend modeled by Song et al. (2020) for the YRSR for the same
623 period and smaller than the 4.3 cm modeled by Gao et al (2018) in the upper Heihe catchment. Yet it is
624 similar to the 2 cm per decade value modeled by Wang and Gao (2022) for the Qinghai Lake catchment
625 from 1971 to 2015.

626 In *no permafrost* areas, our simulations show that the thickness of seasonal frozen ground shrinks
627 at a rate of 6.8 cm per decade. This rate is faster than the rate of 3.1 cm per decade quantified by Qin et
628 al. (2018) using the Stefan solution for the YRSR (1961-2016) and faster than the 3.2 cm per decade
629 modeled by Gao et al. (2018, Heihe catchment). However, it is similar to the 6 cm per decade rate
630 modeled by Wang and Gao (2022) in the Qinghai Lake catchment from 1971 to 2015 and smaller than
631 the 12 cm per decade modeled by Qin et al. (2017) for the YRSR (1981-2015). All these values fall
632 within the wide range of 3 to 29 cm per decade reported by Wang et al. (2020a) when studying seasonal
633 frozen ground over the whole QTP with in-situ observations. Regrading timing, we report a decreasing
634 trend of 5.3 days of frozen conditions (70 cm deep) per decade which is consistent with the decrease of
635 6.7 days per decade reported by Wang et al. (2020a) just below the surface.

636 Regarding the timing of seasonal ground thaw, our results highlight that the increase in the duration
637 in the seasonal ground thaw (at 70 cm) is mostly driven by a progressive delay of the end date of the
638 thaw period. This result contrasts with those from Song et al. (2020) for the same period in the YRSR
639 who also modeled an increase in the seasonal thaw (at a 2 cm depth) but driven by an advancing trend
640 of the start date of the seasonal thaw.

641 Our warming trends at a 4 m depth for permafrost areas is 0.1 °C per decade, which is substantially
642 smaller than the 0.43 °C per decade observed at this depth between 1996 and 2006 in permafrost
643 boreholes along the Qinghai-Tibetan Highway in the North East of the QTP (Wu and Zhang, 2008).



644 Zhang et al. (2019) reported a 1.3 °C per decade of warming of the permafrost top during winter that is
645 consistent with the trend of 1.4 °C per decade we observe at 2 m depth (mean AL between 1.4 and 1.7
646 m in our simulations) for the months of December, January and February.

647 5.2.2. *Evaporation and runoff changes*

648 Our results are characterized by (i) an increase of both evaporation and runoff (Fig. 8), mainly
649 driven by an increase in precipitation (Fig. 3), (ii) a runoff/(runoff+evaporation) ratio exhibiting an
650 increasing trend as a result of ground warming and permafrost disappearance that both enable more
651 subsurface runoff along time (Fig. 8 and 9) and (iii) an increase in the proportion of liquid water in the
652 ground compared to ice. Regarding all these points, our results find a good consistency with the
653 evolution reported by Gao et al. (2018) for the upper Heihe catchment (northeastern QTP) using a
654 similar approach for a comparable period (1971-2013). The increasing trends in evaporation and runoff
655 they report for the thawing season (dominant period for both processes) are comparable with the yearly
656 values we report: +100 mm cm⁻¹ for evaporation (our study: +101 mm per century) and +33 mm per
657 century for runoff (our study: +48 mm per century). Similar evolutions are also reported by Wang and
658 Gao (2022) for the Qinghai Lake catchment and by Qin et al. (2017) for the YRSR (1981-2015).
659 Regarding differences, Qin et al. (2017) modeled a stronger evaporation increase (143 mm per century)
660 linked to a decreasing runoff coefficient. Similarly to Li et al. (2019), we see that an important part of
661 snow melt (49%) infiltrates in the ground and later contributes to runoff and evaporation.

662 5.3. Evaporation vs runoff and sensitivity to climate conditions

663 Our results indicate that evaporation is particularly strong in the Paiku catchment. Over the 40
664 years of simulation, 10% of the total precipitation is converted to runoff, the rest of the water is either
665 directly returned to the atmosphere from the snowpack via snow sublimation or from the ground surface
666 via evaporation. Comparatively, Gao et al. (2018) observed and modeled a ratio of around 35% for the
667 Heihe catchment; Qin et al. (2017) reported an average ratio of 33% for the YRSR and Li et al. (2014)
668 a ratio of 83% for the Qugaqie catchment (central QTP) but modeling hydrological fluxes only.

669 The role of permafrost regarding the runoff/evaporation distribution is a complex question (Bring
670 et al., 2016). Some studies have suggested that landscape-scale permafrost thaw would trigger more

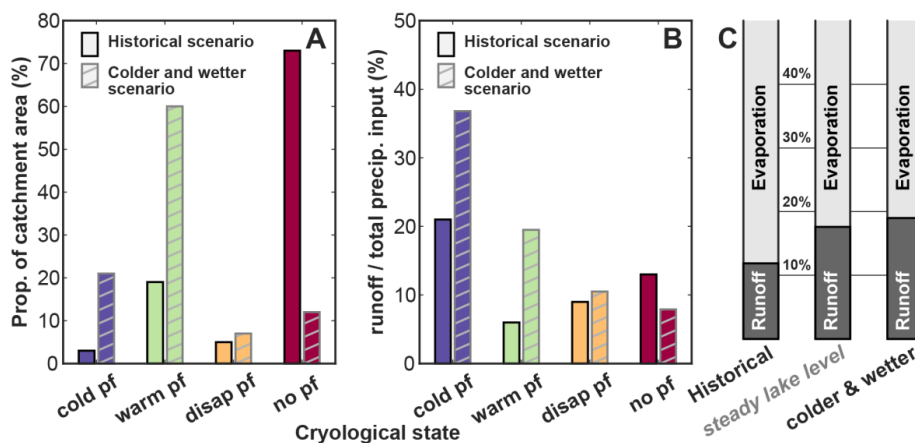


671 evaporation (Walvoord and Kurylyk, 2016, Fig. 4). This phenomenon was modeled by Wang et al.
672 (2018) in the upper Heihe River Catchment for which they reported that the thickening of the active
673 layer increased the ground storage capacity and led to a decrease in runoff and an increase in
674 evapotranspiration. Studying evaporation at the scale of the whole Tibetan plateau, Wang et al. (2020b)
675 also reported that permafrost thawing accelerated evapotranspiration (1961-2014).

676 Conversely, Zhang et al. (2003) and Carey and Woo, (1999) reported that shallow frozen ground
677 conditions (such as a shallow active layer) maintain higher water contents close to the surface,
678 promoting higher evaporation. Sjöberg et al. (2021) modeled this phenomenon with a fully coupled
679 cryo-hydrological model including surface energy balance calculation. They modeled a slope with a
680 simplified geometry in 2D for different permafrost coverages. They found that hillslopes with
681 continuous permafrost have twice as high rates of evapotranspiration compared to hillslopes with no
682 permafrost.

683 As such, the interplay between the runoff/evaporation distribution and the ground thermal regime
684 in areas where permafrost coverage shows a spatiotemporal variability is difficult to apprehend. This
685 complexity is most likely due to a strong sensitivity to the drainage conditions (fast flows of steep
686 mountain environments vs. slow flows of lowland catchments) and to the climate setting, both at the
687 annual scale (arid regions vs. wet regions) and at the seasonal time scale (relative timing of temperature
688 variations, rainfall, snowfall, snow melt and ground freeze/thaw).

689 To further understand this question in the case of the Paiku catchment, we conducted a simple
690 sensitivity test on the climatic conditions. We ran the same 40 years of simulations (with thermal
691 initialization) for a climate 1 °C cooler and 30% wetter (more precipitation) than the historical scenario.
692 We call this new scenario *colder and wetter* (to be compared with the *historical scenario*, i.e. the results
693 of the present study presented in Sect. 4). Results of this experiment are presented in Fig. 10. Because
694 of the difference in climate forcing, the *colder and wetter* scenario produced a greater amount of *cold*
695 and *warm permafrost* areas than the historical scenario, as presented on Fig. 10A. Fig. 10B shows the
696 proportion of the precipitation reaching the surface (rain + snow – snow sublimation) that produces
697 runoff compared to evaporation for the Paiku catchment.



698
 699 *Figure 10. Sensitivity of the distribution between runoff and evaporation to climate. A: distribution of*
 700 *the different cryological states of the ground for the historical scenario (presented in Section 4) and for*
 701 *an alternative scenario where the climate is 1 °C colder and brings 30% more precipitation. B: runoff*
 702 *as a proportion of the precipitation input to the land (rainfall + snowfall – snow sublimation) for the*
 703 *different cryological states of the ground and for the 2 climatic scenarios. C: catchment scale ratio*
 704 *between runoff and evaporation for (i) the historical scenario, (ii) for a steady lake level with the same*
 705 *glacier contribution (same as Fig. 8 bottom left) and (iii) for the colder and wetter scenario.*
 706

707 The *historical scenario* shows that *cold permafrost* areas produces the highest proportion of runoff,
 708 which we attribute to the fact that the ground in these areas is most of the time frozen, turning a
 709 substantial part of the snow melt and rainfall into surface runoff. When considering grounds with a
 710 hydrologically active subsurface (*warm permafrost*, *disappearing permafrost* and *no permafrost*) in the
 711 historical scenario, the proportion of runoff increases slightly from *warm permafrost* to *no permafrost*.
 712 Such an evolution then corroborates the idea that the presence of permafrost tends to increase
 713 evaporation at the expense of runoff, as modeled by Sjöberg et al. (2021). Yet, for the *colder and wetter*
 714 scenario, runoff shows a regular decrease from *cold* to *no permafrost* with a more pronounced trend
 715 than the historical scenario. Several factors can be at play in this transition and most likely involve (i)
 716 a different extent and altitudinal distribution for each cryological types of ground, (ii) a reduced
 717 intensity of evaporation due to cooler surface temperatures, (iii) a higher soil water content driven by
 718 higher precipitation and (iv) difference in the seasonal timings as listed earlier. Altogether, these
 719 processes substantially change the proportion of water that ends up as runoff water available for the
 720 lake, as highlighted by Fig. 10C.



721 5.4. Implications for lake level changes over the QTP

722 At the scale of the Paiku catchment and in regard of lake level variations, the results we present
723 highlight that:

- 724 • The sum of the direct precipitation in the lake, the land runoff and the glacier runoff are not enough
725 to compensate the lake evaporation over the study period, hence leading to the observed lake level
726 decrease.
- 727 • Long term hydrological trends in the catchment are led by trends in the climate, as precipitation
728 increase both drives an evaporation and runoff increase over the 40 years.
- 729 • Ground thermal changes increase the distribution of liquid vs. frozen water in the ground and the
730 duration of seasonal thaw, both directly affecting evaporation and runoff towards the lake.
- 731 • Ground warming and permafrost thawing promote subsurface runoff over time, contributing to
732 increase the runoff/evaporation ratio of the catchment.
- 733 • Over the last 40 years, the presence of permafrost seems to promote evaporation at the expense of
734 runoff. Yet this trend appears to be climate-dependent and the cryological state of the ground might
735 shift the runoff/evaporation distribution in the other direction under colder and wetter climates.

736 At the scale of the QTP, these results have several implications. First, a better understanding of the
737 recent and future lake level variations will come with a better knowledge of spatial patterns and
738 temporal trends in precipitation. Second, climate changes are modifying the ground thermal regime of
739 Tibetan catchments through active layer deepening and changes in the seasonal freeze/thaw cycles,
740 affecting evaporation, runoff volumes and pathways and overall, changing the hydrological functioning
741 of Tibetan catchments (and the waterflow provided to the lakes). Finally, the effect of permafrost on
742 the distribution between evaporation and runoff seems to be dependent on the climate settings and the
743 permafrost coverage of the catchment. Because it can both promote evaporation or runoff depending on
744 the setting, the ground thermal regime of the catchment seems to have the possibility to create a positive
745 feedback both towards lake level decrease or increase. Further studies could therefore focus on
746 comparing the thermo-hydrological regime of different Tibetan catchments with contrasted lake level



747 changes and permafrost coverage, to test to which extent these differences can explain the spatial
748 patterns of lake level changes across the QTP.

749 **6. Conclusion**

750 We confirm that the Paiku catchment presents different types of ground cryological state from
751 seasonal frozen ground to permafrost. Permafrost coverage shrinks from 27 to 22% of the land area
752 from the 1980s to the 2010s (19% loss of permafrost area). The whole catchment warms up at a rate of
753 1.7 °C per century (2 m deep), with a substantial elevation-dependent variability. This warming is
754 concomitant with an increase in the duration of the seasonal thaw, mainly supported by a progressive
755 delay of the end date of the thaw period. Where permafrost is present, active layer deepening is only
756 observed where evaporation is limited ($<150 \text{ mm yr}^{-1}$).

757 Over the simulation period, we also report an increase in evaporation (+101 mm per century),
758 surface and subsurface runoff (+13 and +35 mm per century respectively). Together, this leads towards
759 an increase of the runoff/(runoff + evaporation) ratio of +13% per century. These results highlight the
760 strong interdependence between the ground thermal and hydrological regimes and the necessity to
761 jointly represent them to accurately quantify evaporation and runoff in this type of environment. Indeed,
762 we show that ground thermal changes increase the availability of liquid water in the ground and the
763 duration of seasonal thaw and that both directly affect evaporation and runoff towards the lake.
764 Additionally, permafrost thawing and ground warming promote subsurface runoff over time,
765 contributing to increase the runoff/evaporation ratio of the catchment.

766 Over the last 40 years, the presence of permafrost seems to promote evaporation at the expense of
767 runoff. Yet this trend appears to be climate-dependent and the cryological state of the ground might
768 shift the runoff/evaporation distribution in the other direction under colder and wetter climates. Further
769 studies should investigate this phenomenon and how it might contribute to explain the contrasted lake
770 level evolutions across the QTP.



771 **Appendix A: model parameters**

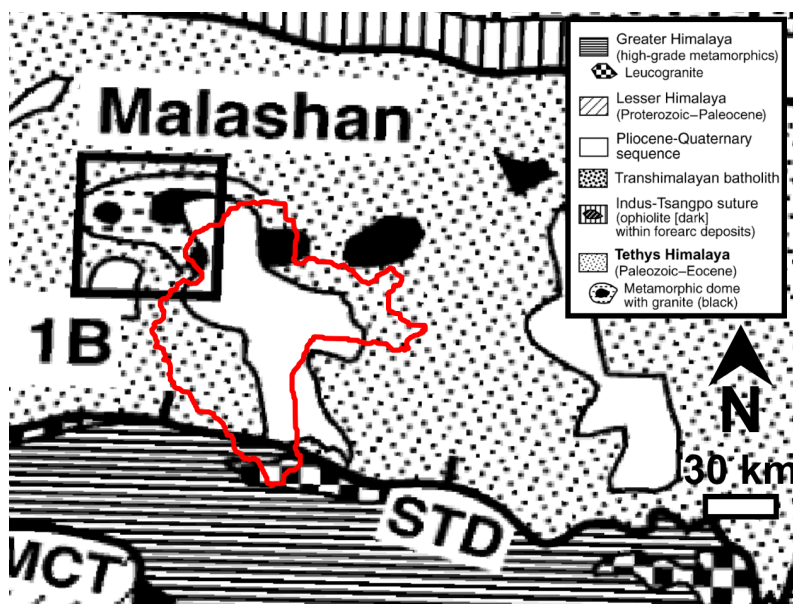
772 *Table A. Parameters of the model.*

Depth	Layer	Parameter	Values	Source	Calculation
0.0 m	Surface	Albedo	0.24	Modis MCD43A3.006	November mean, 4600-5100 masl
		Emissivity	0.95	Modis MCD43A3.006	November mean, 4600-5100 masl
		Roughness	0.024	-	Adjusted to fit loggers T values
0.0 m		Thickness	0.30 m	HiHydro Soil v1.0	modeling framework
		Porosity	0.5	Shangguann et al. 2013	mean
		Organic	8.60%	HiHydro Soil v1.0	catchment mean
		Mineral	41.40%	-	substraction (100 - porosity - orga)
0.3 m	Top soil	Soil type	Sand	Shangguann et al. 2013	dominant fraction
		Field capacity	0.32	HiHydro Soil v1.0	catchment mean
		Hydro cond	0.000030 m s ⁻¹	HiHydro Soil v1.0	catchment mean
		Alpha	0.028 cm ⁻¹	HiHydro Soil v1.0	catchment mean
0.3 m	n	1.481	HiHydro Soil v1.0	catchment mean	
0.3 m		Thickness	1.70 m	Shangguan et al. 2017	truncation, consistent with litterature
		Porosity	0.4	Shangguann et al. 2013	catchment mean
		Organic	4.20%	HiHydro Soil v1.0	catchment mean
		Mineral	55.80%	-	substraction (100 - porosity - orga)
1.7 m	Bottom soil	Soil type	Sand	Shangguann et al. 2013	dominant fraction
		Field capacity	0.32	HiHydro Soil v1.0	catchment mean
		Hydro cond	0.000016 m s ⁻¹	HiHydro Soil v1.0	catchment mean
		Alpha	0.062 cm ⁻¹	HiHydro Soil v1.0	catchment mean
2.0 m	n	1.707	HiHydro Soil v1.0	catchment mean	
2.0 m		Thickness	98.3 m	-	-
		Porosity	0.03	-	-
98 m	Bedrock	Organic	0%	-	-
		Mineral	97%	-	-
100 m		Soil type	Sand	-	-
		Field Capacity	0.03	-	equal to porosity

773

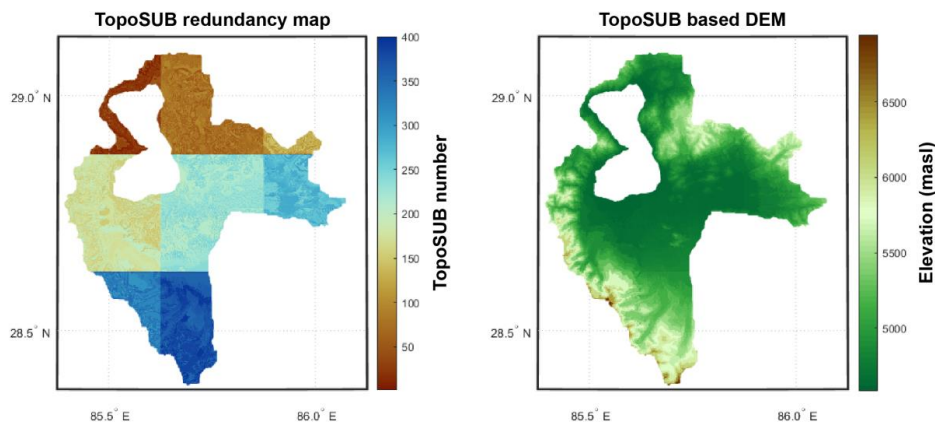


774 **Appendix B: Geological map of the catchment**



775
 776 *Figure B. Geology of the catchment. Modified from Aoya et al. (2015). The red contour indicates the*
 777 *limits of the Paiku catchment.*

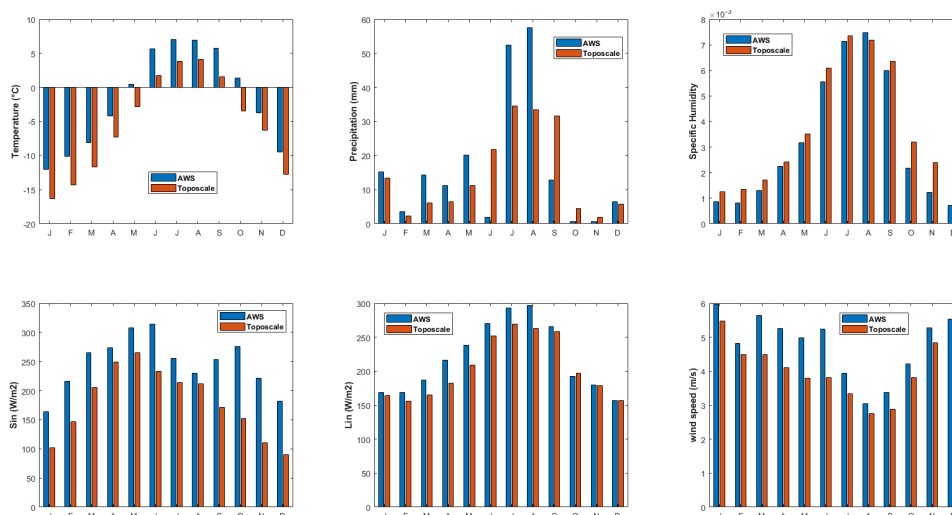
778 **Appendix C: TopoSUB subsampling of the catchment**



779
 780 *Figure C. Application of the TopoSUB clustering method (Fiddes and Gruber, 2012) in the Paiku*
 781 *catchment. Left: number of the TopoSUB points. Strong color changes reflect the footprint of the 8*
 782 *ERA5 pixels that the catchment intersects. Small color changes within a given of these zones show the*
 783 *distribution of the 50 TopoSUB points covering each tile (Sect. 3.2.2.) B: topographic map*
 784 *reconstructed from the TopoSUB approach.*

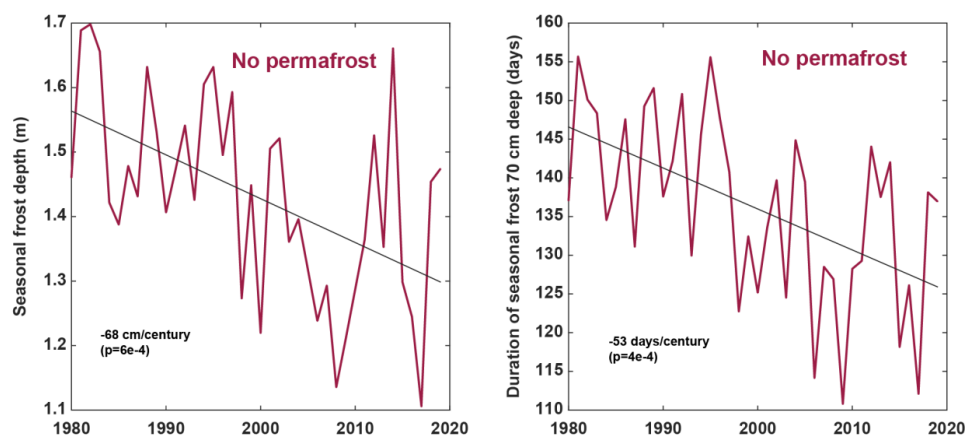


785 **Appendix D: Evaluation of forcing data**



786
 787 *Figure D. Comparison between the AWS data and the model forcing data downscaled from ERA5 with*
 788 *the TopoSCALE and TopoSUB approaches. Based on the AWS data, a monthly correction factor is*
 789 *applied to the downscaled data so that monthly data matches for the observed period for each variable*
 790 *(methodological details in Sect. 3.2.2.).*

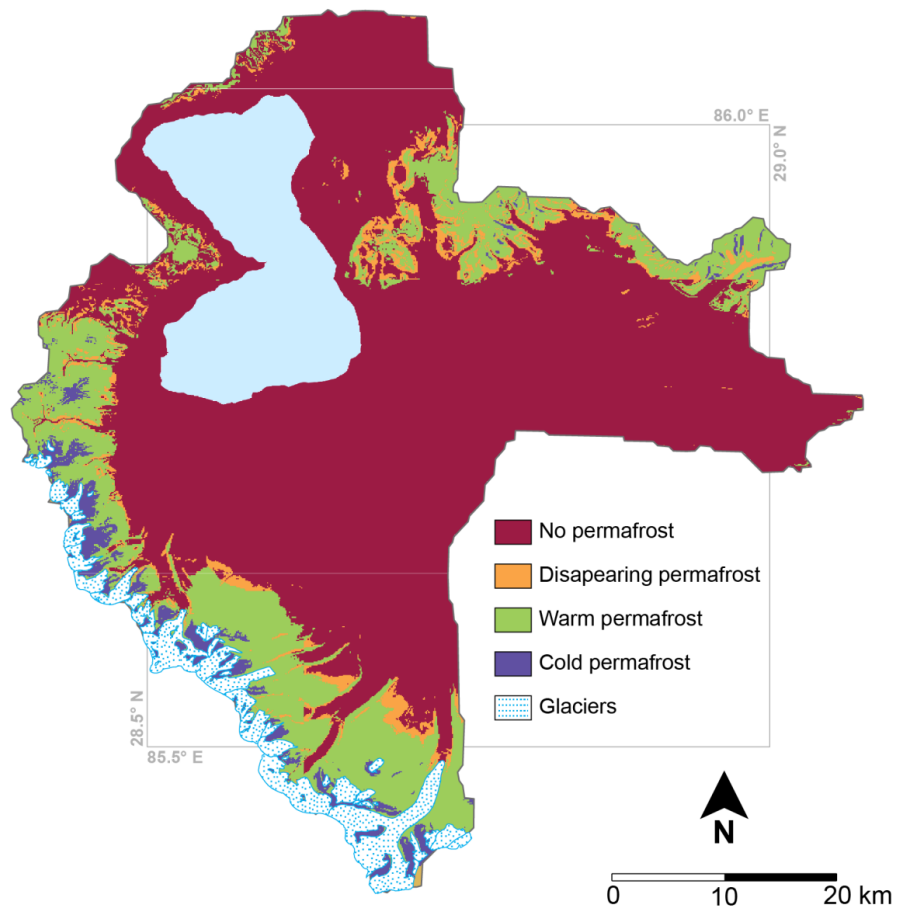
791 **Appendix E: Seasonal frozen ground**



792
 793 *Figure E. Temporal trends for seasonal frozen ground where there is no permafrost. Simulations*
 794 *presenting occurrences of persisting thawed conditions from one year to another were excluded. The*
 795 *presented curves average thus 88% of the total permafrost-free areas of the catchment.*
 796



797 **Appendix F: Cryological state of the ground**



798
799

Figure F. Cryological state of the ground. See methodological descriptions in Sect. 4.2.



Code availability. The CryoGrid community model (version 1.0) and related documentation are available at: https://github.com/CryoGrid/CryoGridCommunity_source.

Data availability. Field data will be permanently deposited on XXX upon acceptance of the manuscript.

Author contribution. L.M, W. I. and S.W. designed the study. L.M. and M.M. conducted the numerical simulations. S.W., M.L. and L.M. contributed to the model development. F.B., W.I., Y.L. and S.A. acquired field data. L.M., F.B., M.M., P.K., Y.L. and T.M. analyzed and processed the data. J.F. provided downscaled forcing data for the model. All authors contributed to result interpretation and to manuscript preparation.

Competing interests. The authors declare that they have no conflict of interest.

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