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1 ***Surface energy and mass balance of Mera Glacier (Nepal, Central Himalaya) and their sensitivity to***
2 ***temperature and precipitation***

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10 **Abstract**

11 The sensitivity of glacier mass balance to temperature and precipitation variations is crucial for informing
12 models that simulate glaciers' response to climate change. In this study, we simulate the glacier-wide mass
13 balance of Mera Glacier with a surface energy balance model, driven by in-situ meteorological data, from
14 2016 to 2020. The analysis of the share of the energy fluxes of the glacier shows the radiative fluxes
15 account for almost all the energy available during the melt season (May to October). However, turbulent
16 fluxes are significant outside the monsoon (June to September). On an annual scale, melt is the dominant
17 mass flux at all elevations, but 44 % of the melt refreezes across the glacier. By reshuffling the available
18 observations, we create 180 synthetic series of hourly meteorological forcings to force the model over a
19 wide range of plausible climate conditions. A +1 (-1)°C change in temperature results in a -0.75 ± 0.17
20 $(+0.93 \pm 0.18)$ m w.e. change in glacier-wide mass balance and a +20 (-20)% change in precipitation results
21 in a $+0.52 \pm 0.10$ (-0.60 ± 0.11) m w.e. change. Our study highlights the need for physically based
22 approaches to produce consistent forcing datasets, and calls for more meteorological and glaciological
23 measurements in High Mountain Asia.

24 **1. INTRODUCTION**

25 The pace of climate warming in High Mountain Asia (HMA) is accelerating (Pepin and others, 2015) and
26 precipitation in these regions exhibits significant heterogeneity and remains insufficiently comprehended
27 (Lutz and others, 2014). Furthermore, the intricate relationship between precipitation and temperature
28 variations proves to be a formidable puzzle. This connection, intricately intertwined with glacier mass
29 balance, poses a challenge for understanding the recent evolution of glaciers in HMA (Oerlemans and
30 Reichert, 2000). While multi-year satellite-based estimates of mass changes allow to map the
31 heterogeneity of glacier mass balance across large scales (e.g., Hugonnet and others, 2021), they need to
32 be complemented by other approaches to further elucidate these patterns of contrasted mass losses. One
33 possible approach is to consider that glacier mass changes are the combination of a change in climate
34 conditions modulated by a glacier sensitivity to these changes (e.g., Oerlemans and Reichert, 2000;
35 Marzeion and others, 2012). Following this approach, Sakai and Fujita (2017) demonstrated that regionally
36 different sensitivity to temperature changes could be the main driver of observed mass losses across Asia.
37 They found that the glacier mass balance sensitivity to temperature was determined by the general
38 climatology, and in particular, by the summer temperature, the annual range of temperature and the ratio
39 between summer and annual precipitation. However, their approach relies on a number of simplifying
40 assumptions that consider only the climate at the equilibrium line altitude (Ohmura and others, 1992) and
41 the climate data they used has a coarse spatial resolution. There is thus room to improve the methodology
42 they applied, in particular through a better representation of processes responsible for glacier mass losses
43 and gains.

44 These processes controlling the glacier mass are determined by the surface energy balance (SEB), which is
45 commonly modelled to investigate how glacial mass balance is governed and how sensitive it is to climatic
46 variables (Fujita, 2008; Azam and others, 2014; Fugger and others, 2022). There is a long history of studies
47 that investigated the glacier SEB at various locations and at various temporal and spatial scales to relate
48 atmospheric variables to glacier mass changes (e.g., Oerlemans and Knap, 1998; Favier and others, 2004).
49 Specifically, in Hindu Kush Himalaya (HKH), a number of studies investigated the SEB of glaciers in different
50 climate contexts (Mölg and others, 2012; Zhu and others, 2015, 2018, 2021; Huintjes and others, 2015;
51 Fugger and others, 2022; Arndt and Schneider, 2023). They highlight the different sensitivities to
52 temperature and precipitation in different climate conditions, with the dry and cold (continental) climate
53 that prevails in the north west margin of HKH being associated to low sensitivities of glacier mass balance
54 to temperature, and the warmer and wetter (oceanic) climate of south east HKH corresponding to larger
55 sensitivities (e.g., Arndt and Schneider, 2023). The larger sensitivities are associated to the prevalence of
56 surface melt in the surface mass balance. Surface energy based studies find highly non linear sensitivity of

57 the mass balance to precipitation, unlike studies based on empirical approaches, such as degree-day
58 modeling (e.g., Wang and others, 2019). This is due to the highly non linear response of glacier surface
59 mass balance to the albedo effect (e.g., Arndt and Schneider, 2023).

60 However, in HKH most of the SEB studies have two main limitations: either they were done at point scale
61 (Kayastha and others, 1999; Azam and others, 2014; Acharya and Kayastha, 2019; Litt and others, 2019;
62 Mandal and others, 2022), or they used meteorological data from reanalysis products (Arndt and
63 Schneider, 2023). The point-scale modelling of the SEB is limited because the SEB is very sensitive to the
64 surface state of the glacier (ice, snow or debris), and to the distribution of meteorological variables
65 (precipitation, temperature, radiative fluxes, etc.) that vary across the glacier area (Oerlemans and others,
66 1999). Modelling the SEB of a glacier across its entire area requires distributed measurements of
67 meteorological variables, and measurements of the glacier surface mass balance at multiple locations,
68 including the accumulation area. Unfortunately, such data are seldom available in HKH (Huintjes and
69 others, 2015; Arndt and others, 2021; Srivastava and Azam, 2022; Oulkar and others, 2022).
70 Meteorological variables obtained from reanalysis can be heavily biased, especially if they are not
71 downscaled with local measurements (e.g., Hamm and others, 2020; Khadka and others, 2022). When
72 meteorological variables from reanalysis are used to force a glacier mass balance model, they first need to
73 be debiased, which is often done by tuning a precipitation correction factor until the glacier mass balance
74 matches observations. While there is usually no alternative, this method is known to be subject of
75 equifinality (e.g., Rounce and others, 2020).

76 This article presents a glacier-wide SEB analysis of Mera Glacier in the eastern part of Central Himalaya.
77 We applied the 'COupled Snowpack and Ice surface energy and mass balance model in PYthon' (COSIPY:
78 Sauter and others, 2020) which has been optimised and evaluated using site specific measurements (Fig.
79 S1 in supplementary material). Among Nepal's monitored glaciers, Mera Glacier stands out for its extensive
80 and continuous meteorological and mass balance data, making it one of the most comprehensively
81 observed glaciers in the region (Wagnon and others, 2021; Khadka and others, 2022). By integrating field
82 measurements, in-situ meteorological data, and the SEB model, we aim to enhance our understanding of
83 (1) the physical processes governing the seasonal and spatial variability of the glacier mass balance, and
84 (2) the sensitivity of the mass balance to meteorological variables. The findings from this comprehensive
85 study will give us a better understanding of the impact of the on-going climate change on Himalayan
86 glaciers.

87 2. STUDY AREA AND CLIMATE

88 2.1 Mera Glacier

89 Mera Glacier, situated in the eastern part of the Central Himalaya within the Upper Dudh Koshi basin, is a
90 plateau-type debris free glacier. Encompassing an area of 4.84 km² in 2018, the glacier stretches from an
91 altitude of 6390 m a.s.l. to a minimum of 4910 m a.s.l. (Fig. 1). This north-facing glacier features a gentle
92 slope with a mean inclination of around 16 degrees. At an elevation of approximately 5900 m a.s.l., the
93 glacier separates into two distinct branches, the Mera branch and the Naulek branch. The Mera branch
94 initially heads north and then curves westward, while the Naulek branch extends ~2 km towards the
95 northeast. The Mera branch is the largest of the two branches and accounts for about 80 % of the glacier's
96 total area.

97 “Figure 1 near here”

98 2.2 Climate

99 Like other glaciers in Nepal, Mera Glacier is a summer accumulation type glacier, gaining mass mainly from
100 the summer monsoon (June to September) snowfalls brought by the South Asian monsoon system
101 (Wagnon and others, 2013; Thakuri and others, 2014; Shea and others, 2015). The glacier experiences
102 most of its accumulation and ablation during the monsoon, which makes it a key season to understand the
103 climatic regime of the glacier (Ageta and Higuchi, 1984). From June to September, the average air
104 temperature measured between 2012 and 2020 at 5360 m a.s.l. on Naulek branch is 0.3 °C, and the
105 average precipitation recorded at 4888 m a.s.l. is equal to 570 mm, with an annual precipitation of 818
106 mm (Khadka and others, 2022). During this season, warm air masses flow from the Bay of Bengal and bring
107 moisture and precipitation in the Himalaya (Perry and others, 2020). In just a few days, marking the start
108 of the post-monsoon (October-November), generally at the beginning of October, meteorological
109 conditions change abruptly to become dry, sunny and increasingly cold and windy. Very occasionally, this
110 season is marked by the intrusion of typhoons in the Himalaya, which bring large amounts of snowfalls
111 above ~4000 m a.s.l. in just a few days, like in October 2013 and 2014 (Shea and others, 2015). The winter
112 (December-February) is similar but harsher than the post-monsoon with constantly cold, dry, and very
113 windy conditions. At Naulek (5360 m a.s.l.), the average air temperature during this season is -10.4 °C. The
114 pre-monsoon starts in March and is characterized by progressively warmer, wetter and less windy
115 conditions until the monsoon is totally installed at the beginning of June. The pre-monsoon is then the

116 second wettest season after the monsoon with approximately one quarter of the annual precipitation on
117 the glacier (Khadka and others, 2022).

118 **3. DATA**

119 **3.1 Meteorological Data**

120 A network of automatic weather stations (AWSs) has been installed and gradually expanded since 2012 in
121 Mera Glacier catchment at different elevations and on various surfaces (Fig. 1). In this present study, we
122 mainly use data from two on-glacier AWSs, one located in the ablation area on Naulek branch at 5360 m
123 a.s.l., AWS-Low (hereafter referred as AWS-L; 4 years of data between November 2016 and October 2020),
124 and one located in the accumulation area at 5770 m a.s.l., AWS-High (hereafter referred as AWS-H; 3 years
125 of data between November 2017 and November 2020; Fig. S2). Both AWSs record air temperature (T),
126 relative humidity (RH), wind speed (u), incoming and outgoing longwave (LWin and LWout, respectively)
127 and shortwave (SWin and SWout, respectively) radiation (Table 1).

128 “Table 1 near here”

129 There are numerous data gaps in both records, due to AWS failure, power shortage during occasional
130 abundant snowfalls covering the solar panels for instance or sensor breakdowns (Table 1; Fig. 2 and see
131 <https://glacioclim.osug.fr/>). The largest data gap occurred at AWS-L, when the station fell down from 12
132 December 2017 to 24 November 2018. To fill these gaps, data from the off-glacier Mera La AWS was used.
133 Linear correlation relationships were established each month between the same variables from the two
134 stations from November 2016 to October 2020, at an hourly time step (Fig. S3 and Table S1). The
135 atmospheric pressure (Pa) measured at Mera La AWS is used at AWS-L without any interpolation, as both
136 AWSs are located less than 2 km apart at almost the same elevation (Table 1; Fig. 1).

137 The Khare Geonor station (4888 m a.s.l.) has been installed on 24-25 November 2016, 472 m lower in
138 elevation and ~3 km northwest of AWS-L. In Mera catchment, this is the only station of the network
139 recording all-weather precipitation, thanks to a weighing device. The precipitation data have been
140 corrected for undercatch following the method by Førland and others (1996) as a function of wind speed
141 and precipitation phase (liquid or solid) depending on air temperature (See the details in the supplement
142 of Khadka and others, 2022).

143 “Figure 2 near here”

144 3.2 Spatial distribution of meteorological forcings

145 Given the complexity and heterogeneity of the local climate and terrain, it is a challenging task to distribute
146 point data spatially. For air temperature, relative humidity and incoming longwave radiation, we derived
147 empirical linear relationships from the respective measurements of the two on-glacier AWSs installed with
148 a 410 m difference in altitude. To take advantage of the longest data series without gaps at AWS-H, we
149 calculate the gradients between 01 March 2018 and 28 February 2019, even though a major part of the
150 data from AWS-L is reconstructed over this period. Since AWS-L has a relatively longer and more consistent
151 dataset than AWS-H, we distribute meteorological data from this lower station across the glacier using
152 observed altitudinal gradients of air temperature, relative humidity, and incoming longwave radiation
153 (Table S2; Fig. S4). In meteorology, the dew-point temperature gradient is more commonly encountered
154 than the relative humidity gradient. However, in this particular study, the relative humidity gradient is
155 utilised because the COSIPY model is developed based on relative humidity input data. For completeness,
156 we also compute the dew-point temperature gradient from data collected at both stations, which we
157 subsequently convert into a relative humidity gradient. This converted gradient is comparable to the one
158 directly obtained from relative humidity measurements at AWS-L and AWS-H, that we use in our study
159 (Fig. S5 and corresponding supplementary text).

160 The incoming solar radiation has been distributed for each grid following the methods of Sauter and others
161 (2020), already tested and applied on Himalayan glaciers (e.g., Arndt and Schneider, 2023). First the
162 fraction of diffuse radiation (F_{diff}) is calculated based on Wohlfahrt and others (2016):

$$F_{diff} = e^{-e^{p1 - (p2 - p3CI)}} * (1 - p4) * p4 \quad (1)$$

163 Where $p1 = 0.1001$, $p2 = 4.7930$, $p3 = 9.4758$, $p4 = 0.2465$ are parameters from Wohlfahrt and others
164 (2016) and CI , for clearness index, is the ratio of incoming solar radiation to maximum incoming solar
165 radiation. F_{diff} may vary from 0 to 1. Second, the measured incoming shortwave radiation is split into
166 beam ($R_b = SW_{in} * (1 - F_{diff})$) and diffuse ($R_d = SW_{in} * F_{diff}$) radiation. Then, the corrected solar radiation
167 (R_c) is calculated on each grid based on Ham (2005).

$$R_c = R_b * cf + R_d \quad (2)$$

168 Where cf is the correction factor calculated based on the azimuth and the slope of each grid following
169 Ham (2005).

170 As our network does not allow to assess precipitation variations with elevation over Mera Glacier
171 catchment, precipitation amounts are assumed constant all over the catchment and equal to Khare
172 Geonor records. Similarly, wind speed is likely spatially variable due to terrain aspect, roughness and
173 heterogeneity but in first approximation, we had no choice but to consider the wind as constant over Mera
174 Glacier and equal to that at AWS-L. These first-order approximations are discussed in section 6.3.

175 **3.3 Mass balance data**

176 Mera Glacier has been monitored since 2007 at least once a year in November and its mass balance series
177 is one of the longest continuous field-based series of the Himalaya. Its glacier-wide mass balance is
178 obtained annually using the glaciological method based on a network of 16 ablation stakes and five
179 accumulation sites on average (Fig. 1). This glacier-wide mass balance series has been calibrated with the
180 2012-2018 geodetic mass balance (Wagnon and others, 2021). Over the period 2007-2023, the mean
181 corrected glacier-wide mass balance is equal to -0.42 ± 0.23 m w.e. a^{-1} , with only four positive mass balance
182 years out of 16. Our study period 2016-20 was characterized by constantly negative mass balance years
183 with a mean glacier-wide value of -0.74 ± 0.18 m w.e. a^{-1} , 2017-2018 being the most negative year (-0.92
184 ± 0.16 m w.e. a^{-1}) and 2019-2020 being the least negative (-0.49 ± 0.22 m w.e. a^{-1}) (Table 2). Between 2007
185 and 2023, the glacier has lost around 10 % of its surface area.

186 Point mass balances measured at each stake or at each accumulation site can exhibit significant spatial
187 variability depending on factors such as elevation, slope, aspect, and wind redistribution. Table 2 provides
188 the annual and mean values of point mass balances over the study period 2016-20 at the two on-glacier
189 AWSs. For AWS-L, it is computed by using all stake measurements available on Naulek branch between
190 5300 and 5380 m a.s.l., using a mean measured snow density of 370 kg m^{-3} and an ice density of 900 kg m^{-3} .
191 For AWS-H, point mass balances measured at sites located between 5750 and 5790 m a.s.l. in the vicinity
192 of the station are averaged, using depth averaged snow densities measured during each field campaign
193 (from 380 to 430 kg m^{-3}).

194 “Table 2 near here”

195 **4. METHODS**

196 **4.1 Model Description (COSIPY)**

197 In this study, we use COSIPY model, which is a python-based coupled snowpack and ice SEB model (Sauter
 198 and others, 2020). The model is a one-dimensional multi-layer discretisation of the snowpack/ice column
 199 that resolves the energy and mass conservation, and calculates the surface energy fluxes using input
 200 meteorological variables as forcings. For spatially distributed simulations, the point model is run
 201 independently at each point of the glacier domain, neglecting the lateral mass and energy fluxes. The
 202 model's reliability has been validated across distinct contexts and geographical regions (Sauter and others,
 203 2020; Blau and others, 2021; Arndt and others, 2021). COSIPY model calculates the energy available for
 204 melt (QM) for each time step and is expressed as:

$$QM = SWnet + LWnet + QS + QL + QC + QR \quad (3)$$

205 where $SWnet$ is the remaining net shortwave radiation at the surface after penetration inside the snow/ice
 206 surface, $LWnet$ is net longwave radiation and Q denotes the other heat fluxes of different subsequent
 207 scripts S: sensible, L: latent, C: sub-surface (called ground-heat flux in Sauter and others, 2020), and R: rain
 208 in $W m^{-2}$. All the fluxes are positive when directed towards the surface and negative away from the surface.
 209 When the surface temperature is at the melting point and $QM > 0$, the excess energy is used to melt.
 210 Additionally, COSIPY calculates a subsurface melt, that is calculated from the penetration of the incoming
 211 shortwave radiation (Sauter and others, 2020). For the rest of the analysis, we refer to total melt as the
 212 sum of surface and subsurface melt.

213 4.1.1 Model settings

214 The COSIPY model is used in its default configuration. The turbulent fluxes, QS and QL , are calculated as:

$$QS = \rho_{air} C_p C_s u (T - T_s) \quad (4)$$

$$QL = \rho_{air} L_v C_l u (q - q_s) \quad (5)$$

215 where ρ_{air} is air density (in $kg m^{-3}$); C_p is the specific heat of air at constant pressure (in $J kg^{-1} K^{-1}$) and L_v
 216 is the latent heat of sublimation/vaporization (in $J kg^{-1}$). C_s and C_l are the dimensionless transport
 217 coefficients calculated using the bulk method with initial roughness lengths taken from Mölg and others
 218 (2012) and further calibrated (see section 4.2), q is the specific humidity of air (in $g kg^{-1}$), T_s and q_s are the
 219 temperature (in $^{\circ}C$) and specific humidity at the surface, respectively. The bulk Richardson number has
 220 been used to assess the stability correction.

221 The snowfall is distinguished from liquid precipitation using a logistic transfer function based on Hantel
222 and others (2000) (Fig. S6):

$$n = \frac{1}{2} \{ \tanh [((T - T_0) - T_{00}) s_0] + 1 \} \quad (6)$$

223 where n is the fraction of snowfall (1 when it is only snow, 0 if only rain and in between 0 and 1 if this is
224 mixed rain and snow), T_0 is the melting point (0 °C), T_{00} is the center for snow transfer function (in °C) and
225 s_0 is spread snow transfer function. The aging/decay of the snowpack's albedo is then based on Oerlemans
226 and Knap (1998), where it depends on the number of days after the last snowfall. Snow density is another
227 important property of snow, particularly for its liquid water content or thermal conductivity. It is obtained
228 by following Essery and others (2013). The default albedo and densification parameterizations used in this
229 study are described in the supplementary material (see additional text related to the method section p. 9-
230 10).

231 *4.1.2 Model description and initialisation*

232 We run COSIPY at point scale at AWS-L and in a distributed way over 51 glacierized grid points of
233 0.003°x0.003° (0.0984 km²) resolution (corresponding to a total glacier-covered area of 5.01 km²),
234 resampled from Copernicus GLO-30 DEM (<https://doi.org/10.5270/ESA-c5d3d65>) using the glacier
235 outlines in 2012 (5.10 km²) from Wagon and others (2021). Additionally, the grid elevations were
236 adjusted downward by 19 meters to align with the elevation of AWS-L. The selection of this particular
237 resolution is a compromise between the computational time and a reasonable representation of the
238 topography. The model is run at an hourly time scale, independently for the four years of data, from 1
239 November of one year until 31 October of the following year over 2016-20, without spin-up time. We
240 impose a temperature of 265.16 K at the glacier sole because the glacier is cold-based (Wagon and others,
241 2013). The model is initialised with 600 layers of glacier ice topped by a snowpack whose profile is specified
242 by the user. In our case, this profile is determined by the snow depth (Table 2), with each layer having an
243 optimal snow layer height of 0.1 m. The initial snow depth in the ablation zone is kept closest to the
244 observations made every November, corresponding to the snow depth measurement at AWS-L. Above
245 5750 m a.s.l., the model is initialised with a snow depth that increases by 20 cm per 100 m with altitude,
246 starting at 50 cm on 1 November at 5750 m a.s.l. (Table 2). This assumption is essential because it ensures
247 that there is always snow in the accumulation zone for the simulations. Even though annual observations
248 in November show that the snow line is always lower than 5750 m a.s.l., which is in line with this

249 assumption, the altitudinal gradient is not verifiable in the field. The snow depth in the accumulation zone
250 is probably greater than that used for the initialisation, as the firn-ice interface is several metres below the
251 glacier surface. However, for modelling purposes, the initial snow depth within this zone is of minimal
252 concern as accumulation consistently outweighs ablation, and the snow depth gradually synchronises with
253 the ongoing snowfall.

254 **4.2 Optimisation**

255 SEB models are sensitive to the choice of parameter sets (e.g., Zolles and others, 2019). Consequently,
256 model parameters need to be calibrated, and the model's ability to reproduce the glacier surface mass
257 balance needs to be evaluated. We optimise the model following a multi-objective optimisation procedure
258 using forcing data measured at AWS-L between 1 November 2018 and 31 October 2019, the mass balance
259 year with the least gaps and the most reliable dataset. The optimisation is performed based on the
260 maximum amount of data available i.e., observed albedo, surface temperature calculated from LWout
261 using the Stefan-Boltzmann equation with a surface emissivity of 0.99 (Blau and others, 2021), and point
262 mass balance at AWS-L (Table 2).

263 *4.2.1 Parameters*

264 There are many parameters in COSIPY and the eight important ones are listed in Table 3. To identify the
265 most sensitive ones among this set, we conducted 108 manual model runs at a point-scale, specifically at
266 AWS-L. In these runs, we alternatively and randomly explored various values for selected sensitive
267 parameters, focusing on five parameters related to albedo and three associated with roughness lengths.
268 This rigorous testing encompassed a plausible range of values, allowing us to qualitatively assess their
269 impact on the model's outcomes. These ranges of albedo parameters and roughness lengths are taken
270 from Mölg and others (2012). As we only have one level of wind speed measurement at AWS-L, roughness
271 lengths cannot be directly calculated at this site. Notably, the roughness lengths exhibited lower sensitivity
272 compared to the albedo parameters, which were identified as the most sensitive (in bold in Table 3). These
273 albedo parameters are known sensitive parameters for energy balance studies (e.g., Zolles and others,
274 2019). We then optimise these five parameters following the procedure described in section 4.2.2 starting
275 from a plausible range of values taken from the literature (Mölg and others, 2012; Zolles and others, 2019).
276 All other parameters are taken from the default settings, except those listed in bold in Table 3, that are
277 optimised.

278 “Table 3 near here”

279 4.2.2 Multi-objective optimisation

280 Multi-objective optimisation is a calibration method that enables the possibility of more than one optimal
281 solution and provides a way to evaluate a variety of parameter sets (Yapo and others, 1998; Rye and
282 others, 2012; Zolles and others, 2019). The multi-objective approach can be expressed as:

$$\text{minimise } \{f_1(\theta), f_2(\theta), \dots, f_n(\theta)\} \quad (7)$$

283 where $f_1(\theta), f_2(\theta), \dots, f_n(\theta)$ are n objective functions of model realisations of parameter sets θ . The
284 optimisation process combines multiple objectives into a single ideal through scalar aggregation. For this,
285 a weighted sum ($f_{agg}(\theta)$) is applied to find the minimum aggregate of different single objectives (Rye and
286 others, 2012):

$$\text{minimise } f_{agg}(\theta) = \{w_1 f_1(\theta), w_2 f_2(\theta), \dots, w_n f_n(\theta)\} \quad (8)$$

287 where w is the weight applied to all single objectives based on their performance and the arguments of
288 the aggregating functions to obtain the Pareto solution (Pareto, 1971). With the multiple single objective,
289 the selection of Pareto solution and multi-objective is more precise. Here, the multi-optimisation is done
290 based on three objective metrics that compare the observation at AWS-L and model outputs:

$$f_1(\theta) = \left[\frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \right]^2 \quad (9)$$

$$f_2(\theta) = \frac{1}{N} \left| \sum_{i=1}^N (y_i - x_i) \right| \quad (10)$$

$$f_3(\theta) = |(MB_{obs} - MB_{mod})| \quad (11)$$

291 where f_1 is the coefficient of determination (r^2) between the observed (x_i) and modelled (y_i) values of
292 albedo and surface temperature (T_s), f_2 is the mean absolute error (MAE) between the observed (x_i) and
293 modelled (y_i) values of both variables and f_3 is the absolute error (AE) between observed (MB_{obs}) and
294 modelled (MB_{mod}) point mass balances.

295 “Figure 3 near here”

296 The simplest way to calibrate the model is to optimise the different objective functions for four study
297 periods (4 years x 3 objective functions = 12 performances). This approach results in a large range of
298 uncertainty with many sensitive parameters for different mass balance years. Similarly, the set of
299 parameters optimised for one period may not perform better in another period, resulting in higher
300 uncertainty (Soon and Madsen, 2005). However, by simulating Pareto solutions for individual mass balance
301 years and evaluating the objective functions over the other years, it is possible to select the best set of
302 parameters.

303 **4.3 Evaluation of the model at point and distributed scale**

304 First, we optimise the five sensitive model parameters highlighted in Table 3 at AWS-L for the 2018/19
305 period. Second, we evaluate the model performance at point scale at AWS-L site for the other three mass
306 balance years, systematically comparing measured and simulated albedo, surface temperature and point
307 mass balance. Third, we run the model in a spatially distributed way and similarly evaluate it at point scale
308 at AWS-H site, over the three years of available data (2017-20). Finally, we also compare simulated mass
309 balance to measured surface mass balance at glacier-wide scale for each year between 2016 and 2020.
310 This allows us to test both the spatial and the temporal transferability of the model optimised parameters.

311 **4.4 Sensitivity analysis**

312 Our study aims to evaluate the sensitivity of the surface mass balance to changes in meteorological
313 forcings. In previous studies, the sensitivity to temperature or precipitation is usually assessed by a
314 constant change in temperature (e.g., $\pm 1-2$ °C) or a relative change in precipitation (e.g., $\pm 10-30$ %),
315 keeping all other meteorological variables unchanged at the same time (Kayastha and others, 1999; Mölg
316 and others, 2012; Sunako and others, 2019; Arndt and others, 2021; Srivastava and Azam, 2022; Gurung
317 and others, 2022; Arndt and Schneider, 2023). The main disadvantage of this method, hereafter referred
318 to as the classical method, is that perturbing a single meteorological variable breaks the physical links
319 between the meteorological variables, which is detrimental to the simulation of surface mass balance (e.g.,
320 Prinz and others, 2016; Clauzel and others, 2023). To overcome this issue, a number of methods were
321 developed to perturb meteorological data while preserving the link between variables (Sicart and others,
322 2010; Prinz and others, 2016; Autin and others, 2022). Here we both perturb the meteorological forcings
323 in a classical way and we produce synthetic scenarios, described below (see also Fig. S7 for a flow chart
324 explaining how scenarios are obtained).

325 4.4.1 Classical scenarios

326 For the classical sensitivity analysis method, the scenarios are developed by varying temperature by $\pm 1^\circ\text{C}$
327 and precipitation amount by $\pm 20\%$ for four mass balance years without changing the other meteorological
328 variables. In total, we produce 16 runs ($+1^\circ\text{C}$, -1°C , $+20\%$ and -20% for each of the four years) between
329 2016 and 2020. In order to determine the sensitivity of the mass balance to temperature or precipitation,
330 it is then simply necessary to calculate the average anomaly in the mass balance over the four-year period
331 for each corresponding perturbation.

332 4.4.2 Synthetic scenarios

333 Utilising the initial four-year dataset, we performed a cyclic selection process, systematically considering
334 each month of the year commencing with November and concluding in October of the subsequent year.
335 During each cycle, we alternately chose data from the unaltered original dataset and data from the
336 warmest, coldest, wettest, or driest month within the four-year period (2016-20). This process allowed us
337 to generate synthetic annual datasets at an hourly resolution. By this way, we create 180 one-year-long
338 synthetic meteorological series, exploring a wide range of climatic variability from very warm to very cold
339 conditions, and from very dry to very wet conditions (see details below). For each scenario, for each
340 month, we keep original hourly data and we only shuffle the months from different years with each other.
341 In this way, both the physical integrity between meteorological variables and the weather conditions with
342 respect to the time of the year are preserved.

343 First, the four most extreme synthetic scenarios are developed by making one-year long series of hourly
344 forcing data that contain the most extreme months among the four years of data. For instance, the wet
345 scenario (hereafter referred as We_We) is obtained by combining the wettest (We) months: if November
346 2017 is the month with the maximum monthly amount of precipitation among the four months of
347 November of the 2016-20 series, all hourly forcing data from November 2017 are selected in scenario
348 We_We; then if December 2019 is the wettest of the four December months, then hourly data from
349 December 2019 will be selected as the second month of scenario We_We; etc. until October. In this way
350 the wet scenario We_We combining the hourly data of all meteorological variables from the 12 months
351 with the maximum monthly amount of precipitation is created. Similarly, we combine the hourly data of
352 all meteorological variables from the 12 driest months to create the dry scenario (D_D), or from the 12
353 warmest months to create the warm scenario (Wa_Wa), or from the 12 coldest months to create the cold
354 scenario (C_C).

355 Second, starting from these four extreme scenarios referred hereafter as baseline conditions, we also
356 create 48 additional scenarios by modifying some specific seasons. For instance, we keep the conditions
357 of the wet scenario We , except during one season, let's say the monsoon, where we decide to take the
358 conditions of the warm scenario Wa . The four considered seasons are winter (win), pre-monsoon (pre),
359 monsoon (mon), and melting season ($melt$). We decide not to consider the post-monsoon which is not
360 critical for the glacier mass balance because there is usually neither any large precipitation nor any large
361 melt but we prefer to introduce a six-month long melting season which we suspect to be more critical to
362 control the glacier mass balance. This melting season covers half of the year from May to October, the
363 only months where significant melt is observed in the field. The synthetic scenarios follow the naming
364 convention AB_x , where A is the climate baseline coming from the four extreme scenarios, so A is either
365 We , D , C , or Wa , B characterizes the conditions of the modified season i.e., B is also either We , D , C , or Wa
366 and X refers to the season that has been modified to create the additional scenario, so X is either win , pre ,
367 mon , or $melt$. In case of the specific example described above, the scenario is named We_Wa_{mon} which
368 means that the dataset is one year long, using hourly forcing data from the wet scenario except during the
369 monsoon where the warmest months are selected. A can take 4 values, B can take 3 values and X can take
370 4 values (the number of values for B cannot be similar to that of A , otherwise we define one of the extreme
371 scenario), resulting in a total of $4 \times 3 \times 4 = 48$ scenarios.

372 Similarly, we also mix the original unshuffled data (U) from each year of the study period with extreme
373 months. U can be alternatively 2016/17, 2017/18, 2018/19 or 2019/20 respectively referred as 2017, 2018,
374 2019 or 2020. These scenarios follow the same naming convention, with U being an additional value for A
375 and B . For example, the scenario 2018_Wa_{mon} corresponds to the unchanged original data of the year
376 2017/18, except during the monsoon where data from the warmest months are selected. We obtain here
377 $4 \times 4 \times 4 = 64$ scenarios. Similarly, D_2020_{melt} corresponds to the driest months, where months of the melting
378 season have been replaced by the original 2019/20 data. Again, we obtain here $4 \times 4 \times 4 = 64$ scenarios. In
379 total, we have $4 + 48 + 64 + 64 = 180$ scenarios.

380 For each of these 180 synthetic annual datasets, we calculate the glacier-wide annual mass balance of
381 Mera Glacier using COSIPY and calculate the difference from the mean annual glacier-wide mass balance
382 simulated by COSIPY using the original 2016-20 dataset. We call this difference the mass balance anomaly.
383 Similarly, we have an anomaly for each forcing meteorological variable. We can now derive the mass
384 balance sensitivity to each meteorological variable by fitting a linear regression between the mass balance
385 anomaly and the anomaly of the variable under consideration. The slope of this linear relationship gives

386 the mass balance sensitivity to the given variable. The error bars on these sensitivities for ± 1 °C
387 temperature and ± 20 % precipitation variation have been calculated using the 99 % confidence interval,
388 given by three standard deviations, of this linear regression.

389 5. RESULTS

390 5.1 Optimisation and evaluation

391 5.1.1 Optimisation

392 The point-scale optimisation strategy at AWS-L results in a well identified group of parameter sets (Pareto
393 solutions) that minimise multiple objective functions simultaneously (Fig. 3). The objective functions of
394 each set of original parameters are largely scattered with the range of r^2 and MAE of albedo being 0.06-
395 0.54 and 0.11-0.25, respectively (Fig. 3a). Similarly for surface temperature, r^2 and MAE are in-between
396 0.81-0.92, and 1.37-3.24 °C, respectively (Fig. 3d). The range of AE is 0-3.92 m w.e. for the point mass
397 balance at AWS-L (Fig. 3b,c,e,f). The 200 solutions closest to the utopia point in terms of how well they
398 perform across all objective functions represent the Pareto solutions (Fig. 3: bold black dots). All these
399 multiple Pareto solutions are almost equally good and plausible. The metrics of the Pareto solutions are
400 less scattered than the original ensemble, with the range of r^2 and MAE of albedo being 0.31-0.54 and
401 0.11-0.15 (Fig. 3a), and the range of r^2 and MAE of surface temperature being 0.87-0.92 and 1.58-2.33 °C
402 (Table 4). The range AE is 0-1.28 m w.e. for the point mass balance at AWS-L (Table 4).

403 Since Pareto solutions perform well over all time and space ranges, the best parameter set among these
404 Pareto solutions is then chosen as the optimised set (Table 3). The r^2 and MAE between the observed
405 albedo and that resulting from the selected optimised parameter set are 0.48 and 0.12, respectively;
406 similarly, for surface temperature r^2 and MAE are 0.91 and 1.92 °C, respectively (Fig. 4), and AE for the
407 point mass balance is 0.17 m w.e. This final optimised set of parameters corresponds to a time scaling
408 factor of three days and a depth scaling factor of four centimetres for the albedo model (Oerlemans and
409 Knap, 1998) as well as values of albedo of snow (0.85), firn (0.55) and ice (0.30) similar to the default values
410 used in COSIPY (Table 3).

411 “Table 4 near here”

412 “Figure 4 near here”

413 5.1.2 Glacier-wide simulation of COSIPY

414 The good performance of COSIPY simulations at point scale with the optimal set of parameters does not
415 guarantee the good performance of the distributed simulations that rely on additional hypotheses, such
416 as the meteorological forcing distribution that changes the meteorological forcings even at AWS-L
417 location, because for instance S_{Win} is re-computed at AWS-L based on the slope and the aspect of the
418 considered grid cell. We thus evaluate the distributed COSIPY simulations over the period 2016-20 with
419 the albedo and surface temperature at AWS-L and AWS-H, and with the glacier-wide mass balance. r^2
420 (MAE) for albedo is 0.32 (0.15) and 0.16 (0.14) for the 2016/17 and 2019/20 years at AWS-L, respectively
421 (Fig. S8). At AWS-H, over the three-year period 2017-20, r^2 for albedo and surface temperature are 0.50
422 and 0.92 respectively, and the mean AE for 2016-20 at AWS-H is only 0.15 ± 0.14 m w.e.. The surface
423 temperature is always highly correlated with a low bias in both sites (Fig. S8). These metrics are close to
424 the ones from point-scale simulations.

425 “Figure 5 near here”

426 Additionally, we compare the observed and simulated surface point and glacier-wide mass balances. The
427 simulated point surface mass balances match well with the in-situ measurements obtained at stakes for
428 all the four years (Fig. 5 and 6). The location of the equilibrium line altitude is well represented in COSIPY
429 simulations and the general shape of the dependency of the surface point mass balance on elevation is
430 satisfyingly reproduced (Fig. 5). The glacier-wide mass balance from the model is the mean value from all
431 51 individual grid cells and it is compared to the in-situ glacier-wide mass balance taken from Wagnon and
432 others (2021). Over the four year period, the mean observed glacier-wide in-situ mass balance is $-0.74 \pm$
433 0.18 m w.e. a^{-1} (Table 2) and the simulated mass balance is -0.66 m w.e. a^{-1} with a standard deviation of
434 ± 0.26 m w.e. a^{-1} . The largest difference between the observed and modelled glacier-wide mass balance
435 happens in 2019/20, with the simulated mass balance being 0.22 m w.e. less negative than the observed
436 one (Fig. 5).

437 “Figure 6 near here”

438 5.2 SEB and mass balance components

439 5.2.1 Seasonal and annual energy balance components

440 Fig. 7 shows the monthly glacier-wide surface energy and mass balance components at Mera Glacier for
441 the period 2016-20, and Fig. S9-S16 are maps of the glacier, showing the distributed annual energy and
442 mass fluxes for each year of the study period. SWnet is the primary energy source available at the surface
443 throughout the year, the second energy source being the QS, that is significant only between November
444 and March. Along the year, SWin is controlled by the position of the sun responsible for the potential SWin
445 and also by cloudiness, explaining why it decreases from 274 W m⁻² in the pre-monsoon to 195 W m⁻²
446 during the monsoon (Table 5). Similarly, SWnet decreases from 83 W m⁻² during the pre-monsoon to 61
447 W m⁻² during the monsoon because of SWin reduction rather than change in albedo (glacier-wide values
448 of 0.71 during the pre-monsoon and 0.70 during the monsoon). The change in air temperature and water
449 vapour (moisture) is responsible for a strong increase of LWin from the pre-monsoon (217 W m⁻²) to the
450 monsoon (296 W m⁻²), the only season when LWin nearly counterbalances the LWout.

451 The total energy intake at the surface is highest and almost similar during the pre-monsoon (496 W m⁻²)
452 and the monsoon (491 W m⁻²) (Table 5). However, the net all-wave radiation, calculated as the sum of
453 SWnet and LWnet, is 32 W m⁻² during the pre-monsoon and 20 W m⁻² higher during the monsoon. This
454 indicates that the change in cloud cover and atmospheric condition has a relatively minor effect on the
455 total energy absorbed at the glacier surface, but does impact the net all-wave radiation. In the pre-
456 monsoon, this net all-wave radiation is equally compensated by QL and QM (~ -16 W m⁻² each). During the
457 monsoon, LWnet and QL are both reduced or close to zero leaving all the energy available for melt with
458 an average energy value of -43 W m⁻². The contributions of QS and QC are always low during the pre-
459 monsoon and the monsoon, while the QR is negligible all the time.

460 The energy balance components vary across different glacier areas; they are analysed in the ablation area
461 at AWS-L and in the accumulation area at AWS-H. When considering the annual means, the magnitudes of
462 SWnet and QM are higher at AWS-L (93 and -34 W m⁻², respectively) than at AWS-H (61 and -15 W m⁻²,
463 respectively). LWnet, QL, and QS exhibit similar annual means throughout the year at both sites. At AWS-
464 L, SWnet remains similar during the pre-monsoon (87 W m⁻²) and the monsoon (88 W m⁻²) because the
465 decrease in SWin (287 W m⁻² in the pre-monsoon and 201 W m⁻² in the monsoon) is compensated by a
466 decrease in albedo (0.70 in the pre-monsoon and 0.56 in the monsoon). The albedo remains high at AWS-
467 H during the whole year, and there is thus a decrease of SWnet in the monsoon (43 W m⁻²) compared to
468 the pre-monsoon (76 W m⁻²). The variation of LWnet at AWS-L and AWS-H is rather small as the difference
469 between LWin and LWout remains similar. Comparing both sites, QL remains rather similar during all
470 seasons. QM dominates QL all year round except during the winter at AWS-L, but at AWS-H, QL always

471 dominates QM, except during the monsoon. QS is significant only during the cold months of the winter
472 and the post-monsoon, with a similar magnitude whichever the location. QC is positive and rather small
473 ($<5 \text{ W m}^{-2}$, slightly higher during the post-monsoon) all year round except during the monsoon at AWS-L
474 where it is slightly negative (Table 5).

475 “Table 5 near here”

476 “Figure 7 near here”

477 *5.2.2 Seasonal and annual mass balance components*

478 Table 6 lists the annual and seasonal mass balance components of Mera Glacier. After the direct
479 accumulation (through snowfalls) and surface melt on Mera Glacier, annual refreezing and sublimation
480 are two major mass balance components, refreezing being even higher than snowfalls. Indeed, at glacier
481 scale, 44 % of the total (surface + sub-surface) melt refreezes annually. The glacier-wide sublimation is -
482 0.15 m w.e. and therefore contributes 23 % of the total mass balance or 6 % of the ablation terms (total
483 melt + sublimation).

484 Looking at seasonal scale, pre-monsoon and monsoon are important seasons in terms of mass balance
485 processes, as more than 86 % of solid precipitation falls and 84 % of annual melt happens from March to
486 September. However, post-monsoon is not completely negligible in terms of melt (-0.30 m w.e. or 14 % of
487 the annual melt). This melt is almost equal to the surface mass balance (-0.17 m w.e.) due to the limited
488 magnitude of the other processes, and in particular the limited refreezing in the snow free areas of the
489 glacier. The winter is characterized by limited mass balance processes, with approximately 11 % of the
490 annual solid precipitation and 2 % of the annual total melt (Table 6).

491 At glacier scale, the total melt (-0.42 m w.e.) and sublimation (-0.05 m w.e.) during the pre-monsoon are
492 balanced by the refreezing (0.30 m w.e.) and snowfall (0.14 m w.e.), leading to a near zero surface mass
493 balance (Table 6). The glacier-wide total melt during the monsoon is -1.42 m w.e., which is higher at AWS-
494 L (-2.15 m w.e.) and lower at AWS-H (-0.99 m w.e.). Depending on the presence and the state of a
495 snowpack (snow depth, density and temperature), melt water refreezes below the surface. Glacier-wide
496 refreezing is 0.49 m w.e. during the monsoon, it is lower at AWS-L (0.19 m w.e.) where ice is often exposed
497 at the surface, and higher at AWS-H (0.70 m w.e.) where there is always a snowpack with negative
498 temperature. The refreezing preserves 35 % (0.49 m w.e) of the total glacier-wide melt during the
499 monsoon; its relative contribution is higher at AWS-H (71 %) than at AWS-L (9 %).

500 The annual glacier-wide sublimation is -0.15 m w.e. and is nearly identical at both AWSs (-0.16 and -0.15
501 mm w.e. at AWS-L and AWS-H, respectively; Fig. S6). Most of the sublimation (93 % glacier-wide) happens
502 outside the monsoon, when cold, dry and windy conditions prevail. Wind is not spatially distributed in our
503 simulations, leading to rather homogeneous sublimation across the glacier. There are few exceptions, like
504 a slightly higher sublimation in winter at AWS-L (-0.07 m w.e.) than at AWS-H (-0.05 m w.e.) due to higher
505 roughness length linked to the surface state (exposed ice at AWS-L versus snow at AWS-H) and to the
506 mixing ratio that depends on the air temperature. Due to the lower wind speed, sublimation is insignificant
507 at both AWS sites during the monsoon (Table 6).

508 “Table 6 near here”

509 **5.3 Mass balance sensitivity to meteorological forcings**

510 *5.3.1 Link between meteorological forcing anomalies and mass balance anomalies*

511 In order to analyse the link between the different input meteorological variables and the outputs from the
512 simulations, we calculate anomalies of each variable from the 180 scenarios by subtracting the mean of
513 the original unshuffled 2016-20 simulations (Fig. 8). From all synthetic scenarios, the magnitude of
514 variation of air temperature is nearly ± 1 °C, whereas for precipitation, it varies from -35 to +55 % annually.
515 The anomalies of relative humidity (± 5 %) and incoming radiations (± 10 W m⁻²) are rather narrow. There
516 are many significant correlations ($p < 0.001$) between the anomalies of the different variables, suggesting
517 that they are likely to be physically related to each other. On an annual scale, the anomaly of air
518 temperature correlates significantly and positively with the wind speed and the air pressure anomalies,
519 and negatively with the precipitation and relative humidity anomalies. Regarding radiations that are
520 expected to have an impact on the mass balance, the SWin anomaly correlates significantly and negatively
521 with the relative humidity, the precipitation and the LWin anomalies. The LWin anomaly correlates
522 significantly and positively with the relative humidity and the precipitation anomalies, and negatively with
523 the SWin and wind speed anomalies.

524 The mass balance anomaly correlates significantly with the anomalies of every meteorological variables
525 except SWin (Fig. 8). The correlations between mass balance anomalies and those of LWin, atmospheric
526 pressure, or wind speed are moderate but significant, positive in case of LWin, and negative for the other
527 variables. The correlation between mass balance anomalies and air temperature is significant and highly

528 negative ($r = -0.79$). Mass balance anomalies are highly and positively correlated with those of precipitation
529 ($r = 0.87$) and relative humidity ($r = 0.84$; Fig. 8).

530 “Table 7 near here”

531 “Figure 8 near here”

532 *5.3.2 Mass balance sensitivity to air temperature and precipitation*

533 From the classical method, we find that perturbing the temperature by +1 (-1) °C leads to a change in
534 glacier-wide mass balance of -0.61 (+0.41) m w.e. (Table 7). A -20 (+20) % change in precipitation leads to
535 a -0.79 (+0.48) m w.e change in glacier-wide mass balance (Table 7). With the synthetic scenario method,
536 we find that a temperature change of +1 (-1) °C leads to a glacier-wide mass balance change of $-0.75 \pm$
537 $0.17 (+0.93 \pm 0.18)$ m w.e., and a -20 (+20) % change in precipitation results in a mass balance change of -
538 $0.60 \pm 0.11 (+0.52 \pm 0.10)$ m w.e. Due to the physical link between variables, and in particular the negative
539 correlation between temperature and precipitation, we find that the sensitivity of mass balance to
540 temperature is significantly higher when calculated from synthetic scenarios than from the classical
541 method, especially in case of cooling. For precipitation, it is significantly reduced in case of a precipitation
542 deficit but almost unchanged in case of an increase.

543 This synthetic scenario approach allows to derive mass balance sensitivities to any meteorological variable,
544 as long as a significant correlation exists between the anomalies of mass balance and the variable under
545 consideration. In particular, as we find a high correlation between mass balance and relative humidity
546 anomalies, we can assess also the mass balance sensitivity to this variable: a -4 (+4) % change in RH
547 corresponds to a -1.02 (+1.38) m w.e. change in mass balance. However, we caution on the interpretation
548 of these correlations, as most of the input meteorological variables covary, the correlations may be
549 significant, but they do not show a causal relationship, that needs to be discussed in the light of the
550 knowledge of the processes (see discussion section).

551 “Figure 9 near here”

552 *5.3.3 Specific meteorological conditions leading to the most positive/negative mass balances*

553 From the synthetic scenarios, the annual glacier-wide mass balances range from -1.76 to 0.54 m w.e. (Fig.
554 9 and Fig. S17), which is a wider range than the historically measured glaciological mass balance since 2007

555 (min = -0.92 m w.e. in 2017/18 and max = 0.26 m w.e. in 2010/11; Wagnon and others, 2021). The
556 simulated annual mass balances are compared with the original mean annual glacier-wide mass balance
557 of -0.66 m w.e. (Table 6) over the 2016-20 study period, referred hereafter as the reference year. Most of
558 scenarios that have warm or dry conditions as a baseline correspond to the first category of scenarios
559 characterised with negative mass balances ranging from -1.76 to -0.81 m w.e. They have a positive SWnet
560 anomaly compared to the reference year (+2 to +17 W m⁻²), associated either with a change in air
561 temperature toward a warming (-0.71 to +1.13 °C) or to a decrease in snowfall (0 to -0.29 m w.e.) or to
562 both, resulting in a low glacier-wide albedo (0.53 to 0.64). With more energy intake, melting is enhanced,
563 and due to the reduced snowfalls, ice is more exposed at the glacier surface favoring runoff, and in turn
564 less than 46 % of this meltwater refreezes, ultimately leading to the most negative glacier-wide mass
565 balances (Fig. S17).

566 The second category of scenarios corresponds to glacier-wide mass balances from -0.80 to -0.25 m w.e.
567 close to that of the reference year. Here, we find scenarios combining a baseline and a seasonal
568 component that would normally lead to opposite mass balance responses such as dry with wet conditions
569 or warm with cold conditions (e.g., Wa_We_{mon}, D_We_{mon}, Wa_We_{win}, D_C_{win}). We also find the majority of
570 scenarios that have the unperturbed data as baseline (Fig. 9 and Fig. S17). The mass balance is affected
571 equally but in an opposite direction by the temperature anomalies (-0.97 and +1.02 °C) and the
572 precipitation anomalies (-0.16 to +0.23 m w.e.). In this category, the refreezing ranges from 37 to 56 % of
573 total melt, which is close to that of the reference year (44 %), and the ranges of SWnet (-8 to +6 W m⁻²)
574 and LWnet (-4 to +3 W m⁻²) anomalies are small (Fig. 8).

575 The third category corresponds to positive or near-balanced glacier-wide mass balances (> -0.25 m w.e.)
576 mostly produced by scenarios with wet or cold baselines. They have temperature anomalies between -
577 1.00 and +0.52°C and precipitation anomalies between -0.04 and +0.45 m w.e. (Fig. 9 and Fig. S17). The
578 higher amount of snowfall increases the accumulation, increases the albedo, and in turn decreases the
579 SWnet (-19 to -4 W m⁻²). In addition, the refreezing is high (46-71 % of total melt). Overall, the scenarios
580 with a wet year baseline always create a mass balance that is close to balance, and specifically, the highest
581 positive mass balance is produced by the wettest conditions all year round (scenario WeWe) (Fig. 9 and
582 Fig. S17).

583 For all scenarios, we find that the mass balance is primarily influenced by the baseline conditions, and not
584 by the seasonal variation. We do not find any season that has an influence larger than the other ones (Fig.

585 S17). In particular, when we look at the scenarios of unperturbed data with seasonal variations, we find
586 that winter seems to have as much influence, if not even more influence, than the other seasons on the
587 mass balance (Fig. S17). This result is rather counter intuitive, as most of the mass balance processes
588 happen in monsoon and pre-monsoon (e.g., Fig. 8).

589 Regarding the classical scenarios, as expected, both -20 % and +1 °C scenarios produce negative mass
590 balances, but less extreme than the dry and warm synthetic scenarios. In contrast, both +20 % and -1 °C
591 classical scenarios are characterised by near-balanced mass balances, far from the positive glacier-wide
592 mass balances obtained with the wet and cold scenarios. The energy and mass fluxes in the classical
593 scenarios are also comparable to those of the synthetic scenarios. The LWnet is similar in all classical
594 scenarios. However, SWnet is 13 W m⁻² higher and refreezing is 25 % lower in the -20 % precipitation and
595 +1 °C scenarios than those in the +20 % and -1 °C scenarios.

596 **6. DISCUSSION**

597 **6.1 Surface energy and mass balance components of Mera Glacier, and comparison with other similar** 598 **studies in HKH**

599 It is difficult to compare different glacier surface energy and mass balance analyses rigorously across the
600 same region because study periods are never similar. Moreover, temporal (multi-annual, annual, or
601 seasonal) and spatial (point scale or glacier-wide) resolutions are often different and not comparable
602 (Table 8). In HKH region, the seasonality of precipitation has a strong impact on the energy and mass
603 balance components. In the western Himalaya, the winter precipitation dominates the annual
604 accumulation, and sublimation strongly contributes to the ablation processes (Mandal and others, 2022;
605 Srivastava and Azam, 2022; Oulkar and others, 2022). In the Central Himalaya, the glaciers are summer
606 accumulation type with significant longitudinal variability in mean summer temperature, which has the
607 strongest impact on mass balance sensitivity (Sakai and Fujita, 2017). Still, precipitation, which depends
608 on the monsoon intensity and duration, is a key variable governing the energy and mass balance of glaciers
609 through the albedo effect and its control on the refreezing (Shaw and others, 2022).

610 The pattern of surface energy and mass balance over the whole Mera Glacier confirms what has already
611 been observed on other glaciers of HKH (Table 8, which is an update of Table 4 of Azam and others, 2014,
612 with the location of glaciers given in Fig. S18). Overall, the radiative fluxes strongly dominate the SEB, and
613 control the amount of energy available for melt (Fig. 7). Between the pre-monsoon and the monsoon, with

614 the gradual establishment of the dense cloud cover typical of this latter wet and warm season, incoming
615 shortwave radiation gradually loses intensity, replaced at the same time by increasing incoming longwave
616 radiation, resulting in a constantly high amount of radiative energy available for the glacier. This amount
617 of energy decreases with elevation mainly because albedo is higher in the accumulation zone, where ice
618 is never exposed at the surface. Turbulent fluxes are only significant out of the monsoon, contributing to
619 bring additional energy toward the surface by sensible heat flux (Fig. 7). Contrary to glaciers in the western
620 Himalaya where resublimation occasionally occurs during the monsoon (Azam and others, 2014), on Mera
621 Glacier, the latent heat flux is always negative which means that sublimation is a non-negligible process of
622 mass loss, especially during seasons with strong wind (winter and post-monsoon), like on Zhadang and
623 Parlung No 4 glaciers on the southeast Tibetan Plateau (Mölg and others, 2012; Sun and others, 2014; Zhu
624 and others, 2018). On Mera Glacier, glacier-wide sublimation accounts for 23 % of the glacier-wide mass
625 balance (Table 6), in agreement with previously published values in the Himalaya (e.g., Gurung and others,
626 2022; Srivastava and Azam, 2022) or lower than that of Shruti Dhaka Glacier in the western Himalaya (55
627 %; Oulkar and others 2022). However, this value on Mera Glacier is under-estimated because wind speed
628 strongly increases with elevation (Khadka and others, 2022), an effect that has not been taken into account
629 in our study. Refreezing is also an important process, because at annual and glacier-wide scales, as much
630 as 44 % of meltwater refreezes on Mera Glacier, with a clear increase of this percentage with elevation
631 (Table 6). This finding is again in agreement with other studies in the region (Stigter and others, 2018;
632 Kirkham and others, 2019; Bonekamp and others, 2019; Veldhuijsen and others, 2022; Arndt and
633 Schneider, 2023). It is noteworthy mentioning that sublimation and refreezing are two important
634 processes for glaciers in this region but they are not included in empirical degree-day models (Litt and
635 others, 2019). Moreover, refreezing is always parameterised in a more or less sophisticated way in physical
636 snowpack models, but field experiments are crucially missing to evaluate the accuracy of such
637 parameterisations.

638 “Table 8 near here”

639 **6.2 Mass balance sensitivity to different meteorological variables and comparison with other studies in** 640 **HKH**

641 *6.2.1 Mass balance sensitivity of Mera Glacier to meteorological variables*

642 Estimating the sensitivity of glacier mass balance to a change in temperature and/or precipitation is a
643 classical problem in glaciology (e.g., Ohmura and others, 1992). Different approaches have been

644 implemented in HKH to assess the glacier mass balance sensitivity at different scales (e.g., Sakai and Fujita,
645 2017; Wang and others, 2019; Arndt and others, 2021; Gurung and others, 2022). However, the classical
646 approach (perturbing temperature and precipitation by certain values or percentages), which involves
647 perturbing individual meteorological variables while keeping others unchanged, has been criticised due to
648 the interconnectedness of these variables (Nicholson and others, 2013; Prinz and others, 2016). For
649 example, changing air temperature directly impacts the water vapor ratio of the atmosphere, which can
650 ultimately affect the turbulent heat fluxes.

651 For Mera Glacier, we find strong correlations among the meteorological variables, which makes difficult
652 to decipher their individual effects on mass balance. Notably, the negative correlation between
653 temperature and precipitation anomalies ($r = -0.56$; slope of the linear relationship: $-0.16 \text{ m w.e. } ^\circ\text{C}^{-1}$) leads
654 to larger mass balance sensitivities to temperature when this relationship is preserved (Table 7). The mass
655 balance sensitivity to SWin is unexpectedly limited ($-0.06 \text{ m w.e. a}^{-1} (\text{W m}^{-2})^{-1}$; $r = -0.22$) due to the role of
656 albedo. Indeed, the correlation between albedo anomalies and mass balance anomalies is very high ($r =$
657 0.97) showing that the surface state, that depends primarily from the amount of snowfalls, is more
658 important than the actual incoming shortwave radiative flux. Despite its direct contribution to the SEB,
659 LWin correlates positively with mass balance due to its strong correlation with precipitation. One limitation
660 of our approach is that we can virtually find sensitivities of the mass balance to any input variable, as long
661 as a correlation exists. For instance, the strong sensitivity to the relative humidity shown in Fig. 8 should
662 not be interpreted as an expected change in mass balance due to a change in relative humidity. Instead it
663 shows that the relative humidity is closely tied to the other meteorological variables, and that
664 meteorological conditions that favor high relative humidity also favor positive mass balances.

665 Another interesting feature is the asymmetry towards negative values in the sensitivities to temperature
666 with the classical method (Table 7). While continental and sub-continental glaciers typically exhibit less
667 sensitivity to negative temperature changes (e.g., Arndt and Schneider, 2023; Wang and others, 2019),
668 maritime glaciers tend to have symmetrical sensitivity, especially when estimated with degree-day models
669 (Wang and others, 2019). However, with the synthetic scenario approach, we find the opposite asymmetry
670 for temperature sensitivity (Table 7), likely due to the correlations between precipitation and temperature.
671 This leads to higher negative mass balances than the simple $+1 \text{ } ^\circ\text{C}$ perturbation (Fig. 8), indicative of the
672 maritime climate setting for Mera Glacier. Regarding precipitation, its sensitivity is asymmetric towards
673 negative values with both methods (Table 7). It is clearly due to albedo feedback effects in the model,

674 which are poorly represented in degree-day models that predict a symmetric sensitivity to precipitation
675 (e.g., Wang and others, 2019).

676 *6.2.2 Mass balance sensitivity comparison with other studies in HKH*

677 The impact of temperature and precipitation changes on mass balance depends on the climate of the
678 region, but it can be attenuated or exacerbated depending on the glacier's morphology and topography
679 (Brun and others, 2019). Contrary to glaciers located in arid cold climates less sensitive to temperature
680 changes (Ohmura and others, 1992), those affected by the Indian summer monsoon, such as Mera Glacier,
681 are sensitive to both temperature and precipitation (Fujita, 2008; Johnson and Rupper, 2020; Arndt and
682 others, 2021). With higher temperature, first less precipitation falls as snow and in turn accumulation is
683 reduced, and second and more important, more shortwave radiation is absorbed through lower albedo
684 leading to enhanced melt (Fujita, 2008). Still the mass balance sensitivity to temperature and precipitation
685 varies among different glaciers. The glacier-wide sensitivity of Mera Glacier to changes in temperature and
686 precipitation is of the same order of magnitude as other glaciers in HKH, even though it is noteworthy to
687 mention that these glacier sensitivities have been assessed through the classical method and in turn are
688 not directly comparable (Fig. 10, Table S3).

689 For instance, on Mera Glacier, with the synthetic scenarios approach, a ± 1 °C temperature perturbation
690 has greater impact than that of a ± 20 % precipitation change, which is mostly the case for glaciers on Fig.
691 10, especially those located in Nepal. However, this pattern differs for glaciers in the Indian western
692 Himalaya, which mostly exhibit lower sensitivities, sometimes higher for precipitation than for
693 temperature like Shruti Dhaka Glacier (Oulkar and others, 2022). Surprisingly, Arndt and Schneider (2023)
694 find extreme sensitivities of glacier-wide mass balances to warming or to increase in precipitation for
695 glaciers in the Central Himalaya (Yala and Halji glaciers) or Nyainqentanglha Range (Zhadang Glacier)
696 compared to what we observe on Mera Glacier, although all these glaciers are submitted to rather humid
697 monsoon dominated conditions.

698 Our approach with the synthetic scenarios does not allow to investigate whether the sensitivity changes
699 linearly. It is well established that the sensitivity to temperature is nonlinear and much higher for larger
700 temperature changes (e.g., Arndt and Schneider, 2023). As we rely only on existing observations, we
701 cannot assess what would be the other meteorological variables in a +2 or +3 °C climate setting. Directions
702 to overcome this issue could be to investigate the links between glaciers' response to synoptic variables
703 (e.g., Mölg and others, 2012; Zhu and others, 2022), to investigate specific monsoon characteristics and

704 their impacts on the mass balance (e.g., Shaw and others, 2022), or to force glacier mass balance models
705 with downscaled global circulation model outputs that preserve the physical relationships between
706 variables (e.g., Bonekamp and others, 2019; Clauzel and others, 2023). Furthermore, the size of the glacier
707 plays a role on its mass balance sensitivity. Glaciers with a higher accumulation area, such as Shruti Dhaka,
708 Trambau, and Mera glaciers, exhibit a lower sensitivity than glaciers whose accumulation zone is strongly
709 reduced, such as Zhadang and Halji glaciers (Zhu and others, 2018; Sunako and others, 2019; Arndt and
710 others, 2021; Srivastava and Azam, 2022).

711 “Figure 10 near here”

712 **6.3 Limitations of our approach**

713 Simulating the distributed surface energy and mass balance of a glacier presents numerous challenges and
714 limitations. One striking example is the relatively large difference between the simulated and observed
715 glacier-wide mass balances for the year 2019/20, where COSIPY simulated mass balance is 0.22 m w.e.
716 larger than the observed one. While we do not have a definitive explanation for such a discrepancy, we
717 can list a number of sources of errors in our approach. Uncertainties arise primarily from (i) the model's
718 process representation, (ii) in-situ data, (iii) their spatial distribution over the glacier area, and (iv) the
719 model's initial conditions.

720 One crucial process in snowpack modelling is the decay of snow albedo over time. COSIPY implements the
721 Oerlemans parameterisation (Oerlemans and Knap, 1998), which has known limitations in certain climate
722 contexts (e.g. Voordendag and others, 2021; Wang and others, 2022). Typically, albedo parameters are
723 fixed or adopted from previous studies using COSIPY or any other energy balance model. However, here,
724 we optimised these parameters at AWS-L before distributing the meteorological forcings. The snow aging
725 and depth scaling factors used in this study fall within the range of commonly used factors (Sauter and
726 others, 2020; Arndt and others, 2021; Wang and others, 2022; Sherpa and others, 2023), but differ slightly
727 from those used in other studies (Sauter and others, 2020; Arndt and others, 2021; Potocki and others,
728 2022). Although the model can accurately predict albedo at a point scale, it is sometimes misrepresented
729 (Fig. S8). The lack of robust parameterisation and uncertainties surrounding the amount of snow deposited
730 on the glacier surface and its redistribution by the wind contribute to this issue.

731 Additionally, refreezing is another poorly constrained process. In HKH region, refreezing has primarily been
732 assessed using models (Steiner and others, 2018; Kirkham and others, 2019; Saloranta and others, 2019;

733 Veldhuijsen and others, 2022), rather than snowpack temperature and density measurements, as is done
734 in the seasonal snowpack (e.g. Pfeffer and Humphrey, 1996). Specific experiments should be conducted
735 to evaluate the effects of refreezing on glaciers, particularly to determine whether meltwater percolates
736 below the previous year's horizon and contributes to internal accumulation. Additionally, COSIPY lacks
737 certain processes, such as wind erosion and wind-driven snow densification. These processes can be very
738 important, particularly during the post-monsoon and winter seasons due to the strong winds at high
739 elevations (Litt and others, 2019; Brun and others, 2023; Sherpa and others, 2023). During November field
740 campaigns, wind erosion features such as sastrugis are frequently observed in the accumulation area of
741 Mera Glacier.

742 Distributing meteorological data over a rough terrain is one of the most challenging task. The spatial
743 distribution of the meteorological data based on a single vertical gradient throughout the year is somehow
744 questionable (section 3.2). Additionally, applying a vertical gradient to distribute meteorological variables
745 weakens the physical links between them, as already discussed in the sensitivity analysis. For the study
746 period and the range of elevation of Mera Glacier, the vertical gradients for temperature, relative
747 humidity, and LWin exhibit high variability (Fig. S3). To derive the gradients, we selected the year with the
748 minimum gaps at AWS-H despite a large portion of the data at AWS-L being reconstructed at that time.
749 Additionally, the T/RH sensor was not artificially ventilated at AWS-H, which introduces some
750 measurement uncertainty. Therefore, we tested a range of gradients to distribute T [-6.5 to -4.2 °C km⁻¹]
751 and RH [-25 to 0 % km⁻¹]. In alpine environments, LWin provides large amounts of melt energy, especially
752 in the ablation area (through valley side walls) and can dominate the energy balance of snow or glacier
753 surfaces. LWin is highly sensitive to surface melt when the atmosphere is saturated, particularly during the
754 monsoon (Sicart and others, 2010). On Mera Glacier, the daily LWin gradient as a function of elevation
755 varies greatly from day to day and season to season, with a minimum of -41 W m⁻² km⁻¹ observed during
756 the monsoon. Various LWin gradients have been tested within the [-40 to 0 W m⁻² km⁻¹] range and
757 optimised to -25 W m⁻² km⁻¹ (Table S2). In conclusion, there is no ideal method for spatially distributing
758 meteorological variables on a complex glacier surface that extends over a large altitudinal range. On Mera
759 Glacier, two on-glacier AWSs enable us to provide reasonable vertical gradients of temperature, relative
760 humidity, and longwave incoming radiation. These gradients are highly variable in time and likely in space
761 as well. To maintain simplicity in our modelling approach, we prefer to use a single gradient for these
762 variables instead of using temporally or spatially variable gradients. The use of variable gradients would
763 require a denser observation network than the two AWSs we currently have. Additionally, using different
764 gradients would alter the set of optimised parameters without necessarily affecting the final results.

765 The depletion of precipitation as a function of elevation in the upper Khumbu region is still a matter of
766 debate due to the lack of reliable data at high elevations, difficulties in correcting the undercatch of snow,
767 and comparing precipitation records obtained with different devices (Salerno and others, 2015; Perry and
768 others, 2020). On the Mera catchment, there is only one all-weather rain gauge located at 4888 m a.s.l.,
769 just below the glacier. The precipitation recorded at this station is considered constant across the glacier
770 surface. The distribution of precipitation is clearly more complex due to the rough topography (Immerzeel
771 and others, 2014) and snow redistribution by wind. We prefer not to apply any vertical precipitation
772 gradient, as it would complicate the modelling and increase equifinality issues, as with other
773 meteorological variables. Similarly, applying a vertical gradient of wind speed based on records at AWS-L
774 and AWS-H is not recommended due to the site-specific nature of the records (Shea et al., 2015).
775 Therefore, like precipitation, wind speed is assumed to be constant and equal to the wind velocity at AWS-
776 L across the glacier. Given that wind speed mainly affects turbulent fluxes, which are of secondary
777 importance compared to radiative fluxes, any assumptions made only impact the total sublimation and its
778 spatial distribution.

779 To initialise the model, the snow depth on each grid cell at the start of the simulation, specifically on 1
780 November, must be known. As field trips typically occur around mid-November each year, and November
781 is a relatively dry month with minimal melting, snow depth initialisation is based on direct observations
782 performed around 15 days later than the initialisation date. However, this method is not entirely error-
783 free as not all grid cells are surveyed and precipitation or wind drift may have occurred between 1
784 November and the survey date. Such error may have large impacts over the entire simulation period when
785 a surface is initially recognized snow free although it is not, or vice versa.

786 In COSIPY, between 10 and 20 % of SWnet penetrates below the surface and is partly reflected at different
787 depths within the snowpack or the ice (van den Broeke and Bintanja, 1995). This amount of shortwave
788 radiation is not accounted for in the outtake term Q_{out} of Table 5, which explains why Q_{in} and Q_{out} do
789 not exactly compensate each other. Therefore, the energy balance is not perfectly closed in the COSIPY
790 model (e.g., Arndt and others, 2021).

791 **7. CONCLUSION**

792 The COSIPY energy and mass balance model was applied to Mera Glacier in the Central Himalaya, Nepal.
793 In-situ meteorological datasets were used, recorded both on and off the glacier at different elevations
794 ranging from 4888 m a.s.l. (for precipitation) to 5770 m a.s.l. The data was collected from 1 November

795 2016 to 31 October 2020 at an hourly time step. The model parameters were optimised at the point scale
796 using data from AWS-L at 5360 m a.s.l. over the year 2018/19. A multi-objective optimisation was
797 employed, and the albedo aging and snow depth factors were selected as the most sensitive parameters
798 and then calibrated. The model was validated both at the point scale with multiple AWS measurements
799 (albedo and surface temperature recorded at 5360 and 5770 m a.s.l.) and at the glacier scale with annual
800 point mass balance measurements obtained at various elevations. The validation indicates that the model
801 effectively simulates the annual glacier-wide mass balance of Mera Glacier, with a simulated mean value
802 of $-0.66 \text{ m w.e. a}^{-1}$ for 2016-20 compared to the observed value of $-0.74 \text{ m w.e. a}^{-1}$.

803 The SEB over Mera Glacier is dominated by radiative fluxes, which are responsible for almost all the energy
804 available during the monsoon, the main melting season. From the pre-monsoon to the monsoon, with the
805 increasing cloudiness, incoming shortwave radiation gradually decreases in intensity in favor of incoming
806 longwave radiation thus maintaining a large amount of energy available for melt. Turbulent fluxes are only
807 significant outside the monsoon. The sensible heat is an energy source at the surface whereas the latent
808 heat flux is always negative. Sublimation is therefore an important ablation process, especially during the
809 windy months of the post-monsoon and winter. Annually and at glacier scale, refreezing is a crucial
810 process, because on average 44 % of meltwater refreezes, with a large positive gradient with altitude.

811 To investigate the sensitivity of glacier mass balance to changes in temperature and precipitation, we
812 generated 180 different scenarios by shuffling our four-year dataset. We aggregated warm, cold, dry, or
813 wet months alternatively, depending on the seasons. These scenarios allowed us to explore a wide range
814 of conditions, from very dry and warm to very cold and wet. As a result, the glacier-wide mass balances of
815 Mera Glacier ranged from -1.76 to $+0.54 \text{ m w.e. a}^{-1}$. The mass balance sensitivity to meteorological
816 variables can be quantified from these synthetic scenarios. A temperature change of $+1 \text{ }^{\circ}\text{C}$ ($-1 \text{ }^{\circ}\text{C}$) results in
817 a change of -0.75 ± 0.17 ($+0.93 \pm 0.18$) m w.e. in glacier-wide mass balance, while a precipitation change
818 of $+20 \%$ (-20%) results in a change of $+0.52 \pm 0.10$ (-0.60 ± 0.11) m w.e. in mass balance. Compared to
819 the classical approach, the sensitivity of the mass balance is more pronounced with temperature, but not
820 significantly different with precipitation. Similar to other glaciers with summer accumulation, Mera Glacier
821 is highly sensitive to both temperature and precipitation.

822 To evaluate the mass balance sensitivity to any meteorological variables, it is advantageous to generate
823 scenarios based on real in-situ data. This not only helps to quantify these sensitivities more accurately but
824 also to explore the inter-relationships between variables. Our study demonstrates, for instance, that

825 temperature has a negative correlation with precipitation. Therefore, classical sensitivity approaches that
826 alter temperature and precipitation independently are likely to be biased. It is worth noting that long-term
827 high-quality datasets are necessary to apply such synthetic method approach. We are lucky enough to
828 have a long-term dataset on Mera Glacier, but we encourage to maintain and develop similar
829 observational networks on other glaciers in HKH, in order to compare glaciers and to assess whether
830 sensitivities obtain locally on a glacier can be extrapolated regionally. Currently, we cannot be certain that
831 this sensitivity is not specific to Mera Glacier.

832 Like any modelling, our approach has limitations inherent to the model used, the quality of input data,
833 their spatial distribution, and the choice of initial conditions. These limitations are difficult to quantify, but
834 our method allows us to provide an accuracy range for the results based on a 99 % confidence interval. A
835 potential next step in this study would be to conduct an uncertainty analysis to assess the weight of all
836 potential errors related to the model and data, as well as to evaluate the equifinality of the results.
837 However, this is beyond the scope of the present study. Nonetheless, such an analysis would be valuable,
838 as many modelling approaches encounter similar issues.

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853 **Author contribution**

854 PW initiated and DS supported the monitoring program on Mera Glacier. PW, FB and AK jointly designed
855 the study. AK performed the analysis, under the supervision of FB and PW, with the support of TS. AK
856 prepared all the figures and wrote the first draft of the manuscript. AK, FB and PW jointly developed the
857 discussion and interpretation of the results. All authors participated in some field campaigns, and
858 contributed to the analysis and to the paper writing.

859 **Data availability**

860 The data utilised in this study are accessible through the GLACIOCLIM database
861 (<https://glacioclim.osug.fr/Donnees-himalaya>). The model outputs are available at
862 <https://doi.org/10.5281/zenodo.10053093>.

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1048 **List of figure captions**

1049 **Fig. 1.** Map of Mera Glacier showing the network of ablation stakes (blue dots) and accumulation pits (cyan
1050 diamonds). The stake location and number are taken from November 2020. The number of stakes vary
1051 from year to year, due to total excavation, reinstallation at the original location, snow burial or destruction.
1052 The pink stars represent the locations of different AWSs with their respective photos and dates (a. Khare
1053 Geonor, b. Mera La AWS, c. AWS-H, and d. AWS-L). The outline of Mera Glacier is from 2018 with a total
1054 area of 4.84 km², and the background image was acquired by Sentinel-2 on 24 November 2018. Elevation
1055 lines are extracted from the 2012 Pléiades DEM (Wagnon and others, 2021). The inset map gives the
1056 location of Mera Glacier in Nepal (black square) and the glacierised areas from RGI6 (shaded blue areas).

1057 **Fig. 2.** Hourly data from 1 November 2016 to 31 October 2020 of (a) air temperature (T), (b) relative
1058 humidity (RH), (c) wind speed (u), (d) incoming shortwave radiation (SWin), (e) incoming longwave
1059 radiation (LWin) at AWS-L, (f) atmospheric pressure (P_a) at Mera La AWS and (g) precipitation (P) at Khare
1060 Geonor. Orange shaded areas indicate data gaps at AWS-L, which have been filled by Mera La AWS data
1061 using linear interpolation, and the light blue shaded areas in panel (g) visualise the monsoons.

1062 **Fig. 3.** Solution space for the multi-objective optimisation for the period 1 November 2018 – 31 October
1063 2019. One dot represents results obtained with one set of parameters, and bold black and red dots define
1064 the Pareto solution space and optimised solution, respectively. Plots show the scatter plot between a) 1-
1065 r² and MAE from albedo comparison, b) MAE from albedo comparison and AE from mass balance
1066 comparison, c) AE of mass balance comparison vs 1-r² from albedo, d) 1-r² and MAE from surface

1067 temperature comparison, e) MAE from surface temperature comparison and AE from mass balance and f)
1068 AE of mass balance vs $1-r^2$ from surface temperature comparison.

1069 **Fig. 4.** Mean daily snow albedo (top) and surface temperature (bottom) from observation (Obs., black line)
1070 and simulated with COSIPY between 1 November 2018 and 31 October 2019 at AWS-L. r^2 and MAE
1071 represent the correlation coefficient and mean absolute error between the observed and simulated
1072 variables, respectively. The red thick line and the brown thin lines represent the simulated variables using
1073 the final optimised parameter set and using all other solution spaces, respectively.

1074 **Fig. 5.** In-situ (blue dots) and simulated at each grid cell (red dots) point mass balances as a function of
1075 elevation on Mera Glacier for each year of the 2016-20 period. MB is the glacier-wide mass balance
1076 obtained from field measurements (blue text) (Wagnon and others, 2021) and simulated with COSIPY (red
1077 text). Also shown are the hypsometries of Mera Glacier used for in-situ glacier-wide mass balance
1078 calculations (light blue histograms) and for COSIPY (light brown histograms).

1079 **Fig. 6.** Distributed simulated annual mass balance (MB, in m w.e.) for each year of the study period. Also
1080 shown as white circles are the point mass balance observations (ablation stakes and accumulation pits)
1081 with the inside colour corresponding to the respective annual measurement. The glacier outlines (black)
1082 is from Wagnon and others (2021).

1083 **Fig. 7.** Glacier-wide monthly (a) energy fluxes, (b) mass fluxes and (c) mass balance from November 2016
1084 to October 2020 on Mera Glacier (left panels) and mean monthly annual cycle (right panels). SWnet = net
1085 shortwave radiation, LWnet = net longwave radiation, QL = latent heat flux, QS = sensible heat flux, QC =
1086 subsurface heat flux, QR = rain heat flux, QM = available melt energy at the surface, SnowF. = solid
1087 precipitation, Subl. = sublimation, Surf. M. = melt at surface, Sub S. M. = subsurface melt and Refr. =
1088 refreezing. Blue shaded areas visualise the monsoons.

1089 **Fig. 8.** Scatter plot between anomalies of different input variables and glacier-wide mass balance
1090 anomalies for the 180 synthetic runs. Also shown are the Pearson correlation coefficients between the
1091 series of annual anomalies. The black lines represent the linear regressions and the grey shaded areas
1092 indicate the standard error. The anomalies of each variable are calculated by subtracting the mean of the
1093 original unshuffled 2016-20 simulation. (stars represent significance levels, accordingly: * = 0.05, ** = 0.01,
1094 *** = 0.001).

1095 **Fig. 9.** Glacier-wide (a) energy fluxes, (b) mass flux components, and (c) mass balance (MB) from (left
 1096 panels) 12 selected synthetic scenarios (in red, grey, and blue, on the x-axis), as well as (right panels) from
 1097 the four mean classical scenarios (in black) and the reference year (RY, in green, on the x-axis). The results
 1098 from the classical scenarios or the reference year have been averaged over the four years 2016-20. Based
 1099 on the MB results, 12 synthetic scenarios are selected (four corresponding to the most negative MBs, four
 1100 from the middle of the MB set with moderately negative MBs, and four most positive MBs) out of the 180
 1101 scenarios (all visible in Fig S17). The colour code of synthetic scenarios visualises the MB range, from the
 1102 most negative (red), to the most positive (blue), grey being intermediate and moderately negative. 2019
 1103 and 2020 represent the 2018/19 and 2019/20 mass balance years, respectively. SWnet = net shortwave
 1104 radiation, LWnet = net longwave radiation, QL = latent heat flux, QS = sensible heat flux, QC = subsurface
 1105 heat flux, QR = rain heat flux, QM = available melt energy at the surface, SnowF. = solid precipitation, Subl.
 1106 = sublimation, Surf. M. = melt at surface Sub S. M. = subsurface melt and Refr. = refreezing.

1107 **Fig. 10.** Location of glaciers where studies of mass balance sensitivities have been conducted in the
 1108 Himalaya and Tibetan Plateau regions. Each panel gives the mass balance sensitivity to temperature and
 1109 precipitation of each glacier, with the associated reference. Table S3 lists all these glaciers, and provides
 1110 additional information.

1111 **List of tables**

1112 **Table 1.** List of the different AWSs operating on Mera Glacier, or in its vicinity, with their elevations, operating periods, list of
 1113 sensors and associated meteorological variables used as forcing, optimisation or validation data of the SEB model. T = air
 1114 temperature, RH = relative humidity, u = wind speed, SWin = incoming shortwave radiation, SWout = outgoing shortwave radiation,
 1115 LWin = incoming longwave radiation, LWout = outgoing longwave radiation, P_a = atmospheric pressure and P = precipitation). The
 1116 numbers in brackets indicate the data gap of the variables (second column) or the uncertainty of each sensor provided by the
 1117 manufacturer (third column).

Station	Variables (gap % during the study period)	Sensors (uncertainty)
Khare Geonor 4888 m a.s.l. 25 Nov 2016 – 18 Nov 2020 Off-glacier, on a grassy surface	P (0)	GEONOR T-200BM (±15%)
Mera La AWS 5350 m a.s.l. 01 Nov 2016 – 31 Oct 2020 Off-glacier, on a rocky surface	T (0), RH (0) u (1) SWin (0) LWin (0) P _a (0)	Vaisala-HMP45C* (±0.2°C; ±2%) Young 05103-5 (±0.3 m/s) Kipp&Zonen CNR4 (±3%) CS100 (±2.0 hPa)

AWS-L 5360 m a.s.l. 01 Nov 2016 – 31 Oct 2020 On-glacier (ablation area)	T (23.2), RH (23.2) u (25.8) SWin (23.8), SWout (24.0) LWIn (24.0), LWout (24.0)	Vaisala-HMP45C* ($\pm 0.2^{\circ}\text{C}$; $\pm 2\%$) Young 05103-5 (± 0.3 m/s) Kipp&Zonen CNR4 ($\pm 3\%$)
AWS-H 5770 m a.s.l. 11 Nov 2017 – 18 Nov 2020 On-glacier (accumulation area)	T (17.1), RH (17.1) u (17.1) SWin (17.2), SWout (17.2) LWIn (17.1), LWout (27.8)	Vaisala-HMP45C ($\pm 0.2^{\circ}\text{C}$; $\pm 2\%$) Young 05103-5 (± 0.3 m/s) Kipp&Zonen CNR4 ($\pm 3\%$)

1118 * artificially aspired during daytime

1119 **Table 2.** Glacier-wide mass balance for Mera Glacier, point mass balance at AWS-L (obtained by averaging all stake measurements
1120 on Naulek branch between 5300 and 5380 m a.s.l.) and at AWS-H (obtained by averaging stake measurements close to AWS-H,
1121 from 5750 to 5790 m a.s. l.), as well as snow depths in the ablation area (annually measured during field campaigns in November)
1122 and in the accumulation area (assumed for the model). An ice density of 900 kg m^{-3} and measured snow densities were used to
1123 compute point mass balances (370 kg m^{-3} for Naulek, and 380 to 430 kg m^{-3} for the accumulation area). The error range for point
1124 mass balances is the standard deviation of all measurements.

Glaciological mass balance of Mera Glacier					
	2016/17	2017/18	2018/19	2019/20	2016-20
Glacier-wide mass balance* (m w.e. a^{-1})	-0.76 \pm 0.16	-0.92 \pm 0.16	-0.80 \pm 0.19	-0.49 \pm 0.22	-0.74 \pm 0.18
Mean point mass balance around AWS-L (m w.e. a^{-1})	-2.26 \pm 0.12	-2.34 \pm 0.19	-2.27 \pm 0.10	-2.10 \pm 0.24	-2.24 \pm 0.09
Mean point mass balance around AWS-H (m w.e. a^{-1})	0.16 \pm 0.01	-0.08 \pm 0.07	0.12 \pm 0.13	0.35 \pm 0.12	0.14 \pm 0.15
Snow depth in the ablation zone (< 5750 m a.s.l.) used for the model initialisation (m)	0.50	0.12	0	0.20	
Snow depth in the accumulation zone (> 5750 m a.s.l.) used for the model initialisation (m)	0.50 m at 5750 m a.s.l. and an additional 0.20 m for each 100 m increase in altitude				

1125 * updated from Wagon and others (2021)

1126 **Table 3.** List of selected parameters used in COSIPY, and manually tested before running our optimisation procedure. In bold are
 1127 the 5 most sensitive parameters that are optimised from a plausible range of values (Min-Max range, taken from the Mölg and
 1128 others (2012) and used in this present study). The investigated range of max-min values for the roughness lengths is also shown.

Parameters	Min	Max	Optimised/default
Fresh snow albedo	0.82	0.88	0.85
Firn Albedo	0.50	0.60	0.55
Ice albedo	0.25	0.35	0.30
Albedo time scaling factor (days)	3	9	3
Albedo depth scaling factor (cm)	2	14	4
Roughness length for fresh snow (mm)	0.19	0.29	0.24
Roughness length for firn (mm)	1.5	6.5	4
Roughness length for ice (mm)	0.7	2.7	1.7

1129 **Table 4.** The range of different objective function values in the first 200 Pareto solution space for 2018/19 period at AWS-L.

Objective function	Albedo	Surface temperature	Mass balance
$f_1(\theta)$	0.31-0.54	0.87-0.92	
$f_2(\theta)$	0.11-0.15	1.58-2.33 °C	
$f_3(\theta)$			0-1.28 m w.e.

1130 **Table 5.** Annual and seasonal surface energy fluxes ($W m^{-2}$) and their contribution to the total energy intake (Q_{in}) and outtake
 1131 (Q_{out}) over the whole Mera Glacier area, at AWS-L and at AWS-H. The annual values are calculated between 1 November to 31
 1132 October of the following year, using all data over the study period. The negative (-) sign indicates the energy loss from the surface.
 1133 Winter = Dec-Feb, Pre-monsoon = Mar-May, Monsoon = Jun-Sep, Post-monsoon = Oct-Nov.

	SWin	SWout	SWnet	albedo	LWin	LWout	LWnet	QL	QS	QC	QR	QM	Qin	Qout
Annual values ($W m^{-2}$)														
Glacier-wide mean	215	-139	76	0.65	229	-273	-43	-13	4	4	0	-22	453	-447
AWS-L	227	-134	93	0.59	235	-278	-43	-14	4	3	0	-34	470	-460
AWS-H	218	-157	61	0.72	225	-269	-44	-13	4	5	0	-15	453	-454
Seasonal Glacier-wide ($W m^{-2}$)														
Winter	183	-107	76	0.59	172	-237	-66	-22	13	4	0	-2	372	-368
Pre-monsoon	274	-191	83	0.71	217	-268	-51	-16	1	4	0	-17	496	-491
Monsoon	195	-133	61	0.70	296	-306	-10	-2	0	2	0	-43	491	-485
Post-monsoon	217	-121	96	0.56	199	-265	-66	-15	4	9	0	-18	429	-420
Seasonal AWS-L ($W m^{-2}$)														
Winter	196	-113	83	0.58	178	-247	-69	-26	13	5	0	-2	392	-388
Pre-monsoon	287	-200	87	0.70	223	-275	-52	-16	1	5	0	-22	517	-513
Monsoon	201	-113	88	0.56	302	-307	-5	-1	1	-3	0	-66	504	-490
Post-monsoon	235	-108	127	0.46	205	-273	-68	-18	4	6	0	-33	450	-432

Seasonal AWS-H (W m ⁻²)														
Winter	183	-120	63	0.66	167	-231	-63	-19	15	3	0	0	368	-369
Pre-monsoon	280	-204	76	0.73	212	-265	-52	-17	1	4	0	-13	496	-498
Monsoon	198	-155	43	0.78	291	-305	-13	-4	-1	5	0	-29	494	-493
Post-monsoon	221	-146	75	0.66	195	-261	-66	-15	4	10	0	-12	430	-433

1134 **Table 6.** Glacier-wide annual and seasonal mass balance components (mm w.e.) over the total glacier area and at point scale at
 1135 AWS-L and AWS-H using all data over the study period 2016-20. The negative (-) sign indicates a mass loss from the surface.

	Snowfall	Sublimation	Surface melt	Subsurface melt	Total melt	Refreezing	Mass balance
Annual means (mm w.e.)							
Glacier-wide mean	718	-150	-2095	-88	-2183	956	-656
AWS-L	641	-164	-3194	-88	-3282	659	-2144
AWS-H	792	-149	-1434	-88	-1522	1174	297
Seasonal Glacier-wide (mm w.e.)							
Winter	77	-62	-43	-4	-47	27	-4
Pre-monsoon	137	-48	-395	-20	-415	298	-27
Monsoon	479	-10	-1366	-53	-1419	489	-461
Post-monsoon	25	-30	-291	-11	-302	142	-165
Seasonal AWS-L (mm w.e.)							
Winter	77	-74	-51	-6	-57	41	-12
Pre-monsoon	136	-50	-519	-29	-548	368	-94
Monsoon	403	-4	-2098	-47	-2145	191	-1554
Post-monsoon	25	-36	-526	-6	-532	58	-485
Seasonal AWS-H (mm w.e.)							
Winter	77	-54	-11	-1	-12	11	22
Pre-monsoon	138	-51	-309	-17	-326	275	37
Monsoon	551	-15	-929	-57	-986	701	251
Post-monsoon	26	-29	-185	-12	-197	187	-13

1136 **Table 7.** Mass balance anomalies as compared to the mean of the four 2016-20 years from the classical and synthetic scenarios'
 1137 methods.

Sensitivity	Classical method (m w.e.)	Synthetic scenarios (m w.e.)
-1 °C T	+0.41	+0.93 ± 0.18
+1 °C T	-0.61	-0.75 ± 0.17
+20 % P	+0.48	+0.52 ± 0.10
-20 % P	-0.79	-0.60 ± 0.11

1138
 1139 **Table 8.** Comparison of SEB components on different glaciers in HMA, whose location is visible in Fig. S18. The various studies
 1140 already included in Azam and others (2014) are not reported in this table. (All the fluxes are in W m⁻²)

Glacier Name	Study type	Altitude (m a.s.l.)	Region (ISM dominated, Y or N)	Study Period	SW net	LW net	QS	QL	QC	QM	Reference
Parlung No. 4	Point/annual	4657-5937	southeast Tibetan Plateau, China (N)	1 Oct 2008 to 21 Sept 2013	77	-46	11	-21	1	-22	Zhu and others (2018)
Zhandang	Point/annual	5515-5947	western Nyainqen Tanglha Range, China (Y)	1 Oct 2008 to 21 Sept 2013	69	-49	14	-13	-1	-20	Zhu and others (2018)
Purogangri ice cap	Glacier-wide/annual	5350-6370	Tibetan Plateau, China (Y)	Oct 2000 to Oct 2011	36	-39	28	-22	-1.3	-2	Huintjes and others (2015)
Qiangtang No.1	Point/annual	5882	inland Tibetan Plateau, China (Y)	Oct 2012 to Oct 2016	49	-56	26	-15	2	-6	Li and others (2018)
Rikha Samba	Glacier-wide/annual	5427-6515	Central Himalaya, Nepal (Y)	Oct 1974 to Sept 2021	105	-74	-20*		NA	-12	Gurung and others (2022)
Naimona'nyi	Glacier-wide/annual	5545-7262	western Himalaya, China (Y)	Oct 2010 to Sept 2018	77	-69	12	-16	2	6	Zhu and others (2021)
Dokriani	Glacier-wide/annual	4050-6632	western Himalaya, India (Y)	1979 to 2020	68	-35	9	-32	NA	-10	Srivastava and Azam (2022)

Chhota Shigri	Point/monsoon	4670	western Himalaya, India (Y)	8 Jul to 5 Sept 2013	202	-14	31	11	4	-233	Azam, and others (2014)
Chhota Shigri	Glacier-wide/annual	4070-5850	western Himalaya, India (Y)	1979 to 2020	77	-57	15	-25	NA	-10	Srivastava and Azam (2022)
Srutri Dhaka	Glacier-wide/annual	4500-6000	western Himalaya, India (Y)	Oct 2015 to Sept 2017	157	-85	7	-5	-3	-71	Oulkar and others (2022)
Muztag Ata No. 15	Point/annual	5237-5935	eastern Pamir, China (N)	1 Oct 2008 to 21 Sept 2013	69	-61	18	-24	0	-2	Zhu and others (2018)

1141 *corresponding to QS+QL here

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